Centralized operational strategy for container transport in a synchromodal transport system

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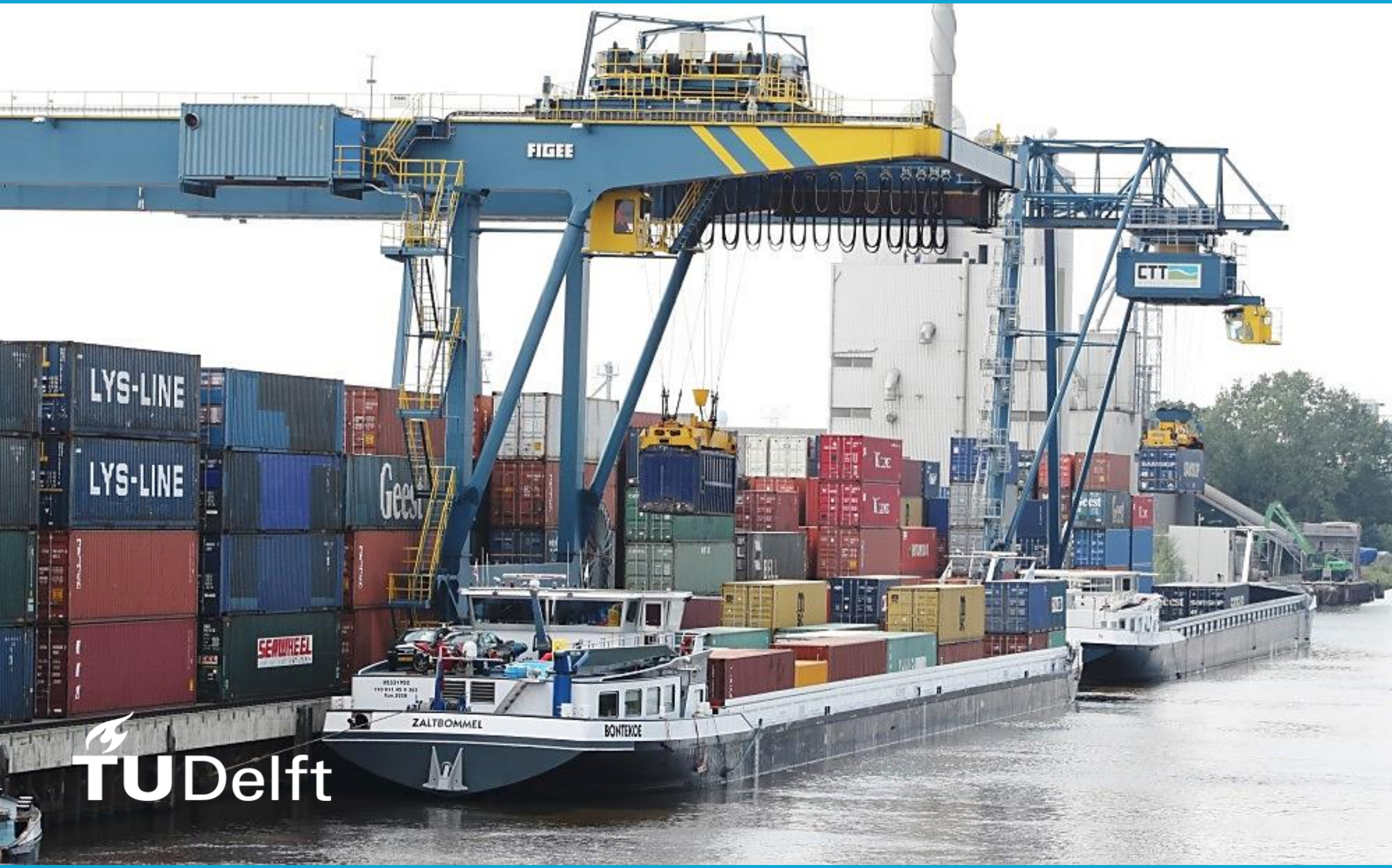

Centralized Operational Strategy for Container Transport in a Synchromodal Transport System

By

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Abstract

In time of fast globalization and urbanization, the volumes of transported containers have significantly increased in the last decades. The challenges of operating with high volumes of containers have propagated from the deep-sea terminals into the hinterland network resulting in extensive use of road transportation, long waiting times and high carbon emissions. Synchromodal transport has addressed these challenges by promoting integration of services and real-time decisioning to increase the overall flexibility of the system. However, little is known about the effects of applying flexible concepts on operational planning decisions and whether these decisions have reflection on the performance of the system when centrally taken. This paper proposes a research for a design of an operational strategy which supports operational decisions on container routing and mode choice among trucks and barges. Model Predictive Control planning approach is applied to optimize the simultaneous routing of containers, trucks, and barges. The effectiveness the proposed strategy is evaluated in the presences of increased container volumes and compared to a Benchmark strategy by the means of simulation experiments. The impact of implementing flexible decisions on system performance and realized operational costs is investigated.

Keywords: Synchromodality, Container routing, Centralized Model Predictive Control, Simultaneous Routing Modelling, CTT network

1. Introduction

1.1. Background

Since the introduction of containers in the 1960s, a revolution in transport has been observed. Containerization has essentially facilitated the growth in global trading of goods on the one hand and the demand for capacity and sufficient infrastructure on the other. In 2017, a considerable increase of port activities and cargo handling was observed as more than 752 million of TEUs were transported according to United Nations Publications, (2018). This amount of containerized cargo is a rise of 42 million TEU containers compared to the previous year of 2016.

Overall, in 2017 container transport was estimated to count for slightly higher than 17% of the world seaborne trade. Induced by the global economy expansion the tendency for growing volumes is foreseen to continue with similar tempts until 2023 as the containerized cargo is expected to grow the fastest. The main routes between Asia, North America, South America, and Europe tend to remain busy. Containers are transported on regular linear services operating on fixed schedules. The cargo is transferred between specialized container terminals equipped with specific sea-to-shore gantry cranes to load and unload the containers. Once on the shore, the inbound containers are carried to a stacking area by port vehicles which may be operated either manually or automatically (AGV's). Subsequently, containers are loaded on alternative transport modes as trucks, trains or barges and sent to their destination. The outbound containers follow the same steps but in inverse order.

Of the top 10 ports of the EU, five are located on the North Sea. Rotterdam, Antwerp, and Hamburg ports maintain the top three European ports with the highest volumes of processed containers. According to Eurostat, (2020) Port of Rotterdam is the largest European port where 13.8 million containers were handled in 2018. Container hubs serve as a door to the mainland of Europe, hence an efficient transport system with the hinterland is essential for keeping a competitive position on the market. Nowadays, seaports not only invest in infrastructure and equipment to maintain their competitive position on the market, but also focus on the development of their connections to the hinterland network for several reasons. As part of the global supply chain, the hinterland network has the responsibility to transport the cargo in the most efficient and cost-effective manner (Behdani et al., 2020). Cheaper and faster hinterland connections are the focal point for ports in terms of their attractiveness to shippers and carriers (Konings and Priemus, 2008). Moreover, investing in reliable hinterland access may also lead to a reduction in terminal congestion and faster container release (Franc and van der Horst, 2010).

Due to the continuous growth of container volumes, the hinterland connections evolve to multi-modal transport logistic centres where high-quality and cost-efficient services are offered. Yet, the enormous increase of container throughput in seaports propagates further into the hinterland network and provokes disturbances to the entire supply chain. The hinterland transport of goods is still considered the weakest point of the chain which presents the notable 60% of the total supply chain cost (Beresford et al. 2012).

To understand the dynamics of the present hinterland networks and the involved actors, Notteboom and Rodrigue (et. al, 2007) propose a four-layer approach. This approach consists of locational, infrastructural, transport and logistical layers. The latter two layers comprise the freight transport operations provided on multi-modal links in a transport network and the integration of the supply chains into the hinterland logistic chain. These two layers are going to be briefly introduced in the following sub-section.

1.1.1. Hinterland Transport Network

The transport layer of hinterland networks has been defined by Notteboom and Rodrigue (2007) as: *'The transport layer involves the operation of transport services on links and corridors between the port and other nodes within the multimodal transport system and the transhipment operations in the nodes of the system. It is a matter of volume and capacity '.*

The transportation services on the hinterland links are executed mainly by three transport modes: trucks, trains, and barges. Each of the transport modes has its characteristics and advantages over the others. Further in this section, the specifics of each transport mode are going to be briefly covered.

Road transportation remains the most intensively used way for moving containers between seaports and hinterland. The well-developed road network, especially in Northern Europe, is extensively used for freight transport. Trucks can cover large distances and reach almost any point on the continent. Once an inbound container is unloaded from a vessel, it can be easily loaded on a truck without the necessity of sophisticated and expensive equipment. Containers remain unsealed and can be sent to other inland terminals, hubs or directly to its consignee thus offering a door-to-door service Furthermore, the truck industry is extremely competitive, and its temps of development are visible compared to the other modes of transport. In technical terms, trucks have become more safe, economic, and reliable. For instance, researchers are investigating the possibilities for minimizing operational cost and energy consumption by using alternative fuels and implementing truck platooningIn terms of operations, barges and trains are often routed on fixed schedules.

As opposed to trucks, reliability and attractiveness of barge and train transportation are strongly dependent on the quality of services at the terminals. Nowadays, terminals play crucial role in the efficiency of a transport supply chain by offering wide variety of services. Terminals do not offer only transshipments of containers, but also empty container storage, container maintenance and sometimes container warehousing and assembling activities. Containers are usually being moved from a main stack by a straddle carrier and brough to a gantry crane which load the container to a barge. Regularly at sea terminals, the handling of inland barges is performed with the same cranes which handle deep sea vessels. Yet, with the more extensive use of barges, many terminals invest in smaller barge quay-cranes. Train compositions are loaded with containers in the same manner as trucks, only by the means of straddle carriers. In terms of equipment type, layout and working methods, inland and sea terminals do not differ considerably.

Promoting the use of alternative modes as inland shipping and railway transport is the primary measure to decrease not only the environmental footprint of trucks, but also to generate economies of scale and reduction of costs (Fransoo & Lee, 2012). Trains and barges are favoured for their potential to consolidate cargo and transfer it to distant destinations. Compared to trucks, barges and trains have higher capacities and are able carry significantly more containers. By taking advantage of economies of scale, lower costs for transporting a container can be offered to the customers. Moreover, the additional capacity can be used for repositioning of empty containers and facilitate different services at inland terminals. Water transport and trains are environmentally friendly alternative to road trucks with their more energy efficient characteristics.

1.1.2. Hinterland Logistic Layer

The logistical layer involves the organization of transport chains and their integration in logistical chains. In this layer we can observe the presence of many actors as terminal operators, freight forwarders, shippers, operators, consignees, etc. The interaction among the actors is driven by the desire to fit the requirements of the supply chain which they operate with. The types of decisions taken in the logistic layer are mainly towards 1) the design of the used network; 2) the choice of the appropriate transport terminals and frequency of services ;3) the selection of suitable combination of transport services to route in the inland section of the transport chain (Notteboom and Rodrigue ,2007). The specifications of the three types are presented in Table 1.1.

Decision Type	Time Horizon	Core Activities	Factors
Strategic	Long term	Network Design	Government policies Market size Link accessibility Land nature Labour characteristics
Tactical	Mid-long term	Service Design Frequency of offered services	Network connectivity Available transport modes within the network Cargo volumes
Operational	Short term	Routing of transport modes	Customer requirements Fleet specifications Product Costs Congestion on links

Table 1.1: Decision types in the logistical layer

In Northwest Europe, we can observe many large deep-sea terminals and inland locations which accommodate different services and interact strongly with each other. Sea terminals no longer solely rely on their internal performance and tend to expand their reach in hinterland network by creating strong links with inland terminals. At the other end, inland terminals tend to establish increasingly efficient links to maritime gateways hence they can provide customers with higher range of services. Thankfully to the well-developed infrastructure and connectivity, actors in transport chains can choose among several types of modes and terminals to use. There are sufficient volumes of containerized cargo from and to the ports of Rotterdam, Antwerp, and Hamburg. Logistic providers have many opportunities to forward their containers and satisfy the demand of customers. On the one hand, they offer frequent services with inland barges or cargo trains and take advantage of economies of scale. On the other hand, flows can be propagated via the fast truck connections to almost any point in Europe. Based on customer requirements, companies can opt for direct shipping without going to distribution centres, go through a main distribution centre where cargo is consolidated or split the flows through several regional or national distribution centres. The choice depends on many varied factors as perceived economy of scale, product, and fleet specifications, share of transport cost out of total operational cost and many more. Companies differ in their operational strategies and opt for the decisions which best fit customer and market requirements.

Overall, port-hinterland dynamics at the logistic layer are overly complicated. This complexity has driven the desire in different actors to adopt approaches which are more oriented to their supply chains. Apart from costs and capacities, more attention is given to modal-choice and routing decisions. Nowadays, it is realized that the position of ports in the market does not only depends on its internal performance. What bring value to the competitiveness is the ability of ports to establish reliable and flexible connections with their hinterland partners in the face of inland terminals. Greater options for routing provided to shippers and logistic providers enhances the logistic attractiveness of a respective location (Notteboom and Rodrigue 2007).

1.2. Synchromodal Transport

Driven by the ambition to improve the performance of multi-modal networks and answer the new dynamics in transport business, many researchers have investigated the potential of a relatively new concept called "Synchromodal transport". Bart van Riessen et al., (2015) provided a concrete definition of the concept as:*" Synchromodality is the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for his (inland) transport."*

Synchromodality is the opportunity of logistic providers to design unique services to each of their customers. What makes this possible is the feature of synchromodal transport to integrate horizontally the transport system. 'Horizontal integration' is knowns the possibility to use different combinations of modalities based on their characteristics, availability in real-time, and customer requirements (Bart van Riessen, 2015). As a result, not only each customer can be served by the most suitable mode, but also logistic providers can constantly take optimal decisions by balancing service quality and operational costs.

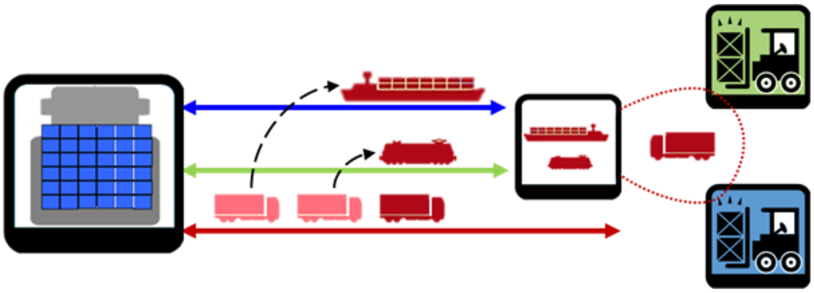


Figure 1.1: Horizontal integration of transport services (Bart van Riessen, 2015)

Even though Synchromodality is a relatively new concept, there are several assumptions which hold among all research. Synchronization of "Moving Resources "and "Stationary Resources" is aimed to be achieved by implementing flexible deployment of transport modes, mode-free bookings (a-modal booking), network- wide planning and Real-time switching. The integration of all network resources is expected to achieve favourable economies of scale and increase customer satisfaction with the supply chain. Synchromodality is considered as an extension of intermodal transport by including real-time re-routing of modes over a given infrastructure to cope with the presence of disturbances and customer requirements.

There are many factors which are assumed crucial for the adoption of synchromodality. Singh et.al., (2018) identifies three categories of ‘pre-requisites’ which can facilitate the successful implementation. Some of the key ‘enablers’ include integrated policies and governance towards cooperation, integrated transport system with shared infrastructure, coordination of supply chains, and high volumes of freight. Technologies are essential as well as intelligent systems can be used to reflect on the real-time changes in the system and organize the data shared among the different shareholders.

Additional success factors were found by Pfoser et al., (2016) who verified them by conducting interviews with experts in the transport markets. The most crucial factors for success were identified to be cooperation and trust between involved stakeholders followed by awareness and mental shift. Moreover, he identifies the need for new pricing and cost strategies. Nowadays, prices for customers are formed based on their mode preferences and time requirements. In synchromodal transport this decision is left in the hands of the logistic providers based on real-time availabilities of modes and terminals. A full list of the factors with descriptions is presented in the further in the literature review in the following Section 2. Additional elaboration on the distinct categories of enablers can be found in the works of Tavasszy et al., (2015) and van Riessen et al., (2015).

The reason for all the attention which Synchromodal transport concept receives from both researchers and experts is the eventual positive effects on the supply chain performance. By performing flexible planning and real-time scheduling logistic provider can achieve higher utilization rates of their resources and avoid the presence of dominant routes in their network. Furthermore, synchronization of routing decisions and mode combinations is believed to increase the reliability of the supply chain and eventually reduce operational costs. Environmental benefits are also possible in synchromodal networks, as all resources are used efficiently hence more cargo is assigned to greener modes as barges and trains (Pfoser, 2016).

Even though synchromodality needs more time to develop to its full potential, the number of companies which implement the concept is increasing considerably. An instance of the enthusiasm of logistic actors to collaborate and share the benefits is the Dutch project ‘Lean and Green’ (*Deelnemers*, 2019). List of all participating companies and their achieved goals is presented in the official website.

1.3. Problem Statement

Frémont (et al., 2009) divide the factors for successful inland barge and train transportation in five categories. An overview of the factors and the necessary conditions for the development of waterway and train transport is presented in Table 1.2. It is observed that the first two factors require considerable investments, while the other three factors are highly dependable on the individual actors in the system. Generally, the barge and terminal operators, as well as the forwarders operate separately and barely integrate their actions.

Available infrastructure	**Presence of infrastructure and equipment which serve larger container flows and provides connection to hinterland locations**
Characteristics of the market	Sufficient transport flow between the seaports and hinterland locations
Services at the terminals	Presence of inland terminals where container flows are stored, transhipped, or sent to their destination

End-haul Road transport	Competitive price for the last leg of container transport
Organization of the market	Integrated and coordinated end-to-end service provided to the customers

Table 1.2: Factors and conditions for successful inland waterway and rail transport (Frémont, 2009)

Current representations of a synchromodal transport network consider that only trucks operate in a flexible manner reaching all locations while barges are routed on predetermined schedules between fixed points. Terminal operators predetermine the free spots for both barges and trains and the time when they can be handled. In this manner terminal operators are not available to take advantage of the additional capacity of barges when are not scheduled efficiently. Because of this, it is interesting to investigate the possibilities which open to transport operators when their barge services and routing decisions are not strictly scheduled.

When barges are routed on linear services, it is more challenging for a system operator to react on different scenarios in the system. If barges are operated on fixed schedules, a coordinator of a synchromodal transport network is not able to utilize the additional barge capacity when its needed. For instance, a batch of containers is unloaded from a deep-sea vessel at container terminal, the coordinator has the options either to store the containers onsite and wait for a barge or to transport them immediately by trucks. When optimizing the performance of the entire system, the coordinator can send a barge with available capacity to pick up containers and release the pressure from congested terminals. Flexible routing of barges can provide more freedom to the system operator by giving him the options to route not only containers and trucks, but also to optimally route barges. This freedom can result in less cases of cargo delays, lower operational costs, higher utilization of transport modes and shorter time spent at terminals by barges.

What is more, barges often need to wait to enter a terminal because of inadequate planning or given priority to bigger vessels. As a result, considerable deviations from the original schedule took place and propagate further in the supply chain. Subsequently, trucks are extensively used to transport the container orders intime and compensate for the delays. When barges are not sticked to a fixed schedule, the coordinator of the synchromodal network can change the destination of the barge and reallocate the containers onboard. In this way, not only available capacity at terminals can be used more efficiently, but also barges stay at terminals is optimized.

1.4. Objective and Research Goal

Generally, synchro-modal transport concentrates thoroughly on improving the performance of the hinterland network in terms of costs, capacity, environmental impact, and customer satisfaction. Yet, number of existing research and models in this field are limited. A gap in the literature is the individual routing of barges together with containers and trucks and taking more advantage of economies of scale. This research elaborates on the consequences of introducing non-schedule services of barges and considering introducing flexible barge routing. This has the potential to results in higher service quality, by new optimal routes for both containers and transport modes and better utilization of the network. This study can contribute for the adoption of synchromodal network by showing the benefits of giving more freedom to the planner operator of the system.

To be able to access the overall system performance when more flexible services are introduced, it is important to determine the efficiency of the taken planning actions. This research especially focuses on routing container flows in hinterland network simultaneously with transport modes. The objective of the proposed research is to study the effects of proposed planning strategy for operational decisions on container transport in a synchromodal transport network with the presence of increased demand for container flows. The main objective of the research will be reached by answering the following research question:

How can a decision-making strategy for flexible container and mode planning facilitate operators to achieve a desired performance of a synchromodal transport system?

The main research question is going to be answered with the aid of the sub-questions presented in the further in this paragraph. Firstly, the design and control of a multi-modal synchromodal transport network are defined and examined:

1) *How are operations and disturbance management currently organized in a synchromodal transport system?*

Subsequently, a sub-question investigates how evaluation criteria of synchromodal transport correlate with performance indicators for hinterland transport system:

2) *What are the performance indicators for hinterland container transport according to stakeholder's perspective and what are the additional performance requirements applied to synchromodal transport?*

The subsequent sub-question below considers the definition of the system and achieving its desired performance by:

3) *How can a Model predictive control (MPC) approach be implemented in a decision-making strategy for the flexible planning of containers, trucks, and barges in a synchro-modal system?*

The following sub-questions below aims to evaluate the effectiveness of the proposed operational strategy towards a desired system performance with fluctuations in demand:

4) *Which transport variables and parameters should be incorporated in the design of well-founded cases for making a performance analysis?*

5) *To what extent can an MPC system operator handle system disturbances emerging from increased demand in container flows?*

6) *How does short-time scheduling of barges influence the overall operational cost of a synchro-modal system compared to a fixed long-term scheduling?*

1.5. Outline

In the present chapter of the report, an introduction to synchromodal transport was made followed by a problem definition, objectives of the current research and the research questions which we will try to answer. In the following Section2 a review of the literature on different decision-making strategies on operational level is going to be performed. Tendencies in modelling approaches of network configurations, dynamics and fleet compositions are going to be analysed. The recent work on synchromodal transport and the application of Model Predictive Control (MPC) is going to be review. In the following Section3 a planning strategy with a centralized MPC approach is going to be presented. Further in this section, the formulations of the designed strategy and a Benchmark strategy are given.

Section4 presents the Case study of the CTT network and the construction of the conditions under which numerical simulation experiments are going to be conducted. In Section5 the results from the simulations with the proposed strategy are analysed and compared to the results of the runs with the Benchmark. Both strategies are applied on identical scenarios. In Section6 conclusions from the performed research are presented. Answers to the research questions are given. Section7 presents practical insights of the work and its limitations. Recommendations for further research in the area are proposed as well in the last section.

2. Literature review

In this chapter, the literature is revised in fields found to be relevant for this thesis. In Section 2.1 the studies which are considering the main types of decisions in hinterland container transport are revised. Studies related to the concept of synchromodal transport is presented in Section 2.2 describing system dynamics, expected performance indicators, and revising previous studies which model a synchromodal hinterland network. Subsequently, studies with previous applications of model predictive control (MPC) on container transport systems are presented in Section 2.3. Lastly, Section 2.4 a literature summary is provided.

2.1. Hinterland Container Transport

The first definition of 'Hinterland transport network 'came in the beginning of the last century by Sargent et. Al. (1938) as 'the area which a port serves. Since then, hinterland transport networks have been extensively investigated by the researchers through the years in terms of its structure and internal dynamics. A more detailed research about the trends of evolution in the port-hinterland concept can be found in the review of Sdoukopoulos and Boile (2020).

A port-hinterland transport system generally aims to transfer cargo from the deep-sea terminals to the final customers via different transport modes as trucks, barges, and trains. With the extensive developments of infrastructures and increased volumes of container flows, more actors got involved into the operation and offering of transport services in hinterland systems. Instances for involved actors are barge operators, terminal operators, and shippers. With the development of technologies and introduction of innovations the operations and dynamics of these system evolves as well. Example for this is the evolution of barge activities which nowadays offer a door-to-door logistic solutions to the customers (Tavasszy, 2015).

2.1.1. Strategic Decisions

Currently, the focus in literature is put mainly on the development of the hinterland network and the design of the terminals in it. These works consider the decisions which are taken on a strategic level. We recognized three main directions of strategic research: design of networks, evaluation of the networks and bottlenecks of networks. There are variety of approaches which are observed as case studies, optimization models and simulations systems. For the purposes of this project, we are going to shortly review the papers where optimization strategies are applied.

LIMBOURG AND JOURQUIN (2005)

In terms of network design, different combinations of network configuration and mode combination can be found in literature. Limbourg and Jourquin (2005) investigate the potential locations for intermodal terminals in a hub-and-spoke network. They develop an optimization model which incorporates international rail and road transport of containers. The developed model estimates the best location for such a hub by estimating an objective function with pre and end-haulage costs. An iterative procedure based on a p-hub median problem and multi-modal assignment model. Transhipments of containers are allowed in hubs, yet with a limited number. Furthermore, capacity constraints on the railway network are not considered. The same approach is applied in a hub-and-spoke design of Rodríguez-Martín and Salazar-González (2008) applied on a capacitated road and air network.

YAMADA (ET AL., 2009)

Apart from network design, existing studies evaluate the performance of hinterland networks, efficiency, resilience, etc. For instance, Yamada (et al., 2009) proposed a strategy for strategic planning of freight transportation particularly proposing new road links, railways, sea ways or freight terminals for improving the current state of the network. The best combination of improvement activities is selected from a predefined set of actions that includes the feasible options for developments. Their model was applied to the network of the Philippines. More examples for application of optimization models on strategic and tactical level can be found in literature (Limbourg & Jourquin, 2009; Iannone (2012); Lu and Yan (2015); Button et al. (2017)).

2.1.2. Operational Decisions

Mathematical modelling also widely applied on solving problems and analysing decisions taken on operational level. The most common goal of these models is to identify the lowest value of an objective function which incorporates the costs for operating the services in the network. For the construction of our operational strategy, we are going to dive into the literature which discuss the operations of a hinterland network offering multiple transport services. Papers which incorporate the routing of barges without the presence of trucks or trains are going to be revised as well due to the used modelling techniques.

ALFANDARI ET AL. (2019)

Alfandari et al. (2019) addresses a problem of optimal planning of container shipping company which operates on a linear service. The designed strategy aims to maximize a profit function by determining which containers to transport and how to route a barge fleet among predefined set of ports. The model is based on several assumptions. Firstly, the ports which are visited in the outbound-inbound direction is given. This is considered as the natural way of scheduling routes in the inland waterway transport. Secondly, the port calling sequence starts and end at port 0. Thirdly, there is no possibilities for transhipments. Lastly, the port at which the ship turns its direction it is not known in advance. In this way, there is no limit for the turnaround time of the routed ship.

The contribution of this work is twofold. On the one hand, the paper of Alfandari (2019) gives an exact solution approach for barge routing which simultaneously choose the optimal barge route, considers empty container repositioning, optimize the turnaround time of a barge, and selects the final port of the rotation. On the other hand, a second formulation of the problem is provided where a utilization of node variables is applied for the route design instead. In the alternative formulation of the problem, the empty containers are modelled as single commodities which can be picked up or delivered at any port in contrast to the full containers. The pros of this formulation are that there are less decision variables and problems of bigger scales can be solved fast.

The results of the applied strategy showed an increase in profit when turnaround is optimized together with empty container repositioning and splitting of demand. Yet, these results were obtained by considering identical routes for all ships where transhipments of containers are not allowed. Furthermore, the model does not consider the presence of other transport modes operating in the hinterland network.

FAZI ET AL. (2015)

Fazi et al. (2015) investigated the problem of imbalance inbound and outbound containers in the Northwest European supply chains. A case study is investigated with two available modes of transport: barges and trucks. In a hinterland transport network, a transportation planner decides how to route containers and modes based on information about the composition of the fleet, the release and due dates, the travel times and transport costs. The goal of the planner is to reduce the operational costs of delivering the containers by prioritizing the usage of barges to trucks due to economies of scale. This operational problem is referred by Fazi (2015) as hinterland allocation problem (HAP).

Barges and trucks are routed in a hub-and-spoke port-hinterland network with small number of terminals and possible routes between them. The sea terminals are modelled as clusters. The distance between a port in a cluster and other sea or inland terminals is defined as the distance from the cluster itself to these terminals. As the model considers the volumes of inbound containers the due dates are defined at the inland terminal. The fleet of trucks is limited to the overall number of containers and always available for transportation. Barges in the model starts and end their route at an inland terminal. They are available for routing only when containers at sea terminals are released. Modelled in this manner, eliminates the waiting time of barges at sea terminals.

The problem is modelled as Bin-packing problem with an objective to minimize the total cost of delivering all containers to the inland terminal and routing the transport modes. The problem is solved by the means of a Metropolis algorithm (MA) which is a remarkably like Simulated Annealing (SA) and Threshold Acceptance algorithms. More information about SA can be seen in Kirkpatrick et al., (1983). The MA algorithm starts by generating an initial feasible solution with a greedy procedure. Then these solutions are tested with a fixed parameter after which the best results are chosen. In this step all containers are allocated to barges. Subsequently, the barge route which satisfy the capacity constraints is determined by performing a local search.

The contribution of the paper is twofold. Firstly, the proposed model incorporates factors which are important for the transport planners and often missed in previous works as due dates, capacities, utilization levels and number of port visits. Secondly, the model integrates many strategic and tactical goals into an operational planning to provide a tool which optimize the routing of modes in a hub-and-spoke network. However, the model has its strong limitations as well. The fleet of trucks operating in the system is practically unbounded and always available for transport which practically unrealistic. Furthermore, the model lacks flexibility as barges are not allowed to start their journey before the containers are released at sea terminals. Transhipments of containers between barges and trucks at sea terminals is not assumed in the model.

ZWEERS ET AL., (2019)

Following this direction, Zweers et al., (2019) proposed a decision-making tool for the routing of inflow containers by trucks and barges with defined capacities. The focus of the work is the transportation of containers from multiple dee-sea terminals to a single inland terminal. Container shipments are characterized by time-windows, demurrage costs, and storage costs as container sizes are not considered. According to their call date, containers are given a priority class of being either low or high priority for transportation. Low priority containers are stored at the terminals or loaded on a barge whilst high priority containers are routed by trucks for a faster service. Barges are operating on a fixed schedule while trucks can depart and reach any point in the network. The goal of the planner is to maximize the number of containers which are routed by barges. If barge transportation can benefit from economies of scale, Zweers (2019) believes this goal might result in minimal transportation costs as well.

To solve the problem Zweers (2019) proposes three different algorithms: an optimal Integer Linear Program (ILP) formulation, a two-stage heuristic based on the ILP formulation, and an algorithm which simulate the behavior of an experienced planner based on interviews with experts. The optimal ILP formulation presents an optimization model with an objective function and capacity and conservation flow constraints. The proposed model does not calculate a route but only if a terminal is visited or not which reduces the computational complexity. This is used as a ground for two-stage heuristicc which first determine the barge routes and terminal visits, and later considers their allocation on the barge. Lastly, an algorithm based on experts' interviews is constructed to imitates the actions of an inland planner. The algorithm is a greedy algorithm which uses the first come first serve (FIFS) approach.

The three developed algorithms were applied on a real-life data case. The ILP formulation and the heuristic algorithms developed by Zweers (2019) showed benefits in cost savings compared to the planner approach by avoiding potential penalties for container demurrages supported by less visits of barges in the terminals. Even though container types were introduced to the model to support barge utilization, more containers were transported by trucks. Generally, the study has its contribution to the literature by introducing approaches which can deal with both small and large-scale instances in relatively brief time. However, the study has its limitations in considering only inbound container flows which can be transported on a given barge schedule. The work considers the possible collaboration of terminal and barge planners but does not provide a flexible approach which can adapt to any kind of changes within the network.

2.2. Synchromodal Transport

Even though, the concept of Synchromodal transport has been introduced relatively soon, researchers are investigating the potential benefits of its application. This Section includes the definition of the concept and the expected dynamics within a synchromodal network presented in Section 2.3.1. The main challenges towards a successful synchromodal transport network and their relevance for this thesis are explained in Section 2.3.2. Finally, the existing model representations of synchromodal networks are introduced in Section 2.3.3. with its contributions and limitations.

2.2.1. Dynamics in Synchromodal Transport Network

Synchromodality has emerged recently to provide more flexibility and reliability to the demand driven supply chains. The main purpose of the concept is reducing costs, emissions and delivering times while complying with customer requirements through smart utilization of available resources and synchronized transport flows. Synchromodality is considered as the optimal and flexible deployment of transport resources. The definition of Synchromodal transport used in this research is given by Bart van Riessen (2015) as:" *Synchromodality is the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for his (inland) transport*".

The characteristics of the synchromodality which are consistent with this definition and the purposes of the research are described below:

1) *Mode free booking:* In a synchromodal transport network a logistics service provider (LSP) has the freedom to decide how to transport the freight. By considering the available transport services the LSP can plan which vehicle to use, and which route should it take. In this way, the shippers or the consignees of the cargo give up on their transport mode preferences and only provide the volumes to be transported. Mode free booking is an essential characteristic of synchromodal transport as it allows LSP to choose the most efficient service for their customers.

2) *Dynamic planning of transportation:* Following the direction of the first concept, cargo is no longer assigned to a fixed type of transport vehicle. Hence, according to the demand the LSP manages to allocate the most suitable transport vehicles at separate places and optimize their usage. The dynamic planning gives the opportunity for introducing more flexibility in the system and increasing its robustness by taking advantage of the beneficial characteristics of each transport mode.

3) *Decisions based on network utilization:* The main driver for routing and allocations choices of both cargo and modes is the availability of capacity. As a result, network resources can be used more efficiently in terms of utilization and sustainability. Many researchers believe that this characteristic of synchromodality can achieve a desired modal shift to more sustainable and environmentally friendly transport modes.

4) *Real-time mode switching and replanning:* Nowadays, the well-developed infrastructure gives the LSP the possibility to use different transport modes to deliver the desired cargo. In a synchromodal transport network the LSP can change its decisions in real-time according to the situation and adopt adequately to changes in the system. In this way, the LSP can comply more efficiently with customer requirements for reliability and safety by offering continuous frequencies and availabilities.

5) *Cooperation between actors:* Coordination of services and infrastructure is one of the most vital enablers of synchromodal transport. Different actors cooperate among each other and share transport capacity and cargo volumes. The integration of moving and stationary resources is recognized as horizontal integration of freight transport planning which allows for parallel usage of different transport modes from origins to destinations. In comparison, intermodal transport strives for vertical integration of a chain where freight flows cannot be split to different nodes at any node of the network. The actors can cooperate in different structures to organize their responsibilities and information flows.

6) *Information systems:* Apart from infrastructure and capacity sharing, synchromodal transport requires information sharing among actors as well. Integrated intelligent systems can be used to share data and coordinate the actions of the LSP in terms of system disturbances and changes. Coordination of information can improve the trust among actors and their desire for cooperation.

The dynamics of operations in synchromodal freight transport system are specific. An agreement for freight transportation is made between shippers and service providers who can be LSP, terminal operators or freight forwarders. In this section we are going to refer to the service provider as transporters (T). The mode-free booking concept gives the freedom to transporters to choose the appropriate transport mode and its routing. Hence, instead of specifying typical parameters as departure time and mode of transport, the shippers provide only the volumes and due dates of freight in the order. In this manner, the T can decide which mode to use and when to start the journey.

The cooperation between the actors and the constant information sharing gives the opportunity for the T to replan the route and reschedule the operations. Depending on the actual situation, the transporters decide which modality can be used to meet the due time. For instance, a transporter decides to accept an order and transport a container from a seaport to a hinterland port by the means of a truck. Yet, the T receives information about possible delays on the highway and change its initial plan into loading the container on a barge and still satisfy the customer requirements of delivery time. This might also promote the more intensive usage of modes which benefits from economies of scale as barges and trains. However, the efficient use of network capacity in a synchromodal network is a result of the beneficial characteristics of trucks which does not concentrate only on barge and train utilization.

The core of synchromodality is the integration of the stationary resources (e.g., roads, rails, navigable waterways, terminals, and transshipment hubs) and moving resources (e.g., trucks, trains, and barges) which are constantly aligned with the requirements of the customers. This integration offers many advantages for the whole transport system including beneficial economies of scale and offering personalized service to each customer. Moreover, it is important to highlight that there are many actors who are involved in this system integration. The full benefits of synchromodality can be obtained if these actors are active in cooperation and information sharing especially when handling with uncommon operations. This can result in greater flexibility in mode choice and increase utilization of road, rail, and inland waterways (Behdani, 2014).

2.2.2. Performance Indicators of Synchromodal Transport

Despite being a promising idea, synchromodal transport is not as widely implemented as intermodal transport. As it was indicated in Section 1, many researchers display the factors which can lead to a successful implementation of a synchromodal transport network. For the purposes of this research, we are going to refer to the findings of Pfoser (2016). The deliverables of his work were found valuable due to the implemented methodology. He identified seven groups of critical success factors (CSF) by firstly conducting extensive review on synchromodal literature. Secondly, by conducting interviews with Dutch professionals involved in the implementation of a synchromodal project between Rotterdam-Moerdijk and Tilburg. In this way theoretical and empirical data was gather which was further listed and clustered. A CSF is defined is his research as: "*those critical factors or activities which are required to ensure the success of a business or a project, in the case of synchromodality, success factors which are necessary for a functioning synchromodal transport chain*". The seven groups of CSFs based on Pfoser (2016) are described below:

1) *Network Collaboration and Trust:* The coordination between highly diverse actors involved in a transport chain is a difficult challenge. Many companies are reluctant to cooperate with competitors due to uncertainties about risk-sharing or benefit-sharing. A mental shift is required to establish a transport network which is run by trust and desire for cooperation instead of severe competition. The main goal is to find the appropriate balance between both competition and cooperation, so different actors can successfully integrate their capacity and services.

2) *Sophisticated Planning:* An essential element of creating a functioning synchromodal transport network. The increased complexity of networks and real-time changes requires dynamic planning to comply with system disturbances and increased volumes of freight. The overall performance of the network can be optimized by the means of simulation models which include customer preferences, dynamic allocation of resources, forecasting and dynamical replanning when latest information is available.

3) *Information and Communication Technologies (ICT)/ Intelligent transport systems (ITS) Technologies:* The cooperation between actors is impossible when exchanging high-quality and standardized data is missing. Information from different stakeholders must be available to all actors of the transport chain so it can be effectively used it in dynamical planning and optimization. ICT and ITS technologies are needed to handle these challenges and reliably provide and organize the e data in the system. Further issues with security and protection of the acquired data must be solved so stakeholders have trust in either the system or the data.

4) *Physical Infrastructure:* The presence of developed infrastructure is important driver of synchromodal transport. One of the goals of synchromodality is to obtain better utilization rates of the existing infrastructure. This can be a result of using transport modes as inland barges and trains which can bundle cargo and carry more than one container compared to trucks. Therefore, to obtain this goal, there is a need of established infrastructure and operating corridors for these transport modes.

5) *Legal and Political Framework:* The legal and political conditions in the region make the other CSF possible. Regulations are needed to capture the new dynamics introduced by dynamical switching and last-minute planning. More specifically, there should be a clear understanding who is liable for losses, damages, or delays during the transportation process. Furthermore, there is a need for regulation which ensure the protection of sensitive data gathered and shared by the actors in the system.

6) *Awareness and Mental Shift:* There is a need for all involved stakeholders to understand the benefits from synchromodality. On the one hand, shippers/customers need to provide the transporters with more freedom by choosing only the destination of the order, the arrival date, and its volume. On the other hand, transporters have to justify the customer ‘s trust and provide reliable and safe service. It is crucial to raise the awareness on the benefits of synchromodal transport and to generate a mental shift in both customers and transporters. Moreover, the mental shift also includes the awareness of all actors that what brings the greatest contribution to the system performance is not the preparation of the transport but the ability to adapt to changes in the system and adequately select the best alternatives in such a case.

7) *Pricing/Cost/Service:* What would make synchromodality a competitive logistic concept is its fit with customer expectations for quality of the offered services. Customer perception for quality is found to be driven strongly by the price which needs to be paid for a service. Since synchromodal transport requires mode-free bookings and last time decisions, the pricing of the services gets more complicated. Routes and modes are unknown in advance and pricing cannot be formed in

advance based on these criteria. Therefore, there is a need for the introduction of new pricing schemes which are aligned with customer expectations.

This research intends to propose a decision-making strategy which can take flexible operational decisions and comply with real-time changes in the system. Based on the CSF presented above, the proposed strategy is going to be under the category of *Sophisticated Planning*. The proposed operational strategy needs to consider the dynamical allocation of available resources, forecasting and dynamical switching of decisions to model a well-organized synchromodal system. To evaluate the efficiency of the strategy we need to define appropriate performance indicators (KPIs) which are going to be applied on a simulated system. In the previous section, characteristics of the operations and decisions in a synchromodal transport network are described. The indicators need to focus on these dynamics which occur at operational level in the network and capture the effects of flexible decisions.

The first categories of performance indicators are describing the core activities of ports and transporters. The core activities relate to operations with transport modes, cargo storage and cargo handling operations. What can be found common between them is the limitation in capacity. For instance, terminals are not able to store infinite number of containers or park infinite number of trucks at their site. Similarly, each transport mode can store and transfer finite number of containers at one time moment. What synchromodality gives to transporters is the opportunity to allocate containers to terminals and transport modes according to the current available capacity in the network. Many researchers propose that synchromodality is going to support the more efficient use of modalities as barges which can bundle container flows and take advantage of economies of scale. It is interesting to investigate either the decisions towards more flexibility in a synchromodal network are going to release the pressure on terminals and increase the utilization of barges. Therefore, capacity utilization of different network components is going to be used as a performance indicator for the effectiveness of the taken decisions.

From the seven categories of CSF defined by Pfoser (2016), this work aims to contribute to the *Pricing/Cost/Service* factor as well. According to expert's opinion in the work of Pfoser (2016), customers make trade-offs between price and quality of a service. Generally, service costs are the main driver for customer attraction to a port or transport service. When a certain level of quality is established, users start looking for the lowest possible price to fulfil their order (Ha et al., 2017). If synchromodal transport network can offer the users attractive and lower costs for the operation of stationary and moving resources, the concept might gain more interest. Hence, service quality and operational costs are going to be selected as indicators for the potential user's satisfaction with the system.

Overall, the KPIs used in this thesis can be classified into three categories: 1) Service Quality, 2) Operational Costs, and 3) Capacity Indicators. These KPIs can also be prioritized according to the objectives of the research. Considering the main research question, the term 'a desired system performance' is used relevant to delivering all container orders on time. Therefore, the KPI which counts the number of delayed containers and categorized as 'service quality' is going to have the highest priority among the other KPIs. Afterwards, the KPI 'operational cost' is going to be considered as the second most important indicator. As it is described in the paragraph above, customers are constantly making the trade-off between service quality and costs. Therefore, better values in this KPI can facilitate the adoption of the synchromodal transport concept. Lastly, the third priority category of KPIs is 'Capacity Indicators'. This category incorporates the utilization levels of stationary and moving system components. Even though, this category is essential for evaluating the effectiveness taken decisions in a synchromodal system, it does not gain as much interest for the adoption of synchromodality as the previous two categories. Therefore, capacity indicators have the lowest priority among identified KPIs.

2.2.3. Studies of Synchromodal Networks

An overview of the papers which relate themselves to synchromodal transport can be found in Ambra et al. (2018). Among the two most frequently applied methods in the literature are found to be analytical modelling and simulation modelling. The main directions of synchromodal operational research identified in the literature are discussed further in this section. A comparison between synchromodality and the applied concept of intermodal transport is presented further in this section.

JIN ET AL. (2018)

The benefits of synchronized operations in a supply chain and transportation have been indicated in the works of Jin et al. (2018). Jin (2018) proposed a design for feeder services in a network where feeders visit port terminals on fixed schedules. The main goal of the paper is to synchronize the transhipment of containers between large sea vessels and feeder vessels within a terminal hence the schedules of both are adjusted optimally and terminal congestions are avoided. Jin (2018) formulates the problem as a set covering model in which each column includes compact information related with feeder vessels: sequence of port-calls; vessel types; number of vessels; cycle time; hub-visiting slot assignment. A column generated based approach is applied to solve a case study on the Southeast Asia container shipping network. More details about the formulation of the problem and the characteristics of the designed services can be seen in paper JIn (2019), yet the descriptions are short and excessively summarized.

QU, ET AL (2019)

The possibility to change decisions dynamically and adapt to disturbances in a synchromodal network is applied in the methods used in Qu, et al (2019) and Rivera & Mes, et. al. (2017). Qu (2019) refers to the need of adequate changes in pre-designed schedules of hinterland transport systems when system disturbances are presence. Accordingly, the paper proposes a mixed integer problem formulation under the concept of synchromodality to deal with rerouting of shipment flows and replanning of terminal operations and services including transshipments. Flexibility on operational level in the system is achieved by the decisions of splitting or bundling of shipments supported by the opportunity to delay a barge or trains service from its predefined schedule. As a result, more shipments can be transferred from trucks to other transport modes. The model is tested on dealing with cases of late release of shipments, volume fluctuations and latency of barge and train services in the Rotterdam hinterland transport network. The model showed potential in reducing operational costs, improving the modal split and barge and train utilization.

The problem is formulated as a mixed integer programming model constructed in three parts: 1) shipment flow re-planning for a capacitated network; 2) service rescheduling at arc level; 3) shipment re-planning and service rescheduling synchronization. The goal of the model is to find the minimum cost solution by combining decisions for shipment rerouting and service rescheduling using a CPLEX solver. Shipments are characterized with time -windows including their release and due dates and can be loaded by capacitate fleets of trucks, barges, and trains. Transshipments are defined in the model being a result of the dynamic change of routing decisions and can be performed within terminals. The proposed model is applied on instances representing the Rotterdam hinterland network and its behavior is tasted on instances with different system disruptions. Detailed information about the case studies, the performance indicators applied, and the performance of the approach can be read in the paper (Qu, 2019).

RIVERA & MES, (2017)

Rivera & Mes, (2017) investigated the problem of scheduling drayage request by the means of trucks. Drayage operations are the transportation stages of pre and end-haulage. The work introduced an approach which makes dynamic decisions about the assignment of terminals, the routing of containers and trucks. The dynamic nature of their approach is the ability to change plans when there are disruptions present to the system. For the purposes of their research, they formulate the problem as a Mixed Integer Linear Programming and later introduce several adaptations to introduce its dynamic natures. The outcome of their model is a schedule for the drayage requests as the schedule can be changed in relation to a new incoming request.

The proposed formulation in the work of Rivera & Mes, (2017) has the goal to perform all jobs within a given time window, while minimizing the costs for routing and assigning containers. The considered requests are characterized by container type, origin, and volume. The used transport modes to route the containers is a heterogeneous fleet of trucks with a maximum working time. Terminals in the model can accommodate a definite number of containers and generate a cost when are assigned to a request. The formulation of the model allows for trucks to route in the network either loaded with a container or empty so they can reposition itself.

Rivera & Mes, (2017) design two types of metaheuristics: Static and Dynamic. The former solves a single instance of the problem, while the latter introduce flexibility in routing decisions. The static metaheuristic is additional constraints to the original formulation of the MILP problem which reduce the feasible solution space of the problem. On the other hand, the dynamic metaheuristic allows replacing the schedules for jobs which are not routed yet. Two options are available to the planner: to execute the already planned schedule or to re-plan the jobs. This is performed by the introduction of two Fixing Criterias (FC). The FCs identify feasible routes from the old schedule which are feasible for the new jobs. If not, the second FCs is applied, and a new route is chosen by applying again the static metaheuristic.

ZHANG & PEL (2016)

A direction of research in literature is found to be the comparison between intermodal and synchromodal transport. Zhang & Pel (2016) used a capacitated schedule-based assignment algorithm applied on the Rotterdam hinterland network to explore the potential impact of synchromodal transport on hinterland distribution compared to the traditional intermodal freight transport. The model incorporates three transport modes: trucks, trains, and inland barges. The characteristics of the modes are considered in terms of their sizes, operational speed, travel times and departure times. At the level of terminals, the model incorporates handling times of containers to the vehicles and allows transhipments of containers between modes.

The model is applied on a ‘multimodal scheduled-based service network’ with direct truck services. The proposed model is named SynchroMO and consists of 4 parts: 1) demand generator which describe the profiles of container shipments; 2) a super-network processor which represents the network characteristics with links and associated cost functions; 3) a scheduled based flow assignment module which route the containers with a transport mode on a specified path; 4) and a system performance evaluator which incorporates economic, societal, and environmental indicators. In the model each shipment is assigned with route with specified modes, terminals, service lines and associated departure time for the shipment. The second-best route is going to be chosen once the available capacity on the first-choice route is reached so there is no remaining capacity. Under this assumption, the capacitated schedule-based flow assignment algorithm reduces to a repeated schedule-based cheapest route problem.

The quantitative analysis is applied on a large-scale network with 18 regions selected from the Lower Rhine region. The results indicate better performing indicators for a network operating in a synchromodal manner compared to an intermodal network. The benefits of applying synchromodal transport are enlarging the competitive delivery distance of the system, shorter delivery times and modal shift from trucks to other more sustainable modes which respectively results in CO2 emissions reduction. Even though, a direct economic benefit is not observed, service line occupancies increased by 10%.

The study has its limitations in terms of incorporating fully the concepts of synchromodal transport. Service variations and disruptions are not considered in the model followed by possible rerouting decisions of terminal operators. Furthermore, time-windows and destinations for shipping orders are not incorporated in the constructed demand profiles. In this way the effects of the routing decisions on the robustness and reliability of the system are not fully captured.

XU ET AL. (2015)

Modeling operational decisions in a synchromodal transport network can be challenging in terms of computational power and time. A research from Xu et al. (2015) proposes an algorithm for container allocation with random freight demands aiming for improved computational performance. The problem is investigated in the perspective of container carriers and represented as a stochastic integer model with an objective to determine an optimal container capacity allocation for maximizing the transport profit. Containers can be moved by three different transport modes: trains, barges and trucks within a network constructed a single origin node and multiple destinations. Empty containers are left out of the scope of the work.

To solve the large-scale integer problem with random demands in reasonable time, Xu (2015) proposes a hybrid algorithm called Simulated-Annealing-Based Genetic Algorithm (SAGA). The proposed algorithm incorporates characteristics of the genetic algorithm and simulated annealing approaches. The potential benefits of SAGA were investigated by applying it on several case studies. A branch-and-bound approach is used as a benchmark method in the cases. The results indicate relatively shorter time needed for the SAGA algorithm to process and solve the problem supported with better values of the objective function.

The main goal of Xu (2015) is twofold. Firstly, an algorithm which can deal with stochastic demand is proposed. Secondly, the proposed algorithm showed potential in solving large-scale problems and obtaining optimal solutions in relatively short computational time. However, the proposed model does not fully incorporate the concept of synchromodality except from the adoption of a centralized planner who takes all operational decisions in a transport system. A strong limitation of the modal is that the planner has a constant access to available transport modes as the container demand does not exceed the available capacity. Moreover, the proposed approach cannot adopt to changes and replan the container allocation.

2.3. Model Predictive Control Implementation

The concept of synchromodality gives more freedom to operators and broadens the scope of actions and decisions which can be taken. By considering future events in the system, operators will narrow the scope of all possible actions. Subsequently, only the optimal actions can be picked out by predicting their effects on system performance. In this way, selection of optimal actions will be a result of justified measurements and expectations of system dynamics. Model Predictive Control (MPC) is recognized in literature as an approach which adopts this concept of making predictions in planning. With a MPC, a system operator takes decisions by reflecting on future events expected in the system. This process is continuously repeated so planning is always founded on the predictions. More information about the concept of MPC can be found in the work of Negenborn et al., (2010, p. 14).

The most common designs of MPC found in transport literature are centralized and distributed. The centralized MPC structure is managed by a single agent who has access and control over the complete system. The distributed MPC structure is constructed of several agents which controls only their part of the system but communicate between each other. In cases when agents do not share information the MPC structure is defined as decentralized. An interest for the purposes of this research is the applications of centralized control which can be found in the existing literature. Further in this subsection system operators are referred as a 'controller'.

NABAIS ET AL. (2015)

Nabais et al. (2015) investigates the problem of increasing volumes of containers and the need of their on-time delivery. A centralized controller algorithm is designed for assigning containers to transport modes in the perspective of a terminal operator. To reach its destination on time, the system planner can assign containers in advance driven by the goal of optimizing a cost function. By the means of different cost parameters in the optimization function, the controller can prioritize the use of desired modes. For instance, if containers are not delivered on time on its due destination a cost penalty is activated. By introducing a modal split target, the controller can achieve a shift of cargo from trucks to other modes.

The dynamics in the system caused by the transported cargo are described by destination, type, and remaining time until due date. The dynamics of an intermodal hub are represented by a state-space model using state-space vectors as each element of the vector indicates the state of the hub at a timestep. At each timestep of the algorithm, the vector is updated according to the current state of the vector, the cargo assigned to transport modes and the cargo arrivals over a timestep. The main goal of the controller is to assign the cargo to available transport capacity and delivered it to the desired destination on time. The solution of the formulated optimization function is an optimal sequence of actions over a prediction horizon which provides the most suitable predicted performance. The controller implements only the first sequence of actions until the beginning of the next timestep of the horizon when a new optimization problem is solved based on the current state, available information, and goals.

The proposed approach is applied on a network with a single origin node and multiple destinations. The available routes between the nodes are pre-defined. Barges and trains operate on a scheduled service with predefined frequencies and capacities. The results of the numerical experiments indicate that the performance of the model is highly dependable on the network configuration, the length of the prediction horizon, and the demand patterns. The effects of these specifics on the overall flexibility of the system are described narrowly in the paper Nabais (2015).

LARSEN ET AL., (2020)

In comparison to Nabais (2015), a centralized MPC approach was proposed by Larsen et al., (2020) which combine the routing of containers and trucks. Both are routed simultaneously as truck operate in a flexible manner. Hence, the controller of the system can reposition empty trucks to nodes of the network where they will be needed in future timesteps. Containers are characterized by their destination and due date. Barge and train services are available as well and operate in a scheduled manner. Each terminal in the network is represent with a state-space vector which incorporates the number of container and trucks parked at it plus the number of approaching containers and trucks. Transport modes and terminals are both limited in capacity. Moreover, trucks are not considered to be constantly available to the needs of the controller and the size of the fleet is also defined.

The proposed model is applied on a network with multiple origin and destination nodes. To test the effects of routing simultaneously trucks and containers, the approach was tested under conditions of uncertainty of truck travel times. Multiple scenarios were applied with fixed cost parameters and different capacities and fleet sized. The results indicate that the proposed MPC is encouraged to transport containers on only when the deadline for a shipment is approaching, but also when an empty truck is available at the appropriate location. This increases the robustness of the system in terms of travel time delays and besides indicates the appropriate size of the truck fleet.

FEBBRARO ET AL. (2016)

Instances for distributed MPC applied on transport problem also can be found in literature as well. Di Febbraro et al. (2016) investigates the problem of container transportation by decomposing it into a set of sub-problems, each representing the operations of an actor which are connected by a negotiation scheme. The problem is optimized on a rolling horizon scheme. Similar approach is used by Li et al. (2017) where the network is divided into non-overlapping sectors according to their geographic location and served by different cooperating stakeholders. Both works assume that trucks in the network are constantly available for the need of the MPC agents.

In the literature there are vast amount of works which investigate problems in various aspects of transportation and supply chain. Intermodal transport has been investigated extensively not only on strategical and tactical level, but also on operational. Many decision-making tools have been proposed to route various compositions of fleets in different network configurations. Researchers intensively investigate different combinations of transport modes ether homogeneous or heterogenous. The tendency to combine at least two transport modes is observed. Trucks are regularly modelled due to their flexible nature of operations and extensive use in practice. In combination of trucks, trains or barges are modelled to capture the effects of economies of scale and carry bigger amounts of cargo. Although, trucks are modelled with the possibility to visit various parts of the network, this is not the case of barge and train modelling. The services of this transport modes are often routed on a fixed schedule with predefined sequence of visiting points on the network. Therefore, there are fixed routes in the network which barges, and train can use. Distinctive characteristics of terminals are also observed in the literature. Terminals are characterized with capacities, working hours and most importantly the possibility of transshipments at terminal nodes. Transshipments are crucial part of the concept of intermodal transport, yet this terminal characteristic is often neglected due to small network sizes or modeling techniques.

2.4. Summary

The concept of synchromodal transport has brought a new direction in operational research. Even though the concept is new to the research area, it has gained a lot of attention and different problems were investigated under the conditions of synchromodality. In literature there are works which investigate diverse scales of networks from including only a single pair of terminals to large scale networks modelled on European level. The concepts of a central operator of the system who can apply *open bookings* is largely accepted by researchers. However, there is a scarce number of models and operational strategies which consider dynamical switching of modes and real-time changes of routing decisions in terms of disruptions in the system. In this manner the full potential in terms of synchromodal flexibility is barely investigated.

As a conclusion from the conducted review, we observed a gap in literature for decision-making strategies which benefits from the full potential of synchromodality on operational level. With this research we would like to propose an operational strategy for routing decisions which can reflect on the robustness and reliability of a multi-modal transport network with the presence of increased demand for container flows. The proposed approach needs to have the possibility to readapt its routing decisions according to current state of a synchromodal transport system. Furthermore, by the means of a Model Predictive Control (MPC), the strategy will have the ability to perform optimal decisions based on predictions of future states of the system. In this section, answers to Sub-question 1 and 2 are provided. The answers are going to be used as a base ground to answer the following sub- questions and the main research question.

3. Operational Strategies: Formulation and Planning Control

To evaluate the consequences of taking real-time routing decisions for inland barges in a synchromodal transport network, one operational strategy is created and a second is going to be used as a Benchmark. The Benchmark is an operational strategy which was previously introduced by Larsen (2020). The Benchmark is used as a basis for the design of an alternative strategy, which in turn is referred as Free Barge Routing (FBR).

In the Benchmark strategy trucks and containers are routed simultaneously while inland barges are operated according to a schedule. In contrast, the proposed FBR, determines the optimal routes of barges together with truck and container routes. Both strategies use a centralized Model Predictive Control (MPC) planning approach which enables the operator of the synchromodal network to take decisions based on the latest available information.

The structure of this chapter is as follows: In Section 3.1, the design of the MPC is introduced. Subsequently, the mathematical formulation of the benchmark and proposed strategies are presented in Section 3.2. Finally, the chapter is summarized in the last Section 3.3.

3.1. Design of Model Predictive Control (MPC)

It is considered that the MPC operator of the synchromodal network has an accurate representation capturing the dynamics of the system. The operator is also available to analyse the global state of the system every ΔT minutes which is considered as one timestep ($t = i\Delta T, i \in N)$. Moreover, the operator is aware of the present demand and can make a prediction of the future demand. The prediction is used to determine a sequence of actions which will minimize a cost function over a prediction horizon Tp. Only the actions which require to be implemented at the first timestep of the horizon Tp are implemented by the operator. At the next timestep ($t = i\Delta T + 1$), this is repeated.

3.1.1. MPC Approach

The MPC planning approach is represented on Figure 3.1. The MPC consists of a single controller who oversees the whole synchromodal system. The use of single layer planning approach has already been applied on transport systems (Nabais (2015) and Larsen (2020)). The operator uses the measurements y(k) to determine the current state of the transport system represented by x(k). Subsequently, disturbances which can have effect on the system are estimated. In this thesis ‘disturbances’ are the amount of new container orders which enter the system in the future. Thereafter, the system operator solves an optimization problem by making predictions and finding the optimal actions which can be taken in the further steps. At last, he returns a sequence of optimal actions to the system and repeats the procedure with the new measurement of the system y(k+1).

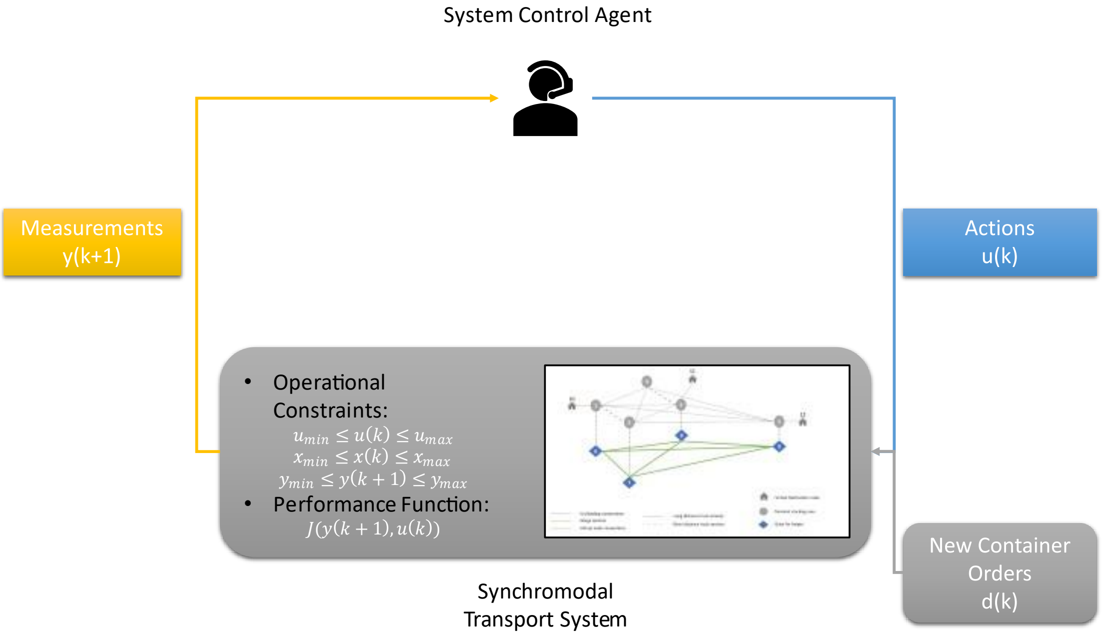


Figure 3.1: MPC system representation (Adapted from R.R. Negenborn, ME44300 "Coordination for Real-time Logistics", TU Delft)

On Figure 3.2 a summary of the actions which the operator can apply to the system are presented. The measurements to which there is an access at each timestep of the optimization are presented on the figure as well. The operator can take decisions anticipated with the operations of containers, trucks, barges, and terminals. The overview on Figure 3.2 is a summary of the presented strategy conceptualization.

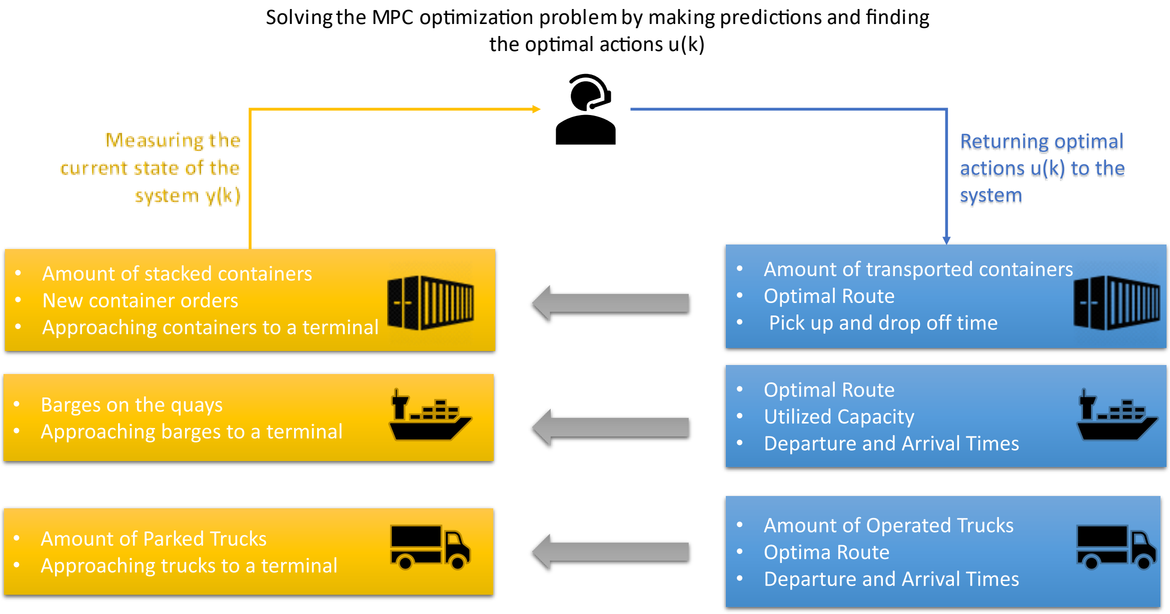


Figure 3.2: Overview of strategy conceptualization

3.1.2. System Input

The input consists of the information which is available at each timestep to the system operator. The input consists of network parameters and information about the states of trucks, barges, and containers in the system. Further in this section, the characteristics and assumptions of the different inputs are presented.

NETWORK

System network consists of nodes and arcs which connects them. The nodes are representation of origins, destinations, and transhipment points in a transport system. The arcs between these nodes represent a transport service between them. The network layout has three types of nodes and three types of arcs. The first type of nodes is a representation of a terminal. At these nodes different type of trucks can be parked, and a barge can be handled. Containers can be stored at nodes or transhipped to a transport mode and delivered to their destination. These nodes are limited in capacity of storing containers and accommodating trucks. The distance between the nodes is represented in travel time in timesteps. The arcs connecting the first type of nodes represent truck services. Arcs are undirected and trucks can travel on them either full or empty. This assumption allows the system planner to send truck capacity to a node when its needed and performing a positioning trip.

The second type of nodes is called Virtual Destination Nodes (VD). VDs nodes are respective of the origins and destinations of the containers which enter the system. Therefore, containers enter and leave the network from VDs nodes. These nodes are adjacent to terminal nodes and connected via different type of arcs. These arcs are incapacitated and undirected. There is no travel time imposed on the arcs so the planner can decide when to pick up or drop a container at the VDs.

The third type nodes represent a barge quay at a terminal. They form an additional network used for barge routing. These nodes are adjacent to the terminal nodes. The two adjacent nodes are connected via the third type of arcs. These arcs are undirected, but with a capacity limitation which represent the available handling capacity. The third type of nodes are connected via arcs from the first type. Therefore, barges can be routed on them either empty or full. The distance between these nodes is known and represented in travel time in timesteps. In addition to the travel time, an operational time is considered for barges to enter or leave a node which is added to the total travel time. Working hours are not considered so nodes are accessible anytime during the simulations.

CONTAINERS

Containers in the system are classified by their origin and destination. Each container is part of an order and has a pickup and delivery time. Containers which cannot comply with the delivery time requested in the order are considered as unsatisfied demand and respectively penalized. Containers can be stored at nodes or transported by either trucks or barges.

In Containers have many diverse types in relation to size: (20 ft. (TEU); 40ft. (FEU), 45ft.) and type (regular container, reefer or container carrying hazardous materials). For simplicity in terms of representation of the system, containers are described only by their origin and destination. Size of containers are not incorporated as well as their loading condition. It is not distinguished either a container is empty or full. Containers are not prioritized according to this condition. These assumptions simplify considerably the representation of the synchromodal transport network.

TRUCKS

There are two types of trucks which operate in the system. The first type is port trucks which are used to transfer containers within a terminal or between terminals in proximity. These trucks can travel only on arcs which connect nodes with short travel time. The second type of trucks operating in the system are long distance trucks which can travel between distant nodes. Both type of trucks can be routed either empty or fully loaded. Trucks can pass through a node in transit without unloading already loaded container. The system planner has the possibility to change the location of trucks, yet since a truck starts a journey, it must be finished. Therefore, a planner cannot change the route of a truck in the middle of a journey. Both type of trucks can be loaded with a single container. The cost for transporting a container by truck is charged per timestep. As times between nodes are deterministic, the cost for transporting a container by truck is known by the system planner. Congestions and disruptions on the links of the road network are not considered.

SCHEDULED BARGES

When barges operate on a schedule, they have fixed arrival and departure times at system nodes. Barges are limited in capacity and can load a certain number of containers onboard. The schedule service is presented as a separate node in the network layout. The schedule of the barge is implied by time dependent arc capacities between the service node and other nodes. When a barge is at a terminal there is a fixed number of timesteps unloading operations after arrival and loading operations prior to departure according to the schedule. The schedule service is paid per container slot per timestep.

FLEXIBLE BARGES

When barges are considered flexible, they can be routed between nodes independently of a schedule. The system operator decides whether to send a barge to a terminal or not without previous notice to the terminal operator. Flexible barge service is charged as truck service: according to the distance they travel. The level of utilization of barges does not affect the prices for routing. While entering or leaving a barge quay, barges must spend time in maneuvering which is added to the total travel time between two nodes. Terminal operating hours are not considered, so a barge can be routed to a quay node at any time. Like trucks, once a barge journey is commenced it must be finished before being rerouted. With this assumption, a barge must spend at least one timestep at a terminal when arrive there.

3.1.3. Performance Function

The goal of the system operator is to deliver all container orders in time and minimize the overall cost for operating the system. The on-time delivery of containers is considered as the most important criteria for system performance. Delayed containers of an order are integrated into the performance function as cost penalties. To motivate the system operator to deliver all containers within their due dates, the penalty has a considerably high weight. Thus, when a container is potentially late the operator must use pricey services instead of postponing the container transport. The cost for system operation consists of the costs for containers storage, trucks, and barge routing, trucks and barge parking, handling costs of containers. The system operator applies a MPC planning approach and performs a prediction for the future demand at each timestep of the simulation. At each timestep the performance function is optimized and the costs for operating the system are derived considering all events within a prediction horizon.

3.1.4. Outputs

The outputs of each optimization are the decisions of the system operator. The decisions are related to either store a container or transfer it, mode choice, optimal routes for both containers and transport modes as well as containers and modes departure times.

CONTAINERS

After an optimization at the end of the prediction horizon, the operator of the system has determined the routes for each container. The routes are optimal for the complete system and include containers pick up time and delivery time within the prediction horizon.

TRUCKS

The decisions related to trucks after the optimization process are the optimal routes to pick- up and deliver container orders. The operator decides when to send a truck to a certain node of the network and respectively when the truck will be on its destination. Positioning trips are allowed in the strategy, so trucks can be sent to a node either empty or fully loaded.

BARGES

When the barge service is scheduled, the system operator cannot make decisions about routing. Decisions result in the number of containers which are transported by a scheduled barge. On the other hand, when barge service is flexible, the system operator can choose the sequence and timing for visiting terminals. Thus, the output is the volume of containers which are assigned to a barge, the optimal route of the barge and the optimal amount of time the barge spends on the quay for handling operations.

TERMINALS

Based on the optimal routing of containers and transport modes, the utilization level of different terminals can be determined. The objective function includes costs for terminal services as costs for storing a container, parking a truck, berthing a barge, and costs for container handling operations. The outcome of each strategy is the utilization level of terminals stacking area, truck parking and terminal quays.

3.2. Operational Strategy Formulation

In this Subsection the mathematical formulations of two operational strategies are presented. The first formulation is based on the work of Larsen (2020) and is used as a Benchmark in this thesis. It is presented in Section 3.2.1. The second strategy is designed as a built-up of the Benchmark and presented in Section 3.2.2. The second strategy is named Flexible Barge Routing or shortly FBR. Units are introduced as well in the description of variables and parameters. The abbreviation of $ is used for the units of all cost parameters to indicate a generic cost.

3.2.1. Benchmark Strategy

A strategy proposed by Larsen (2020) is used as a Benchmark Strategy. The research of Larsen, (2020) introduces a Model Predictive Control (MPC) for a multimodal transport system. The system in accommodates flexible trucks and scheduled barge and train services. Commodity flows are containers of a single size. They are modelled as continuous variables. Flexible trucks are implemented in the same manner as well. Both containers and trucks are coupled by a constraint that containers can only flow on an arc if there is at least the same number of trucks moving on this arc. A summary of the major features of the strategy is presented below:

1) Centralized MPC control is applied to support decision-making process.

2) Unsatisfied demand is penalized.
3) Scheduled services are presented as separate nodes of the network layout.
4) Limited numbers of containers can be loaded and unloaded from trucks and barges at one timestep.
5) Trucks can wait to enter a node or pass-through node without unloading their container.
6) Travel times and capacities are known for the planning horizon at all timestep.
7) Terminal operational hours, resting hours of truck drivers and congestion on roads are not considered.

Sets	***Description***
N	Network nodes
VD	Virtual demand nodes
V	Set of truck types
K_{max}	Horizon length
Tp	Prediction Horizon length
$\mathrm{T_i}$ $\mathrm{i \in N}$	Set of nodes with truck connection to node *i*

Table 3.1: Benchmark Strategy: Sets

Costs	***Description***	***Units***
$\mathrm{M_i^c}$	Cost for storing a container at node *i.* This cost is paid per timestep *k*	*$*Timestep*
M_i^v	Cost for parking a truck at node *i.* This cost is paid per timestep *k*	*$*Timestep*
M_i^s	Cost of moving a container to and from a scheduled service	*$*
M_{ij}^{tv}	Cost of a truck trip from node *i* to node *j* of type *v*	*$*Travel time*
M_i^{lv}	Operational cost for moving a container from a stack to a truck of any type	*$*
M_i^d	Cost of unsatisfied demand at Virtual Demand node *d*	*$*Timestep*

Table 3.2: Benchmark Strategy: Costs

Parameters	***Description***	***Units***
nc	Types of containers. Type is defined based containers destination	Container *Unit*
nv	Types of trucks. Hereby, two types of trucks are considered	*Port trucks, Long-distance trucks*
τ_{ij} $i, j \in N$	Truck Travel time between *node i* and node *j*	*Timesteps*
k	Timestep	*1 Timestep = 1 hour*
Si $i \in \mathrm{N}$	Set of nodes to which node *i* is linked via a time-dependent arc connect	
Di $i \in \mathrm{N}$	Demand at virtual destination node	*Container Units*
$c_i^c \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$	Maximum number of containers of each kind which can be stored at a node	*Container Units*
$c_i^s(k) \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$	Time-varying crane speed at node *i* which operates with barges	*Container Units / Timestep*
$c_i^v \in \mathrm{R}_{\geq 0}^{\mathrm{nv}}$	Maximum number of vehicles of each kind which can be parked at a node	*Trucks per type*
c_i^t	Crane capacity which operates with trucks	*Container Units / Timestep*
$\mathrm{d_i} \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $\mathrm{i} \in VD$	Amount of incoming and outgoing demand which can be satisfied at Virtual destination node *i* at timestep (*k*)	*Container Units*
$K_{max} = \{1,2, \dots k\_max\}$	Horizon length	*Timesteps*
Tp	Prediction Horizon length	*Timesteps*

Table 3.3: Benchmark Strategy: Parameters

Node States	***Description***	***Units***
$x_i^c \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $i \in N$	Number of containers parked at a node *i*	*Container Units*
$x_i^v \in \mathrm{R}_{\geq 0}^{\mathrm{nv}}$ $i \in N$	Number of vehicles parked at a node *i*	*Trucks per type*
$x_i^d \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $i \in \mathrm{VD}$	Number of unsatisfied demands at virtual destination node *i* which is penalized	*Container Units*
$\mathrm{u_i^{hv}}(k)$ $\mathrm{i, j} \in N, \quad v \in V$	Number of containers approaching node *i at* timestep *k*	*Container Units*

Table 3.4: Benchmark Strategy: Dynamics at system nodes

Action variables	***Description***	***Units***
$\mathrm{u}_{\mathrm{ij}}^{v}(k) \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $\mathrm{i,j} \in N, \quad \mathrm{v} \in \mathrm{V}$	Number of containers send from node *i* to node *j* by truck of type *m* at time step *k*	*Container Units*
$u_{si}(k) \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $\mathrm{i} \in N, \ \mathrm{s} \in \mathrm{S_i}$	Containers moved from node *i* over a time-dependent connection to node *s*	*Container Units*
$v_{ij}(k) \in \mathrm{R}_{\geq 0}^{\mathrm{nv}}$ $\mathrm{i,j} \in N,$	Number of truck vehicles send from node *i* to node *j* at timestep *k*	*Trucks per type*
$u_{id}(k) \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $\mathrm{i} \in N, \quad \mathrm{d} \in \mathrm{VD}$	Containers used to satisfy the incoming demand form network node *i* to virtual destination node *d* at timestep *k*	*Container Units*
$u_{di}(k) \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $\mathrm{i} \in N, \quad \mathrm{d} \in \mathrm{VD}$	Containers used to satisfy the outcoming demand form network node *i* to virtual destination node *d* at timestep *k*	*Container Units*
$\mathrm{z}_{\mathrm{i}}^{v} \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $\mathrm{i} \in VD, \quad v \in V$	The number of containers which leave from node *i* at timestep *k* on the same vehicle which they arrived with and have not been unloaded from	*Container Units*

Table 3.5: Benchmark Strategy: Action Variables

Most of the variables in the strategy formulation are vectors. The vector $\mathrm{u}_{\mathrm{i}}^{\mathrm{hm}}(k)$ is used to keep a record of the incoming containers to node *i* by all truck types at timestep *k*. This is necessary to represent the travel time of trucks τ_{ij} in the truck network as a delay. The formulation of the delay is:

$$\mathrm{u}_{\mathrm{i}}^{\mathrm{hv}}\,(\mathrm{k}) = \left[u_{ji}^{v1}(k-1) \ldots u_{ji}^{v1}\left(k-\tau_{ji}\right) \ldots u_{j'i}^{v_{nv}}(k-1) \ldots u_{j'i}^{v_{nv}}\left(k-\tau_{j'i}\right)\right], \qquad \{j, \ldots, j'\} \in \mathrm{T_i}, \quad \{v1, \ldots, v_{nv}\} = [1, nv]$$

, where $u_{ji}^{v}(k-1)$ is the number of containers on all types of trucks sent to node *i*. Respectively, the record of the vehicles approaching node *I* is:

$$v_i^h(k) = \left[v_{ji}(k-1) \ldots v_{ji}\left(k-\tau_{ij}\right) \ldots v_{j'i}(k-1) \ldots v_{j'i}\left(k-\tau_{ji}\right)\right], \{j, \ldots, j'\} \in \mathrm{T_i}$$

Each node of the network can be described with a state which is measured at every timestep *k* of the prediction horizon. The initial states of each node *i* are the number of stored containers, the number of parked vehicles, the number of vehicles approaching the network node *i* and the number of vehicles on their way to node *i*:

$$x_i(k) = \begin{bmatrix} x_i^c(k) \\ x_i^v(k) \\ u_i^{h,v1}(k) \\ \vdots \\ u_i^{h,v_{nv}}(k) \\ v_i^h(k) \end{bmatrix}, \qquad (1)$$

Containers enter and leave the system through the virtual destination nodes (VDs). Therefore, VDs are considered as the origins and destinations for each container type. There are no capacity constraints on the arcs connecting a VD node and its adjacent network node and the travel time between them is set to zero. For this reason, dynamics of virtual destination (VD) nodes differs from the dynamics of the network nodes. The equation defining the dynamics is:

$$x_i^d(k+1) = x_i^d(k+1) - uid(k) + uid(k) + d_i(k), \qquad (2)$$

The terms incoming and outgoing demand are used in this strategy. The term *incoming* is used when node *i* is the destination of commodities and *outgoing* when node *i* is their origin. Here, the incoming and outgoing demand $d_i(k)$ serve as a disturbance to the state of the system. Container types are defined according to the available VDs in the system. Hence, if there are three VDs in the system there are three container types. An instance for demand for 1 outgoing container of type 2 at node 1 at timestep 1 is formulated as $d_1(1) = (0;1;0)$, while the demand for 1 incoming container of type 1 at node 1 at timestep 5 is formulated as $d_1(5) = (1;0;0)$. In this way both incoming and outgoing containers are formulated as positive values.

The network node dynamics describe the number of containers which are stored at a network node and the amount of truck vehicles which are parked there. The number of containers is related to the new incoming demand and the container used to satisfy the outgoing demand to the destination nodes. Therefore, the dynamics of the node is:

$$x_i^c(k+1) = x_i^c(k) + \sum_{m\in[1,\mathrm{n}]}\sum_{j\in\mathrm{T_i}} \left(u_{ji}^v(k-\tau_{ji}) - u_{ij}^v(k)\right) + \sum_{s\in S_i}\left(u_{si}(k) - u_{is}(k)\right)$$
$$+ \sum_{\mathrm{d}\,\in\mathrm{VD_i}} udi(k) - uid(k)\ , \qquad (3)$$

The variable $x_i^v(k)$ describes the number of trucks of each type which are parked at node *i* at timestep *k.* The dynamics of this variable are described by the equation:

$$\mathrm{x_i^v(k+1) = x_i^v(k)} + \sum_{\mathrm{j}\,\in\mathrm{T_i}} \left(v_{ji}(k-\tau_{ji}) - v_{ij}(k)\right), \qquad (4)$$

In the strategy containers and trucks are routed simultaneously. This gives the opportunity for the system operator to send empty vehicles to nodes where there are going to be needed in the future. Yet, this does not count for containers and there should not be any container routing in the network without being assigned to a truck. The following constrain hinders the routing of containers without the presence of a truck if they are transported on a truck arc:

$$\sum_{m\,\in[\,1,\mathrm{nv}]} [1\boldsymbol{nc}] * \mathrm{u_{ij}^v}(k) \le [\mathbf{1}\boldsymbol{nc}] * v_{ij}(k), \qquad \forall j \in \mathrm{T_i}, \qquad (5)$$

In Eq. (5) $\mathbf{1}\boldsymbol{nc}$ represents a row vector of ones with a size of nc. The following set of constraints define the network capacities:

$$1nc * x_i^c(k) \le c_i^c, \qquad i \in N, \qquad (6)$$

Eq. (6) defines the maximum number of containers which can be stored at node *I* per timestep(*k*). The following Eq. (7) defines the maximum number of vehicles which can be parked at node *i* at timestep *k*:

$$x_i^v(k) \le c_i^v, \qquad i \in N, \qquad (7)$$

The schedules on the time-dependent arcs are implemented by time-varying crane speed constraints. if node i is a barge node and node s is a terminal node then $c_i^s(k)$ and $c_s^i(k)$ are respectively the representing the loading and unloading process. When the barge is at the terminal and can be unloaded then $c_i^s(k) \neq 0 \; and \; c_s^i(k) = 0$, and when the barge is at the terminal and can be loaded $c_i^s(k) = 0 \; and \; c_s^i(k) \neq 0$, otherwise $c_i^s(k) = 0 \; and \; c_s^i(k) = 0$.

$$[1\boldsymbol{nc}] * u_{is}(k) \le c_i^s(k), \qquad s \in S_i, \qquad (8)$$
$$[1\boldsymbol{nc}] * u_{si}(k) \le c_s^i(k), \qquad s \in S_i, \qquad (9)$$

The following two equations Eq. (10) and Eq. (11) concerns the amount of container which pass through a node without being unloaded from their vehicle:

$$z_i^v(k) \le \sum_{j \in \mathrm{T_i}} u_{ij}^v(k), \qquad \forall i \in N, \qquad \forall v \in [1, nv], (10)$$

$$\mathrm{z}_i^v(\mathrm{k}) \le \sum_{j \in \mathrm{T_i}} u_{ji}^v\big(k - \tau_{ji}\big), \forall i \in N, \qquad \forall v \in [1, \mathrm{nv}], (11)$$

With the introduction of $\mathrm{z}_i^v(\mathrm{k})$ the crane capacity can be formulated as a linear constraint and the containers which leave on the same vehicle, they arrived with do not count for a crane move:

$$\sum_{v \in [1,nv]} \sum_{j \in T_i} \Big(u_{ij}^v(k) \; + u_{ji}^v\big(k - \tau_{ji}\big)\Big) - 2 * \mathrm{z}_i^v(\mathrm{k}) \le c_i^t, \qquad \forall i \in N, \qquad (12)$$

By applying the MPC planning approach, the system operator can make decisions which results are observed within the prediction horizon. Thus, the operator can send vehicles to a node only if the vehicles can arrive to their destination by the end of the prediction horizon.

$$v_{ij}(k) = 0, \qquad \forall i \in N, \forall j \in T_i, \forall k > Tp - \tau_{ji}, \qquad (13)$$

The following constraints define the positivity of the action variables and the states of the nodes:

$$v_{ij}(k) \ge 0, \qquad \forall i \in N, \qquad \forall j \in T_i, \qquad \forall v \in [1, nv], \qquad \forall k \le Tp - \tau_{ji}, \qquad (14)$$

$$u_{ij}^v\,(k) \ge 0, \qquad \forall i \in N, \qquad \forall j \in T_i, \qquad \forall v \in [1, nv]\,, \qquad \forall k \in [0, Tp - 1], \qquad (15)$$

$$z_i^v\,(k) \ge 0, \qquad \forall i \in N, \qquad \forall v \in [1, nv], \qquad \forall k \in [0, Tp - 1], \qquad (16)$$

At each timestep *k* the operator solves the optimization problem subject to Eq. (2)- Eq. (16) and measures the states of the node. The measure states of each network node *i* is denoted by $y_i(\,t)$. The initial states of the node at timestep *k* are equal to the measured states. This is showed in the following equation Eq. (17):

$$x_i(k = 0) = y_i(t), \qquad \forall i \in N, \qquad (17)$$

The decision vector U contains all inputs to system: $u_{ij}^v(k), u_{si}(k), v_{ij}(k),\; u_{id}(k) \; and \; u_{di}(k)$ for all $i, j \in N,\; s \in S_i,\; d \in VD_i,\; k \in \;[0, Tp - 1]$. At each timestep *k* the operator solves the optimization problem Eq. (2)-Eq. (17) presented above aiming to minimize an objective function presented below:

$$
\begin{aligned}
\min \sum_{k=0}^{Tp} \Bigg(\sum_{i \in N} \Bigg(& M_i^c x_i^c(k) + M_i^v x_i^v(k) + \sum_{j \in T_i} M_{ij}^{tv} v_{ij}(k) \\
& + \sum_{v \in [1,nv]} M_i^{lv} \Bigg(\sum_{j \in T_i} \big(u_{ji}^v(k - \tau_{ji}) + u_{ij}^v(k)\big) - 2z_i^v(k) \Bigg) + \sum_{s \in S_i} \big(M_i^s (u_{si}(k) + u_{is}(k))\big) \Bigg) \\
& + \sum_{i \in VD} \big(M_i^d x_i^d(k)\big) \Bigg), \quad (18)
\end{aligned}
$$

3.2.2. Flexible Barge Routing (FBR) Strategy

Further in this section, an operational strategy for a synchromodal transport network is proposed. The FBR strategy is a continuation of the strategy introduced by (Larsen 2020). A summary of major characteristics of the strategy related to barge routing are presented below:

1) Truck and barge services does not follow a schedule. They are routed simultaneously with containers.
2) Waiting time of barges is not considered, yet operational time for entering and leaving a port terminal is considered.
3) Limited number of containers can be loaded and unloaded from a barge at each node at timestep. This assumption implies a crane speed capacity per timestep.
4) There is no limitation in the timesteps a barge can be berthed at a quay.
5) Barges do not require a permission to enter or leave a terminal.
6) Congestions at terminals either on terminal roads or berths are not considered.

Sets	**Description**
N	Set of nodes in the network
VD	Set of Virtual demand nodes
T_i , $i \in N, T_i \in N$	Set of nodes with a truck connection to node *i*
B_i, $i \in N$	Set of nodes with barge connection
Q_i, $i \in N$	Set of quay nodes connected to node *i* where barges can be accommodated
V	Set of truck types
S	Set of barge types

Table 3.6: FBR Strategy: Sets

Costs	Description	Units
M_i^c	Cost for storing a container at node *i*.	*$*Timestep*
M_i^v	Cost for parking a truck at node *i*.	*$*Timestep*
M_{im}^{b}	Cost for berthing a barge at a quay m of node *i*.	*$*Timestep*
M_{im}^{bc}	Cost of booking a container spot on a barge at quay *m* at node *i*.	*$*Timestep*
M_{ij}^{tv} $i \in N, j \in \mathrm{T_i}$	Cost of a truck trip from node *i* to node *j*	*$*Travel Time ($*Timesteps)*
M_{ij}^{tb} $i \in N, j \in B_{\mathrm{i}}$	Cost of a barge journey between port *I* and port *j*	*$*Travel Time ($*Timesteps)*
M_i^{lv}	Operational cost for moving a container from a stack to a truck	*$*
M_i^{ls}	Operational cost for moving a container from a stack to a barge	*$*
M_i^d	Cost of unsatisfied demand at Virtual Demand node *i*	*$*Timestep*

Table 3.7: FBR Strategy: Costs

Capacity Parameters	Description	Units
$\boldsymbol{c_i^c} \in \mathbf{R}_{\geq 0}^{\mathbf{nc}}$	Maximum number of containers of each kind which can be stored node *i*	*Container Units*
$\boldsymbol{c_i^v} \in \mathbf{R}_{\geq 0}^{\mathbf{nv}}$	Maximum number of trucks of each kind which can be parked at node *i*	*Trucks per type*
$\boldsymbol{c_{im}^b} \in \mathbf{R}_{\geq 0}^{\mathbf{ns}}$	Maximum number of barges of each kind which can be berthed at quay *m* at node *i*	*Barges*
$\boldsymbol{c_i^t}$	Crane capacity operating with containers and trucks.	*Container Units / Timestep*
$\boldsymbol{c_i^s}$	Crane capacity operating with containers and barges.	*Container Units / Timestep*

Table 3.8: FBR Strategy: Capacity Parameters

Parameters	**Description**	**Units**
nc	Number of container types according to the possible destination	*Container Units*
nv	Types of trucks operating in the system	*Port Truck* *Long-distance Trucks*
$ns \in Z$	Types of barges operating in the system	
Cap	Capacities of barges operating in the network	*Container Units*
τ_{ij}, $i \in \mathrm{N}, j \in \mathrm{T_i}$	Truck Travel time between node *i* and node *j*	*Timesteps*
φ_{imjn} , $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j$	Barge Travel Time between node *i* and node *j*	*Timesteps*
ω_{im} $i \in \mathrm{N}, m \in Q_i$	Operational Barge Time need by a barge to leave or enter quay *m* of port *i*	*Timesteps*
$d_i \in \mathrm{R}^{nc}_{\geq 0}$, $i \in VD$	Amount of incoming and outgoing demand which can be satisfied during at Virtual destination node *i* during timestep (*k*)	*Container Units*
$K_{max} = \{1,2, \dots k\_max\}$	Horizon length	*Timesteps*
Tp $Tp \geq 0$	Prediction Horizon length	*Timesteps*

Table 3.9: FBR Strategy: Parameters

Node States	**Description**	**Units**
$x^c_i(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N$	Number of containers of each type parked at a node *i* at timestep *k*	*Container Units*
$x^d_i \in \mathrm{R}^{\mathrm{nc}}_{\geq 0}$ $i \in \mathrm{VD}$	Number of unsatisfied demands at virtual destination node *i* which is penalized	*Container Units*
$x^v_i(k) \in \mathrm{R}^{nv}_{\geq 0}$ $i \in N$	Number of trucks of each type parked at a node *i* at timestep *k*	*Trucks per type*
$x^b_{im}(k) \in \mathrm{R}^{ns}_{\geq 0}$ $i \in \mathrm{N}, \quad m \in Q_i$	Number of barges of each type berthed at quay *m* of node *i* at timestep *k*	*Barges per type*
$x^t_{im}(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in \mathrm{N}, \quad m \in Q_\mathrm{i}$	Number of containers which are present on a barge berthed at quay *m* at node *i* at timestep *k*	*Container Units*
$\mathrm{u}^{\mathrm{hv}}_{\mathrm{i}}(k)$ $i \in N$	Number of containers approaching node *i* by trucks of all types at timestep *k*	*Container Units*

$\mathrm{u}^{\mathrm{hs}}_{\mathrm{im}}(k)$ $i \in N$	Number of containers approaching quay *m* of node *i* by barges of all types at timestep *k*	*Container Units*
$v^{\mathrm{h}}_{\mathrm{i}}(k)$ $i \in N$	Number of trucks approaching node *i* at timestep *k*	*Trucks per type*
$s^{h}_{im}(k)$ $i \in N$	Number of barges approaching quay *m* of node *i* at timestep *k*	*Barges per type*

Table 3.10: FBR Strategy: Dynamics at system nodes

Actions Variables	**Description**	**Units**
$u^{v}_{ij} \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad j \in T_i$ $v \in M$	Number of containers send from node *i* to node *j* by truck type *m*	*Container Units*
$u^{s}_{imjn} \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j$ $s \in \mathrm{S}$	Number of containers send from quay *m* of node *I* to quay *n* of node *j* by a barge of type *s*	*Container Units*
$v_{ij} \in \mathrm{R}^{nv}_{\geq 0}$ $i \in \mathrm{N}, \quad \mathrm{j} \in \mathrm{T_i}$	Number of trucks of each type send from node *I* to node *j*	*Trucks per type*
$s_{imjn} \in \{0;1\}^{ns}_{\geq 0}$ $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j$	Binary variable indicating if a barge of each type is sent from the quay *m* of node *i* to the quay *n* node *j*	
$u^{l}_{im}(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad m \in Q_i$	Number of containers being loaded on a barge berthed at quay *m* of node *I* from the stack at node *i*	*Container Units*
$\mathrm{u}^{\mathrm{u}}_{\mathrm{mi}}(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad j \in Q_i$	Number of containers being unloaded from a barge berthed at quay *m* of node *i* to the stack of node *i*	*Container Units*
$\mathrm{u}^{\mathrm{d}}_{\mathrm{i}} \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad d \in VD$	Containers used to satisfy the incoming demand form network node *i* to virtual destination node *d* at timestep *k*	*Container Units*
$\mathrm{u}^{i}_{d} \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad d \in VD_i$	Containers used to satisfy the outgoing demand form network node i to virtual destination node d at timestep k	*Container Units*
$z^{v}_{i} \in \mathrm{R}^{nc}_{\geq 0}, \quad i \in N,$ $v \in V$	The number of containers which leaves from node *i* to node *j* at timestep *k* on the same truck which they arrived with and have not been unloaded from	*Container Units*

Table 3.11: FBR Strategy: Action Variables

Most of the variables in this strategy are also vectors. The vector $\mathrm{u}^{\mathrm{hs}}_{\mathrm{im}}(k)$ is used to keep a record of the incoming containers send to quay *m* of node *i* by all type of barges at timestep *k*. This is necessary to represent the travel time of barge φ_{imjn} and the operational time within ports ω_{im} in the barge network as a delay. The formulation of the barge delay is:

$$\mathrm{u}_{\mathrm{im}}^{\mathrm{hs}}(k) = \Big[u_{jnim}^{s_1}(k-1) \dots u_{jnim}^{s_1}\big(k - \omega_{jn} - \varphi_{jnim} - \omega_{im}\big) \dots u_{j'n'im}^{s_{nb}}(k-1) \dots u_{j'nim}^{s_{nb}}\big(k - \omega_{j'n'} - \varphi_{j'n'im} - \omega_{im}\big)\Big], \quad m \in Q_i, \quad \{j \dots j'\} \in \mathrm{B_i}, \ \{s1 \dots s_{nb}\}, \quad \{n \dots n'\} \in Q_j, \quad s \in [1, \mathrm{ns}]$$

Here, the u_{ji}^{s1} is the number of containers of each type send to node *i* from node *j*. Following the same the delay of barges is constructed as well:

$$\mathrm{s}_{\mathrm{im}}^{\mathrm{h}}(k) = \big[s_{jnim}(k-1) \dots s_{jnim}\big(k - \omega_{jn} - \varphi_{jnim} - \omega_{im}\big) \dots s_{j'n'im}(k-1) \dots s_{j'n'im}\big(k - \omega_{j'n'} - \varphi_{j'n'im} - \omega_{im}\big)\big], \ m \in Q_i, \quad \{j \dots j'\} \in \mathrm{B_i}, \quad \{n \dots n'\} \in Q_j,$$

With the introduction of flexible barges in the transport system, there are new states which describe the dynamics of the network nodes, and they need to be added to Eq. (1). The new added states count the number of containers which are ready to be transported by barges and the number of barges which are presence at a node at each timestep (*k*). The state of every network node is completed with the delays presented above.

$$x_i(k) = \begin{bmatrix} x_i^c(k) \\ x_i^v(k) \\ x_{im}^b(k) \\ x_{im}^t(k) \\ u_i^{hv_1}(k) \\ \vdots \\ u_i^{hv_{nv}}(k) \\ u_{im}^{hs_1}(k) \\ \vdots \\ u_{im}^{hs_{ns}}(k) \\ v_i^h(k) \\ s_{im}^h(k) \end{bmatrix}, \qquad (19)$$

The number of containers which are stored at node *i* are now a result of the containers which are loaded and unloaded to and from the berthed barges. Therefore, the dynamic equation of state x_i^c is extended with the variables $u_{im}^l \in \mathrm{R}_{\geq 0}^{nc}$ and $u_{mi}^u \in \mathrm{R}_{\geq 0}^{nc}$:

$$x_i^c(k+1) = x_i^c(k) + \sum_{v \in [1,nv]} \sum_{j \in T_i} \Big(u_{ji}^v\big(k - \tau_{ji}\big) - u_{ij}^v(k)\Big) + \sum_{m \in O_i} \Big(u_{mi}^u(k) - u_{im}^l(k)\Big) + \sum_{d \in D_i} u_d^i(k) - u_i^d(k) \ , \qquad (20)$$

The subsequent Equation (19) defines the number of barges which are present at a quay in node *i* and can be processed by the gantry cranes:

$$\mathrm{x_{im}^b(k+1) = x_{im}^b(k)} + \sum_{j \in \mathrm{B_i}} \sum_{n \in Q_j} \Big(s_{jnim}\big(k - \omega_{jn} - \varphi_{jnim} - \omega_{im}\big) - s_{imjn}(k)\Big), \qquad (21)$$

The set O_i is used to represent the area where the loading and unloading operations at ports are commencing and the barges are berthed. For every node *i* the set contains several elements which can accommodate the barges. Compared to trucks, barges have the capability to transfer higher volumes of containers. As a result, the handling operations with barges take considerably longer time compared to truck operations. The newly added state $\mathrm{x}_{\mathrm{im}}^{\mathrm{t}}$, aims to reflects on these differences and represent the number of containers which are transported from the main stacking area and subsequently loaded on a barge at timestep *k*. The containers which are unloaded from a barge follows the same steps but in opposite direction. They are considered as well in the dynamics of this state. The following equation describes the number of containers which are assigned to barges:

$$\mathrm{x}_{\mathrm{im}}^{\mathrm{t}}(k+1) = x_{im}^{t}(k) + u_{im}^{l}(k)$$
$$- u_{mi}^{u}(k) +, \sum_{j \in B_i} \sum_{n \in \mathrm{Q_j}} \sum_{s \in S} \left(u_{jnim}^{s}\left(k - \omega_{jn} - \varphi_{jnim} - \omega_{im}\right) - u_{imjn}^{s}(k)\right), \qquad (22)$$

The following constraints considers the network capacity and the terminals capacities. Equation (23) limits the available space for barges at node *i*:

$$[1\boldsymbol{ns}] * x_{im}^{b}(k) \le c_{im}^{b}, \qquad \forall i \in N, \qquad (23)$$

Further, the number of containers which are assigned to barges are limited to the capacity of the present barges at node *i.* This is described in Eq. (24):

$$[1\boldsymbol{nc}] * x_{im}^{t}(k) \le Cap * [1\boldsymbol{ns}] * x_{im}^{b}(k), \qquad \forall i \in N,\ m \in O_i, \qquad (24)$$

Variables $u_{im}^{l}(k) \in \mathrm{R}_{\ge 0}^{nc}$ and $u_{mi}^{u}(k) \in \mathrm{R}_{\ge 0}^{nc}$ represent volumes of containers moved to and from the main stacking area of a terminal in handling operations of barges. Such movements are restricted by the productivity of quay gantry cranes and their speed. The next equation constraints the capacity of handling operations according to the crane's capabilities:

$$[1\boldsymbol{nc}] * \mathrm{u}_{\mathrm{im}}^{\mathrm{l}}(k) + [1\boldsymbol{nc}] * u_{mi}^{u}(k) \le c_{i}^{s} * x_{im}^{b}(k), \qquad \forall i \in N, \qquad \forall\, m \in Q_i, \qquad (25)$$

In the strategy it is assumed that a barge cannot transport containers to the same node which she is currently in. This action is allowed for truck dynamics to represent their waiting time before entering node *i*. Yet, in barge dynamics it is considered that containers can be assigned once the barge is already at the terminal. Therefore, their waiting time cannot be expressed in the same way as with truck.

$$\mathrm{u}_{\mathrm{ii}}^{\mathrm{s}}(k) = 0, \qquad \forall i \in N, \qquad i \in Q_i, \qquad \forall s \in S \ (26)$$

Once the containers are ready and loaded on barges, they are assigned on a barge arc, and they can leave the terminal. Eq. (27) ensures that the assigned containers on a barge link does not exceed the capacity of the barges which is assigned to the same barge link:

$$[1\boldsymbol{nc}] * \sum_{j \in B_i} \sum_{n \in Q_i} \sum_{s \in S} u_{imjn}^{s} \le Cap * s_{imjn}(k) \ \ \forall i \in N, \qquad \forall m \in Q_i, (27)$$

The consistency of barges is ensured by Eq. (28), so the number of barges assigned to journeys does not exceed the total number of barges operating in the network. The following Eq. (28) allows a barge journey only if the barge is currently berthed at the origin node of the journey:

$$\sum_{i,j\in N}\sum_{m\,\in Q_i}\sum_{n\,\in Q_j} s_{imjn}(k) \leq [1\boldsymbol{ns}], \quad (28)$$

$$\sum_{j\,\in\,B_i}\sum_{n\,\in Q_j} s_{imjn}(k) \leq [1\boldsymbol{ns}] * x_{im}^{b}(k), \qquad \forall i\ \in N, \qquad \forall m\ \in Q_i, \quad (29)$$

The system operator can make decisions to send trucks if and only if the trucks travel time is within the prediction horizon. The same logic is followed for the barges so barges can be sent out from a port if and only if their arrival at the destination is within the prediction horizon. This term is defined in Eq. (30):

$$\begin{aligned} s_{imjn}(k) = 0, \qquad \forall i \in\ N, \qquad \forall m\ \in Q_i, \qquad \forall j \in B_i, \qquad \forall n \in Q_j,\\ \forall k \geq Tp - \omega_j -\ \varphi_{ji} - \omega_i, \qquad (30) \end{aligned}$$

Furthermore, the operator is not allowed to start loading a barge if the barge cannot arrive to its destination until the end of the prediction horizon. In this way, we eliminate the possibility of loading a barge which is subsequently not allowed to leave node *i* with the assigned containers. This constrained is described in the following Eq. (31):

$$\begin{aligned} u_{im}^{l}(k) = 0, \qquad \forall i \in\ N, \qquad \forall m\ \in Q_i, \qquad \forall j \in B_i, \qquad \forall n \in Q_j,\\ \forall k \geq Tp - \omega_j -\ \varphi_{ji} - \omega_i, \qquad (31) \end{aligned}$$

The next constrains defines the non-negativity of the available actions to the operator:

$$s_{imjn}(k)\ \in \{0,1\}, \qquad \forall i \in\ N, \qquad \forall m\ \in Q_i, \qquad \forall j \in B_i, \qquad \forall n \in Q_j, \qquad \forall k\ \in [0, Tp-1], \quad (32)$$

$$u_{imjn}^{s}(k) \geq 0, \qquad \forall i \in\ N, \qquad \forall m\ \in Q_i, \qquad \forall j \in B_i, \qquad \forall n \in Q_j, \qquad \forall k\ \in [0, Tp-1], \qquad (33)$$

The operator solves an optimization problem at every timestep *k* and measures the state of every node *i Eq.*(35). For the optimization process at the following timestep *k+1*, the operator considers the measured state $y_i(t)$, as an initial condition of the system.

$$x_i(k=0) = y_i(t), \qquad \forall i\ \in N,\ \ \forall k\ \in [0, Tp-1], \qquad (35)$$

The decision vector U contains all inputs to system: $u_{ij}^{v}(k)$, $u_{imjn}^{s}(k)$, $u_{im}^{l}(k)$, $u_{mi}^{u}(k)$, $v_{ij}(k)$, $s_{imjn}\ (k)$, $u_{id}(k)\ and\ u_{di}(k)$ for all $i,j \in N, m\ \in Q_i,\ n \in Q_j,\ s\ \in S\ ,\ d \in VD_i\ , k \in\ [0, Tp-1]$.The new optimization problem which is solved at each timestep *k* by the operator is subject to Eq. (2), (4)-(7), (10)-(16), and (20)-(36). The aim is to minimize an objective function Eq. (36) which now incorporates the operation of barges in the transport network:

$$\begin{aligned} \min \sum_{k=0}^{Tp} \Bigg(\sum_{i\in N} \Bigg(& M_i^c x_i^c(k) +\ M_{im}^{bc}\Bigg(\sum_{m\in Q_i} x_{im}^{t}(k)\Bigg) + M_i^v x_i^v(k) + M_{im}^{b} x_{im}^{b}(k) + \sum_{j\in T_i} M_{ij}^{v} v_{ij}(k) \\ & + \sum_{j\,\in B_i} M_{ij}^{tb}\Bigg(\sum_{m\,\in Q_i}\sum_{n\in Q_j} s_{imjn}\Bigg) \\ & + \sum_{v\in[1,nv]} M_i^{lv}\Bigg(\sum_{j\in T_i}\big(u_{ji}^{v}(k-\tau_{ji}) + u_{ij}^{v}(k)\big) - 2z_i^v(k)\Bigg) + \Bigg) + \Bigg), \quad (36) \end{aligned}$$

3.3. Summary

In this chapter, a MPC operational strategy was proposed to ensure sophisticated planning in a synchromodal transport network. Most works presented in Chapter 2 cannot fully adapt to changes in the system due to predetermined rules and procedures. This research aims to investigate the consequences of introducing flexible barge services to the overall performance of the synchromodal network. Providing more freedom to the system operator it is expected to have significant and positive impact on both stationary and moving resources.

To analyze the potential benefits of applying flexible barge routing in a synchromodal network, two strategies are proposed in this section. A designed Flexible Barge Routing (FBR) strategy and a Benchmark strategy proposed by Larsen (2020). Both operational strategies are implementing MPC planning approach and incorporate limitations in available storage and transport capacity. The MPC operator in both strategies aims to minimize an objective function with costs for handling, storage, and transportation. Both strategies do not consider congestions either on roadways or waterways but implies penalties for delayed orders.

The Benchmark strategy incorporates limited number of flexible trucks which can reach any node within the transport system while barge services operate on a fixed schedule. On the other hand, the FBR strategy routes trucks, containers, and barges simultaneously. The output of both strategies consists of optimal routes for containers and transport vehicles, modal share, and terminal utilization level. With Section3 an answer to research Sub-question 3 is provided by proposing an operational strategy which implement a MPC approach with flexible transport modes withing a synchromodal transport system.

4. Case Study

This chapter firstly introduces the case study on which the two strategies are going the implemented in Section 4.1. Afterwards, Section 4.2 introduces four scenarios on which the two strategies are going to be tested on. Scenarios differ in the number of containers to be transported. Section 4.3 contains details about the configuration of the Benchmark and FBR strategies. This includes the cost and capacity parameters, network layouts, MPC planning horizon length and optimal barge schedule. At last, the chapter is summarized in Section 4.4.

4.1. Case Description

In this Section, a case study is introduced. The case is based on the perspective of a company which is involved in the container transport business in the Netherlands and internationally. For the purposes of this thesis, the case is focused on the activity of the company within the Netherlands and specifically with Port of Rotterdam. The section is going to present insights about the operations of the company and the locations it serves. This information is going to be used for further configuration of the input for the strategies presented in Section 3.2.1 and 3.2.2. Summary of the Case study is presented below:

4.1.1. CTT

CTT itself owns three container terminals at Hengelo, Almelo and one at Rotterdam. At these terminals different services are offered as transportation, warehousing, and maintenance. The inland terminals at Hengelo and Almelo have the possibility to handle barges and trucks. The CTT Hengelo terminal has a 400m long quay side to accommodate barges. There is a day-to-day barge service from this terminal to Rotterdam. The CTT Rotterdam has smaller quay side but has the possibility to accommodate cargo trains. The operations of the latter terminal are 24/7.

- CTT company is operating with 14 terminals within the territory of the Netherlands:
  - 3 terminals are owned by CTT located at Rotterdam, Hengelo, and Almelo.
  - 11 terminals located at Port of Rotterdam (Maasvlakte, Waalhaven and Eemshaven) are operating with CTT.
- The CTT company offers truck and inland barge services to their customers.

The CTT company provided a data set of orders for the period of 03.01.2019 to 07.04.2019 which was used for the purposes of this report. In the dataset there are orders which originates from 30 different terminals. Three of terminals are the CTT owned inland terminals at Hengelo, Almelo, and Rotterdam. Eight terminals in the data set are part of the Maasvlakte area of Port of Rotterdam. The rest of the terminals are in Port of Rotterdam as well but in the areas of Waalhaven and Eemshaven which are closer to the city of Rotterdam. The CTT Rotterdam terminal is part of the Eemshaven's terminals. An overview of the terminals which operates with the company of CTT can be found in Table 4.1.

The road distance between the deep-sea terminals of Maasvlakte and the second group of terminals is less than 40km according to Google Maps. If a truck can travel with up to 90km/h it can be assumed that it can cover the distance for less than 1 hour. Following the same assumption, the distance between the terminals at Hengelo and Almelo and the deep-sea terminals at Waalhaven and Maasvlakte can be covered by a truck respectively in 2 hours and 3 hours.

LOCATION	TERMINALS	NODE REPRESENTATION

GROUP 1	Maasvlakte	APM, APM2, Rotterdam World Gateway (RWG), ECT EUROMAX, ECT DELTA, ECT DELTA BARGE, DELTA CONTAINER SERVICES, ROTTERDAM CONTAINER TERMINAL (RCT)	Node 1, Node 2
GROUP 2	Waalhaven and Eemshaven	CTT ROTTERDAM, MATRANS ROTTERDAM TERMINAL, ROTTERDAM SHORT SEA TERMINALS, UNIPORT MULTIPURPOSE TERMINALS, BARGE CENTER WAALHAVEN	Node 3, Node 4
GROUP 3	Hengelo	CTT HENGELO	Node 5

Table 4.1: Terminals operating with CTT.

Barge transportation is generally slower than trucks as barges ply with much lower speeds. In the area of Port of Rotterdam there is a speed limit of 13km/h which is an equivalent of 7 knots. In this way we can assume that a barge can cover the distance between the terminals of Maasvlakte and the terminals closer to the city of Rotterdam for the period of 3 hours. Accordingly, it is considered that a barge can cover the distance between Maasvlakte and Hengelo within 11 hours. From Hengelo the barge can reach the CTT container terminal at Rotterdam within 9 hours with an average speed of 7knots.

4.1.2. Port of Rotterdam Container Terminals: Overview

Public Information about all container terminals at Port of Rotterdam is gathered and presented in Table 4.2 (*Container Port of Europe*, 2020).

TERMINALS	CAPACITY (TEU)	QUAY LENGTH (M)	TYPE OF VESSELS (DS/B)	PLOT AREA (HA)
MAASVLAKTE				
APM	3350000	1600	DS	100
APM2	2700000	1500/500	DS/B	86
ROTTERDAM WORLD GATEWAY	2350000	1700/550	DS/B	108
ECT EUROMAX	***3000000***	1500	DS	84
ECT DELTA	***5000000***	3600	DS	272
ECT DELTA BARGE	***100000***	890	B	7.5
DELTA CONTAINER SERVICES	***50000***	260	B	2.5
ROTTERDAM CONTAINER TERMINAL	500000	400	B	17
WAALHAVEN AND EEMSHAVEN				
CTTROT	240000	150	B	8
MATRANS ROTTERDAM TERMINAL	300000	1180	DS/B	34

ROTTERDAM SHORT SEA TERMINALS	1400000	1800	DS/B	46
UNIPORT MULTIPURPOSE TERMINALS	1200000	2400	DS/B	54
BARGE CENTER WAAL HAVEN	200000	225	B	6.4
HENGELO				
CTT HENGELO	***400000***	400	B	12.5

Table 4.2: Characteristics of container terminals at Port of Rotterdam and CTT terminal at Hengelo

In the official port map provided by Port of Rotterdam there is no public information about four of the terminals at Maasvlakte area. These are the ECT and Delta container terminals. Their capacity is approximated based on their plot area typed in bold and italic style. As it can be observed from the Table 4.2 the ECT and Delta terminals are among the biggest at the port. In the table, the terms DS and B are used to represent the types of vessels which a terminal is specified to handle respectively “Deep-sea” and “Barges”. In the cases of APM2 and Rotterdam World Gateway deep-sea vessels and barges are berthed on one quay. The quay length is divided in two parts as the first one represents the overall quay length and the second one the quay size where barges are handled.

The terminals located at the Maasvlakte area have different purpose compared to the terminals at Waalhaven. The former has overall five times bigger storage capacity and 54% more space for handling deep-sea vessels. On the other hand, their total quay length dedicated for barge handling is with 37% shorter in comparison with the second group of terminals. Moreover, the plot of the terminals closer to Rotterdam is with 57% bigger than the barge terminals at the Maasvlakte. Generally, the terminals at Maasvlakte have the purpose of handling mainly deep-sea container vessels which require greater storage space and available equipment. Contrastingly, the terminals at Waalhaven focus on handling inland vessels in parallel with smaller deep-sea vessels driven by special and technical limitations.

The CTT terminal at Rotterdam is considerably smaller compared to the other container terminals in the area in terms of available storage space and plot area. Even though, the CTT terminal is tiny, it has the possibility to allocate container freight to three transport modes: barges, trains, and trucks. For the purposes of this thesis, it is considered that this terminal can handle trucks and barges while trains services are left outside of the scope. This assumption is supported by the characteristics of the CTT Hengelo terminal which do not support train services but only truck and inland barges. There is no official information about the container capacity of the CTT Hengelo. An assumption is made based on the plot area of the terminal which is twice bigger than the ‘Barge Centre Waal haven’. Accordingly, it is proposed that CTT Hengelo has a twice bigger container storage capacity compared to the later (400000TEU).

4.2. Simulation Scenarios

In this section, four scenarios are formulated based on CTT order list and data from the annual reports of Port of Rotterdam. Scenarios differ in the number of containers which must be transported by a system operator. Each scenario is tested with the two operational strategies proposed in Section 3. The aim is to evaluate the effects of applying an operational strategy on system performance in situations of different freight flows.

- Four Scenarios built on practical and historical data.

- Each Scenario has unique demand profile with certain volumes of containers:
    - **Base Scenario**: demand profile with 324 containers which is a representation of CTT orders list.
    - **Small Increase Scenario**: demand profile with 356 containers which is 10% increase from the Base Scenario.
    - **Medium Increase Scenario**: demand profile with 420 containers which is 30% increase from the Base Scenario.
    - **Large Increase Scenario**: demand profile with 644 containers which is 100% increase from the Base Scenario.
- Demand profiles of the four scenarios share identical characteristics of the orders in terms of origin, destination, and due times. The uniqueness in each demand profile is arise from the volumes of containers in each order.

For the construction of demand patterns for each scenario, a data sheet with container orders is used provided by the company of CTT. Each transport order has origin, destination, pick-up, and delivery time. A demand profile based on this data sheet is constructed and applied on the first scenario called Base Scenario. The difference between the scenarios comes from the volumes of containers orders which must be transported in the system. The subsequent three scenarios have demand profiles where each order has increased number of containers to be transported, but with the same customer requirements as in the Base Scenario. The four scenarios are going to be applied on the FBR and the Benchmark strategies. The desired performance from a system operator who applies the strategies is all containers from the orders to be picked up and delivered according to their requirements. If a container order is delivered to its destination within the necessary time windows, then it is assumed that the operator satisfied the most essential performance requirement.

The four scenarios which are going to be tested are derived from data provided by the company of CTT in addition to the container activity in the past 10 years at Port of Rotterdam. Figure 4.1 presents a summary of the total amount of containers which were handled in the port from 2010 to 2019. It can be observed from the figure that the throughput of container units handled at PoR are steadily increasing from nearly 700 000 in 2010 to just under 900 000 in 2019. This is a considerable growth of slightly more than 30%. From 2010 there is an evident trend at PoR of handling more containers than the previous year. The average rate of increase for the mentioned period is 4.1%. The most significant raises came in 2011 and 2017 where the container volumes upsurged with respectively 6.5% and 10.5%.

The first of the four scenario is the Base Scenario (BS) where the demand of container orders is derived from the CTT data and presented in Section 4.3. The demand profile is unbalanced with more Import containers than export with a total volume of 324 orders. For the Second scenario, the demand profile from the BS is changed. Parts of the base CTT demand profile are increased with 10% to represent short-term peaks in container orders. In the Third scenario, parts of the CTT demand profile from the BS are increased with 30% to represent the growth tendency at PoR for a decade. The fourth scenario is the most drastic one where volume of container orders is doubled compared to the original demand profile. The main intention of introducing the different scenarios is to analyse the performance of the synchromodal system when volumes of orders rise in random moments of the optimization process. In all four scenarios the available resources are going to be the same. It is assumed that in all scenarios the system operator has an accurate prediction for the upcoming demand orders.

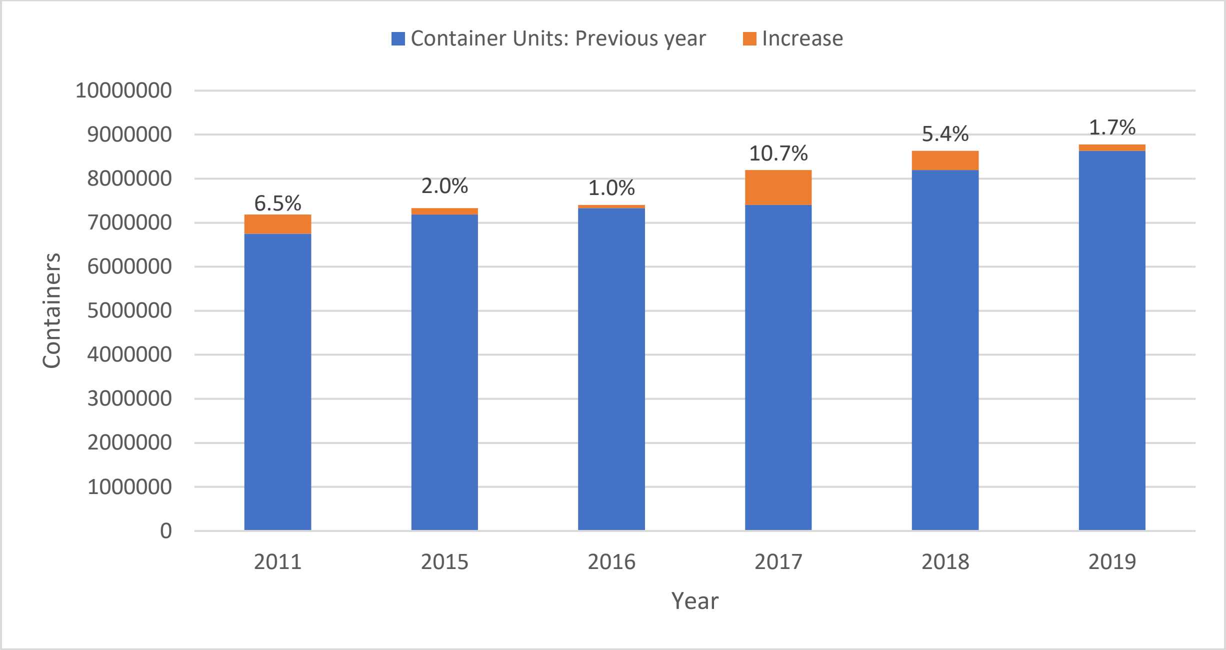


Figure 4.*1*: Total Throughput in PoR and Increase Tendency

With the four scenarios, the effect of greater container volumes on the system performance can be analysed. It is expected that the operational strategy with scheduled services is going to struggle with satisfying the demand on time. As barge capacity cannot be relocated it is also expected that more extensive use of trucks is going to be observed. This will lead to lower utilization of terminal truck parking but also to higher realized costs for operating the system. Moreover, a container delay is going to reflect on the delay of other containers which is going to increase the number of containers being stacked at terminals. This is going to result in higher utilization levels of stacking areas in different nodes of the network.

The FBR strategy with flexible barge services is expected to perform better than the Benchmark strategy in a way to satisfy more container orders on time. As the control agent can send the barge capacity to any point of the network, more available capacity can be relocated to a node where it is going to be needed. The utilization level of stacking areas is expected also to grow as the available transport capacity is limited and containers need to wait to be picked up. It is interesting to observe the share of empty and full truck trips when the demand is bigger and the utilization level of terminal quays for barges. Barges are expected to spend more time at terminals to load and unload larger batches of containers.

4.2.1. CTT Demand Profiles: Base Scenario

This sub-section contains information about the construction and the characteristics of the Base Scenario. The demand profile for this scenario is generated from a dataset of accepted transport orders by the company of CTT. The dataset consists of orders for the period of 03.01.2019 to 04.04.2019. The orders are characterized by a container type: 20ft (TEU) or 40ft (FEU), origin, destination, pick up time and delivery time. There are no preferences for the transport mode in the orders characteristics. It was observed from the data that a considerable part of the orders was performed in the period of 01/02/2019 to 28/02/2019. The share of orders per month is presented in Figure 4.2. The overall amount of container orders was 1206, 1021 of each were transported in February. Thereof, a demand profile is going to be constructed from the orders of this month.

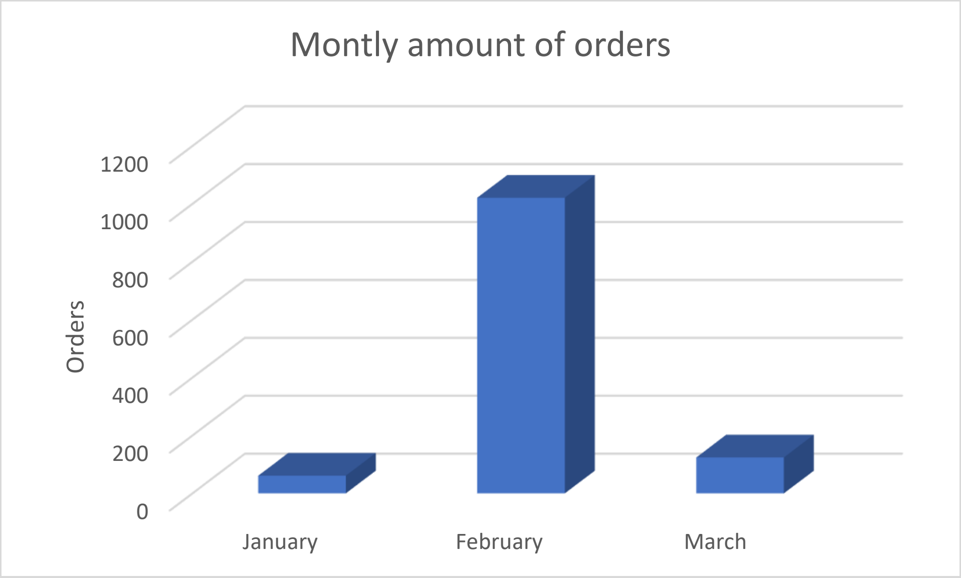


Figure 4.2: Overall number of accepted orders per month

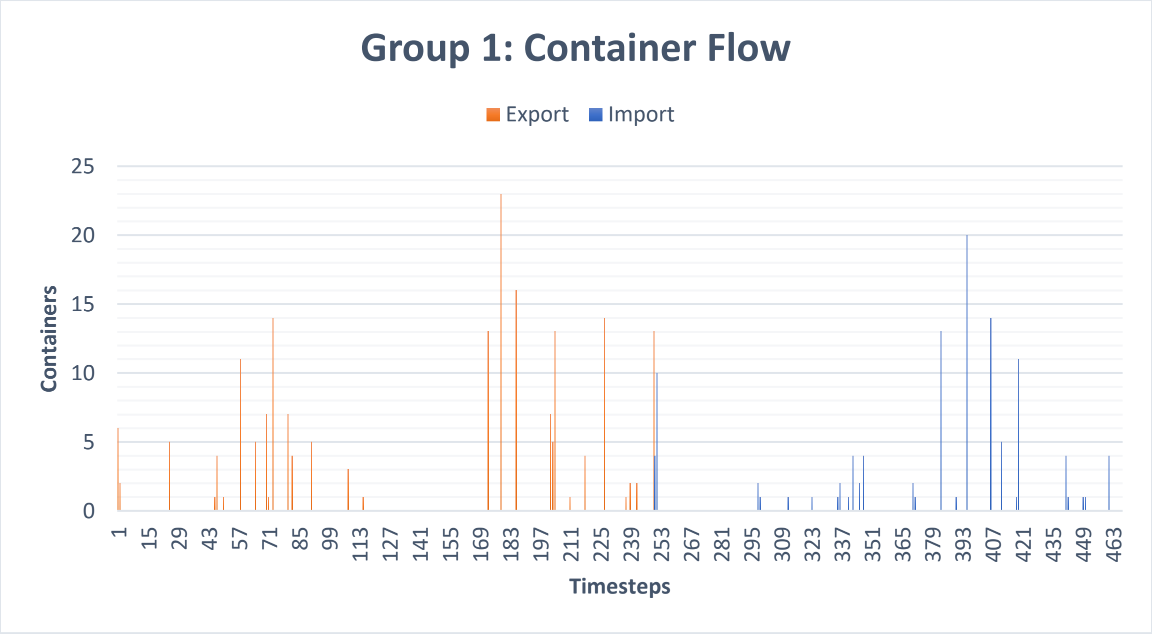
The size characteristics of the containers (TEU or FEU) in the CTT dataset are not considered in the creation of the profiles. In Section 3.1 containers are defined by their origin and destination and not by their size. For simplicity it is not considered that two TEUs can be handled as one FEU. Both port and long-distance trucks have the capacity to accommodate one container unit. The same approach is applied on barges which can load limited number of units onboard regardless of container size. Each order in the CTT dataset is assumed as one container unit which must be transported in the hinterland network. The demand profile is constructed from orders which are scheduled for the period of 05/02/2019 – 25/02/2019 between the terminals presented in Table 4.2. There was a total volume of 324 accepted orders for transportation. This number is used for the definition of the scale factor mentioned in the previous section. For the year of 2019, the Port of Rotterdam (PoR) has an annual throughput of 8781185 container boxes (*Throughput*, 2020). Therefore, the volume of 324 container units has a share of 0.0036% from the total PoR container throughput.

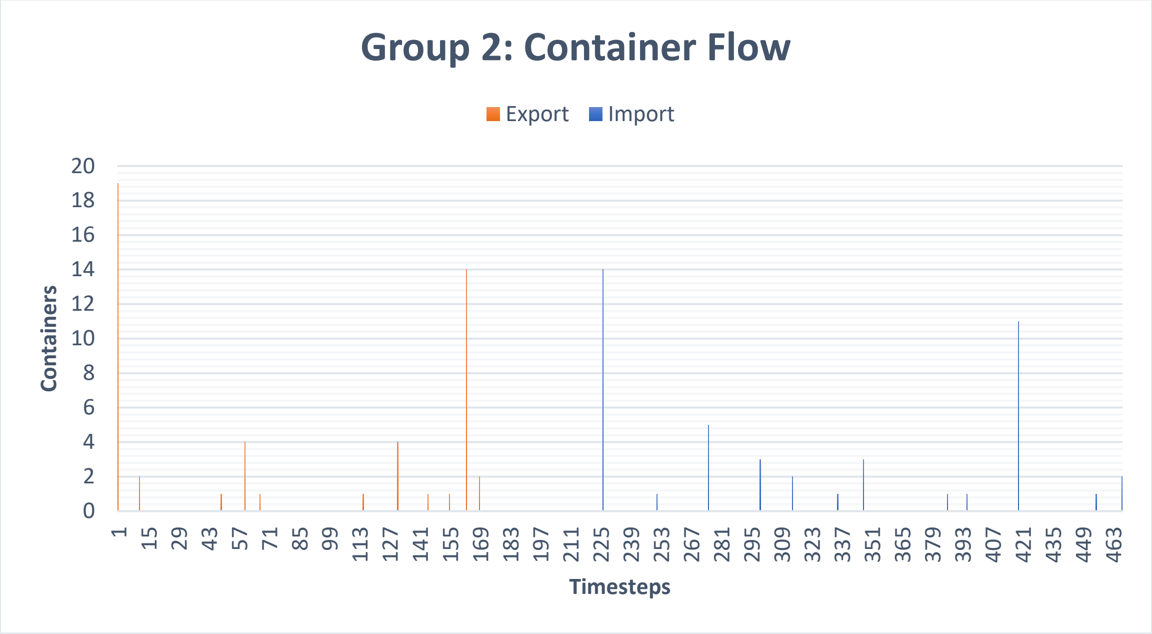
It is considered that the system planner has access to the state of the system every ΔT minute with a forecast for the incoming and outgoing demand for containers. At every ΔT the planner uses updated information to define a sequence of actions which will minimize the cost function (Eq. 18, Eq. 36) over a prediction horizon length (Tp). For the construction of the Base Scenario, the orders from the period of 05/02/2019 to 25/02/2020 are used. By using an update rate of 1 hour ($\Delta T = 1h$), this period can be covered in 468 timesteps ($k\_max = 468$). These values of the MPC parameters are applied in al numerical experiments.

Demand profiles are constructed by considering three Virtual Destination (VD) nodes. Containers are distributed between these VDs. Each VD node in the system is a representation of a geographical group of terminals. Two groups represent the terminals at the area of Port of Rotterdam. Group 1 represent container terminals at Maasvlakte and Group 2 at Waalhaven. Group 3 is a representation of the CTT terminal at Hengelo and Almelo. More detailed information is presented further in this Section 4.3.2.1.

A demand profile is constructed by counting the transport orders which must be routed between terminals of two separate groups. Thus, orders for container transport between terminals within the Maasvlakte area or Waalhaven area are not counted. The real data from CTT shows an expected tendency of unbalanced import and export orders. The import orders are containers which must be transferred from a container terminal of Group 1 or 2 to the CTT Hengelo terminal. Respectively, export orders are containers which must be transported in the opposite direction from the CTT Hengelo terminal to a terminal of Group 1 or 2. As the terminals of Groups 2 are in the middle of the network, the same logic is applied for them. Orders delivered to them from terminals of Group 1 are considered as import and those sent from CTT Hengelo as export.

The constructed demand profile is unbalanced in terms of export and import orders. Almost twice more containers are directed to deep-sea terminals compared to inland terminals. The number of import orders is 210 which takes a share of 65% from the total. Accordingly, the containers for export are significantly less by being 35% of the total with an exact volume of 114. More detailed information about the distribution of the demand is presented on Figure 4.3. There are three graphs showing the demand at the virtual destination nodes which are adjacent to one terminal of each group. The quantity of new demand is shown over timesteps. Outgoing demand is shown on the graphs as a positive number, while incoming demand as negative number.





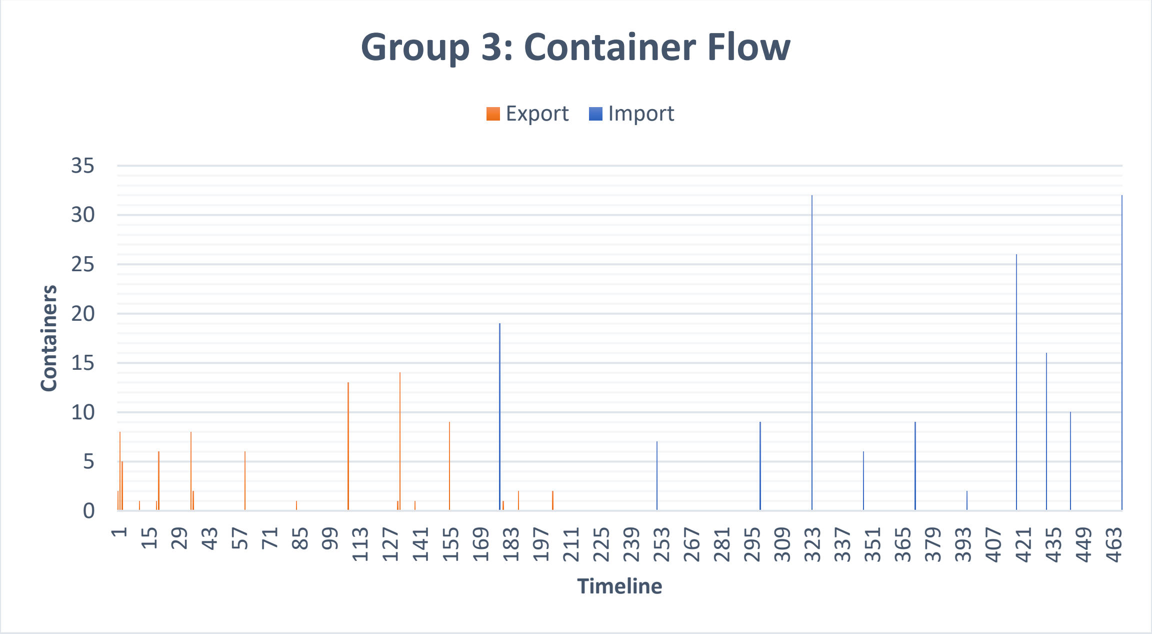


Figure *4.3*: Demand profile of nodes adjacent to virtual destination nodes representing terminals from Group 1, Group 2, and Group 3

4.2.2. Increased Volume Scenarios

This sub-section contains information about the construction and the characteristics of the three additional scenarios. All of them are based on the Base Scenario and apply the same order requirements. The difference to the Base Scenario is the number of containers in orders which needs to be transported. The total amount of containers in the scenarios are increased with respectively 10%, 30% and 100% compared to the demand profile of the Base Scenario. The Demand profile constructed from the CTT data contains 48 orders for 324 containers. The average amount of containers headed to the hinterland is 7 containers. The average amount of containers which must be delivered at the Port of Rotterdam terminals is 9 containers. Based on this observation, only the orders for transporting more than 7 containers are going to be increased in the demand profiles of the following three scenarios. This results in a total number of 16 increased orders which is greater than 30% of the total number of orders.

SMALL INCREASE SCENARIO

The Small Increase Scenario is a scenario which simulates an expected annual increase of container throughput. Similar growth is observed in the reports of PoR between 2016 and 2017. The Figure 4.4 below presents demand profile used in the scenario with the number of containers which enters and leaves the system per timesteps. The number of containers is increased to 354 compared to 324 in the Base Scenario.

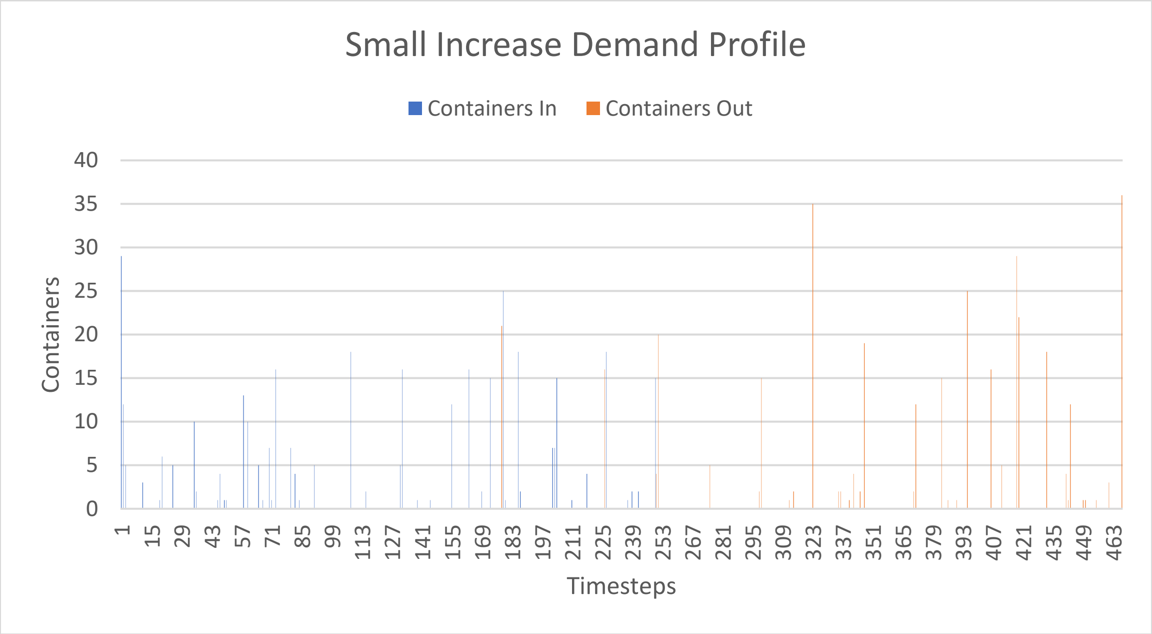


Figure 4.4: Small Increase Demand Profile

MEDIUM INCREASE SCENARIO

The Medium Increase Scenario is a scenario which simulates an increase of container throughput expected for a decade. Similar growth is observed in the reports of PoR between the years of 2010 and 2019. The Figure 4.5 below presents the demand profile used in the scenario with the number of containers which enters and leaves the system per timesteps. The volume of containers is increased to 420 which is a 30% growth compared to the Base Scenario.

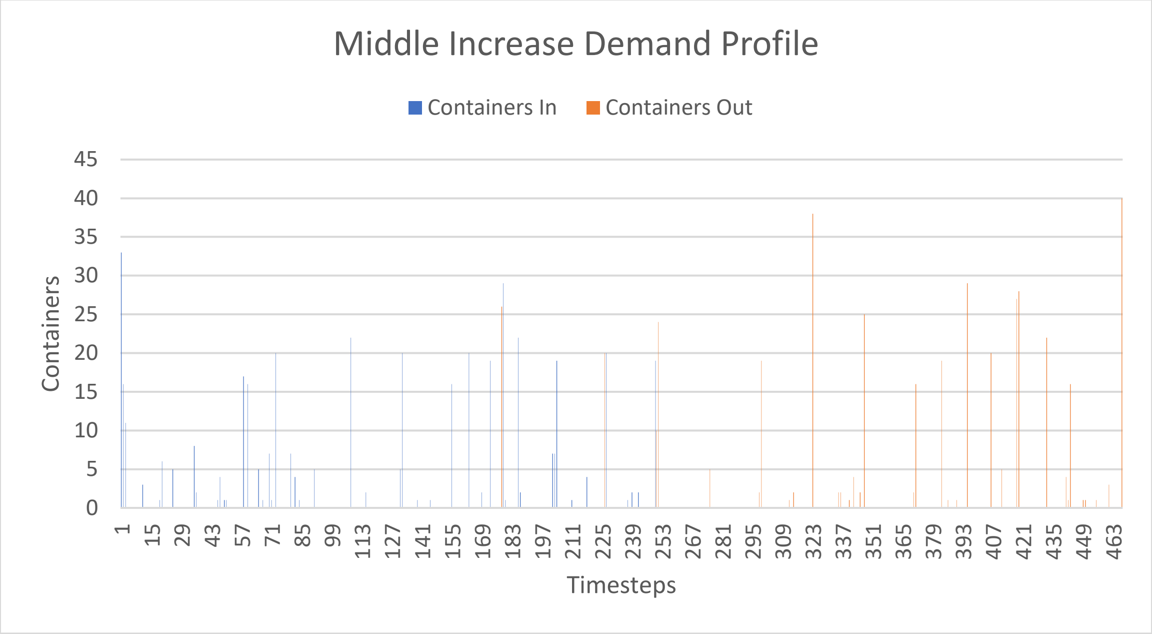


Figure 4.5: Middle Increase Demand Profile

LARGE INCREASE SCENARIO

The Medium Increase Scenario is a scenario which simulates a potential rise of container throughput for a period longer than decade. Similar growth is observed in the reports of PoR between 2000 and 2019. The Figure 4.6 below presents the demand profile used in the scenario with the number of containers which enters and leaves the system per timesteps. The volume of containers in this demand profile is increased to 648 which is a 100% surge compared to the Bas Scenario.

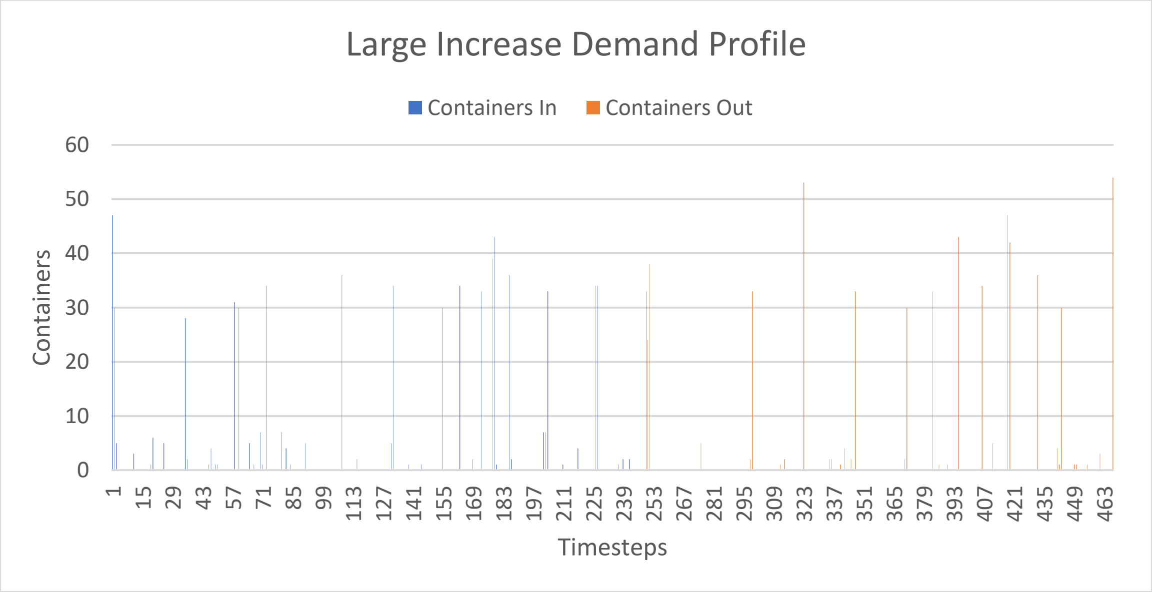


Figure 4.6: Large Increase Demand Profile

4.3. Strategy Configuration

In this section, configurations of parameters, network layouts and MPC parameters for the two strategies are presented. These configurations are applied on the two operational strategies presented in Section 3. The configurations for the two strategies have several similar components. For instance, the cost and capacity parameters have identical values. The purpose of this is to highlight the impact of flexible barge routing in the output of the simulation runs. Moreover, parameter values of the MPC planning approach are also identical for the two strategies. A sequence of numerical experiments is executed to define suitable value for the crucial Tp (prediction horizon length) parameter. The experiments are performed in MATLAB, using Yalmip and Gurobi. A concise summary of the two strategy configurations is presented below:

- Two configurations proposed for each of the operational strategies.
- Identical components of the two configurations:
  - Common set of capacity parameters
  - Common set of cost parameters
  - Common sets of travel times: truck and barge
    - Congestions on truck roads and barge waterways are not considered in strategy configurations.
  - Identical MPC design
- Unique components of each strategy configuration:
  - Benchmark:
    - Network layout: barge service is represented as a single node in the network layout.
    - Optimal Barge Schedule
  - FBR:
    - Network layout: barge service is operating on separate graph in the network layout.

Considering the network layouts used in the experiments, two different layouts are proposed due to the difference in strategies. The two layouts have a similar construction which represents real-life container terminals and a truck network. A difference in representing barge services is observed between the two layouts. In the layout of the Benchmark strategy, barge services are defined as a single node which has capacity limits. The availability to this node is restricted in certain stages of the optimization and this creates the barge schedule. On the other hand, the second layout for the FBR strategy with flexible barge services introduces an additional graph with four fully connected additional nodes. The distances between the nodes in the two layouts are measured in travel times presented in timesteps. The configuration of the travel times is the same for the two strategies.

Compared to the FBR strategy, the Benchmark strategy includes a schedule for the barge. This schedule is crucial for the output of experiments with the different scenarios. For the purposes of this thesis, the company of CTT does not provide information about the schedule of their barge service. Thus, a numerical experiment is performed to obtain a barge schedule which is assumed to be optimal for the proposed configuration. For the formation of the schedule, a simulation run is performed using the demand profile from the Base Scenario applied on FBR strategy. In this experiment MPC planning is not applied, hence optimization is performed at once. The resulted barge routes and terminal visits are used to configure a barge schedule which is further applied on the Benchmark strategy in the scenario testing. The experiment is performed in MATLAB, using Yalmip and Gurobi.

4.3.1. Scenarios Parameters

The selection of costs and capacity parameters has significant impact on the choices made by the system operator. In this section the configuration of the costs and capacity parameters are introduced. They are chosen to reflect on the characteristics of the real container terminals located in the Port of Rotterdam and Hengelo presented in Section 4.1.2.

The proposed costs are based on several assumptions. Firstly, the costs are going to be constructed on the perspective of the company of CTT. Respectively, the costs to berth and handle a barge at nodes representing CTT terminals is lower than at the other terminals. This is also supported by the above-described purpose of the Maasvlakte terminals to prioritize deep-sea vessels. Secondly, based on terminal characteristics data in Table 4.2, it is not cheaper to park a truck or store a container at CTT terminals due to the smaller available space. Especially at CTT Rotterdam where the storage space is limited. Thirdly, it is assumed that there are two nodes in the network, one for each group of terminals, which represent multimodal hubs with greater stacking space. These nodes offer lower costs for storage, parking, and handling services.

The construction of the capacity parameter values is also based on real-life assumptions. The nodes which represent Maasvlakte terminals have significantly higher storage and parking capacities. Furthermore, the crane speed capacity there is also higher compared to other terminals. For instance, the CTT terminals at Rotterdam and Hengelo have only one container crane which reflects on slower crane speed capacities at these nodes. For simplicity, it is assumed that only one barge can be berthed at a terminal, but this can be easily extended by adding additional quay nodes to the network. The storage capacity for containers is modelled by using a scale factor. The scale factor is a result of the total volume of containers transported by the company of CTT according to the provided data and the real-life capacity of the terminals presented in Table 4.3.

All costs and capacity parameters are shown in Table 4.3 and Table 4.4. The costs are formulated in a way which encourages the movement of containers and trucks. Stacking and parking costs are relatively high compared to transport costs except at the hub nodes where costs are lower. Furthermore, a new type of cost is introduced to the strategy to encourage the movement of barges. Barges are charged each timestep they are berthed on a quay node, but also an additional cost imposed on each container already loaded on the barge. This specific cost is charged per timestep and supports the barge movement thus barges are not use as cheap additional storage space while occupying the quay. It is believed that the combination of these costs will improve the efficient utilization of available quays. The cost for unsatisfied demand is not based on information from the company of CTT. It is assumed that an appropriate penalty for delayed container can be nearly 10 times higher than the most expensive container stacking area. This price is not deriver empirically and can be a topic for a further research in the synchromodal literature.

COST PARAMETERS

$\boldsymbol{M_1^c} = \mathbf{2} * \mathbf{1nc}$	$M_1^v = 2 * \boldsymbol{1nv}$
$\boldsymbol{M_2^c} = \mathbf{1.5} * \mathbf{1nc}$	$M_2^v = 1.5 * \boldsymbol{1nv}$
$\boldsymbol{M_3^c} = \mathbf{4} * \mathbf{1nc}$	$M_3^v = 3 * \boldsymbol{1nv}$
$\boldsymbol{M_4^c} = \mathbf{3} * \mathbf{1nc}$	$M_4^v = 1.5 * \boldsymbol{1nv}$
$\boldsymbol{M_5^c} = \mathbf{2.5} * \mathbf{1nc}$	$M_5^v = 2 * \boldsymbol{1nv}$
$\boldsymbol{M_6^{\mathrm{b}}} = \mathbf{3} * \boldsymbol{1nc}$	$M_8^{\mathrm{b}} = 1 * \boldsymbol{1nc}$
$\boldsymbol{M_7^{\mathrm{b}}} = \mathbf{2} * \boldsymbol{1nc}$	$M_9^{\mathrm{b}} = 1 * \boldsymbol{1nc}$
$\boldsymbol{M_{ij}^{tv}} = \boldsymbol{\tau_{ij}} * \mathbf{4.5} * \boldsymbol{1nc}, \quad \forall \boldsymbol{i}, \boldsymbol{j} \in [\mathbf{1}, \mathbf{5}], \boldsymbol{i} \neq \boldsymbol{j}$	$M_{ii}^{tv} = \tau_{ii} * 9 * \boldsymbol{1nc}, \quad \forall i \in [1,5]$
$\boldsymbol{M_{ij}^{tb}} = (\boldsymbol{\omega_{im}} + \boldsymbol{\varphi_{imjn}} + \boldsymbol{\omega_{jn}}) * \mathbf{5.5} * \boldsymbol{1nc},$ $\forall \boldsymbol{i}, \boldsymbol{j} \in [\mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{5}], \forall \boldsymbol{m}, \boldsymbol{n}$ $\in [\mathbf{6}, \mathbf{7}, \mathbf{8}, \mathbf{9}]$	$M_1^{ls} = 2 * 1\boldsymbol{nc}$
$\boldsymbol{M_i^{lv}} = \mathbf{3} * \boldsymbol{1nc}, \quad \forall \boldsymbol{i} \in [\mathbf{1}, \mathbf{3}, \mathbf{5}]$	$M_2^{ls} = 1.5 * 1\boldsymbol{nc}$
$\boldsymbol{M_i^{lv}} = \mathbf{2} * \boldsymbol{1nc}, \quad \forall \boldsymbol{i} \in [\mathbf{2}, \mathbf{4}]$	$M_i^{ls} = 1 * 1\boldsymbol{nc}, \quad \forall i \in [3,5]$
$\boldsymbol{M_6^{bc}} = \mathbf{0.7}$	$M_7^{bc} = 0.6$
$\boldsymbol{M_i^{bc}} = \mathbf{0.5}, \quad \forall \boldsymbol{i} \in [\mathbf{8}, \mathbf{9}]$	$M_i^d = 30\,, \ \forall i \in [10,11,12]$

Table 4.3: Cost Parameters used in Strategy Configurations.

CAPACITY PARAMETERS

$\boldsymbol{c_1^c = 130}$	$c_1^v = [15\ 5]^T$
$\boldsymbol{c_2^c = 530}$	$c_2^v = [15\ 25]^T$
$\boldsymbol{c_3^c = 30}$	$c_3^v = [15\ 5]^T$
$\boldsymbol{c_4^c = 120}$	$c_4^v = [15\ 20]^T$
$\boldsymbol{c_5^c = 50}$	$c_5^v = [0\ 10]^T$
$\boldsymbol{c_{im}^b = 1, \forall \mathbf{i} \in [1,2,3,5], \forall \mathbf{m} \in [6,7,8,9]}$	$Cap = 20$
$\boldsymbol{c_i^t = 5, \forall \mathbf{i} \in [1,2,4,5]}$	$c_i^s = 8, \forall \mathrm{i} \in [1,2]$
$\boldsymbol{c_3^t = 3}$	$c_3^s = 5$
$\boldsymbol{x_i^v(0) = [\ 0\ 0]^T\ \forall \mathbf{i} \in [1,3]}$	$c_5^s = 6$
$\boldsymbol{x_2^v(0) = [\ 15\ 20]^T}$	$x_4^v(0) = [\ 15\ 16]^T$
$\boldsymbol{x_5^v(0) = [\ 0\ 4]^T}$	

Table 4.4: Capacity Parameters used in Strategy Configurations.

4.3.2. Network Layouts

In this section two layout of the CTT network are presented. The first layout is relevant for the strategy presented in Section 3.2.1 while the second one is relevant for the strategy presented in Section 3.2.2. Firstly, the assumptions about the simplification of the CTT network are introduced followed by the presentation of the two layouts.

4.3.2.1. CTT Network Simplification

The number of terminals found in the CTT dataset is near 30. To construct a network design for the experiments we need to simplify the real network and reduce the number of terminals. Three groups of terminals are defined from the data list. The first group of terminals which are part of the Maasvlakte area (Group 1) are going to be presented by two network nodes (Node 1 and Node 2). Each of these nodes have the possibility to use barge and truck services. As these terminals are in proximity, there is the possibility to use short-range trucks to transfer containers between the nodes. For simplicity, each node has the possibility to accommodate only one barge on a quay, but this can be extended easily by adding additional quay nodes to the nodes.

The second group of container terminals located in Waal haven and Eemshaven (Group 2) are also presented by two nodes. One of these two nodes (Node 3) is a representation of the CTT Rotterdam terminal and has both barge and truck services. The other network node (Node 4) has only truck connections. In the same logic as the previous two nodes, due to the proximity of the terminals in this area there is a possibility to transfer containers among Node 3 and Node 4 by short range truck connection.

The last node of the network is a representation of the CTT terminals of Hengelo and Almelo as part of Group 3. The node has both truck and barge connections to the other nodes within the system. Operational hours of the terminals and resting hours of truck drivers are not considered in the strategy. Each of the network nodes has the possibility for transshipment of containers.

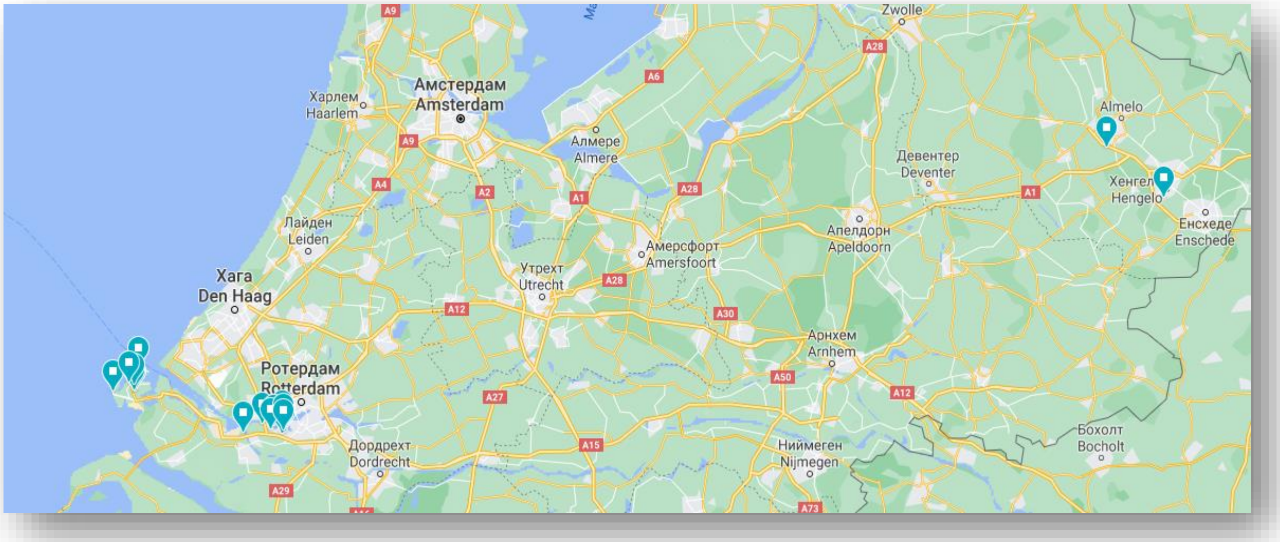


Figure 4.7: Container Terminals found in the dataset of CTT within the Netherlands.

4.3.2.2. Benchmark Strategy Network Layout

The network layout where containers are routed by truck and fixed scheduled barge services is presented on Figure 4.8. The hinterland transport network consists of three virtual destination nodes: one adjacent to Maasvlakte terminals (Group 1), one adjacent to CTT Rotterdam terminal (Group 2) and one adjacent to the inland CTT terminal at Hengelo (Group 3). The last last-mile delivery and pick-up of containers at the inland terminal are assumed to be arranged. The network has a barge connection which operates on a fixed schedule. Within the Maasvlakte area, between node 1 and node 2 there are port trucks which can transfer containers indicated on the figure with grey dotted lines. There is an identical connection between CTT Rotterdam (node 3) and the other terminals of Group 2 (node 4). The network of solid grey lines is used by long distance trucks to transfer containers.

4.3.2.3. FBR Strategy Network Layout

The strategy with flexible barge routing is applied on a modified hinterland transport network presented on Figure 4.9. The number of virtual destination nodes and terminals remains unchained from the network presented in the section above. However, the network layout here is extended by a fully connected graph with four additional nodes. These four new nodes represent terminal quays where a barge can be accommodated called “barge nodes”. Each barge node is adjacent to one “terminal node” and connected via a black dotted link. There is no travel time applied on these black dotted links, but there is a capacity limitation which represents the gantry crane speed. Therefore, a limited number of containers can be transferred from a terminal stacking area to a barge and vice versa. It is assumed that each of the new nodes can accommodate one barge. The network of solid green lines is used by the barges to transfer containers.

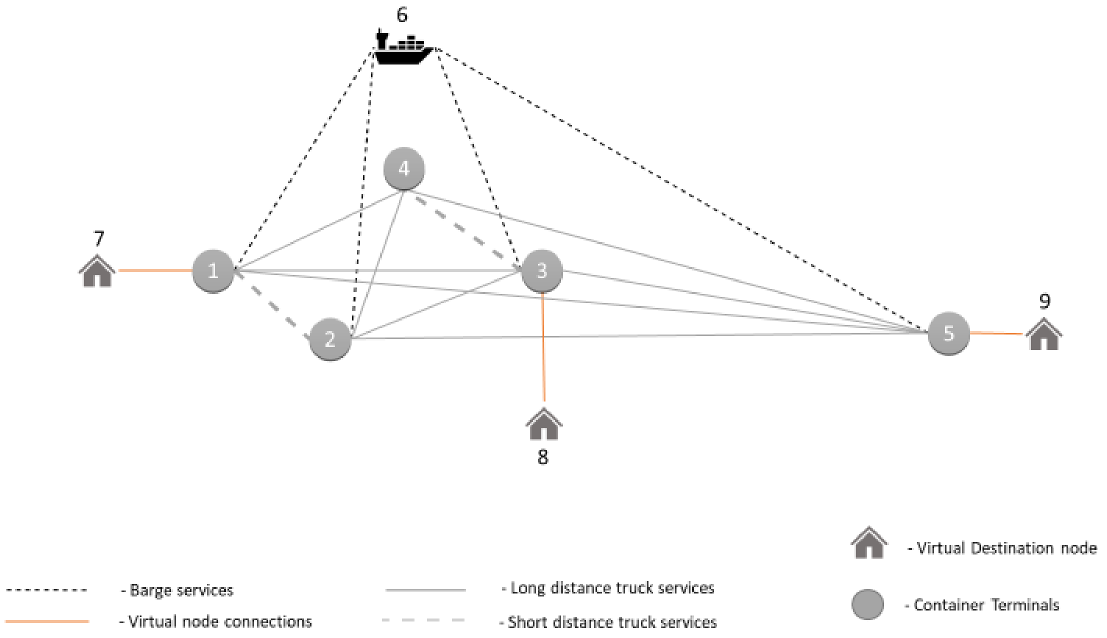


Figure 4.8: CTT Network with scheduled barge service (Benchmark Strategy)

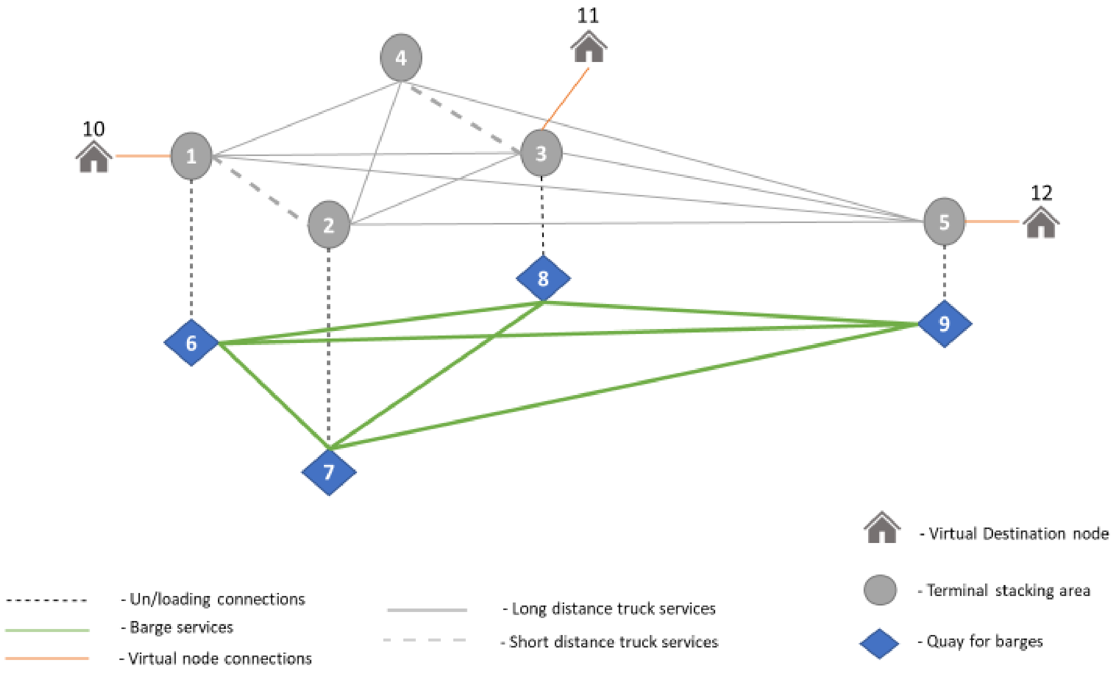


Figure 4.9: CTT network with flexible barge services (FBR Strategy)

4.3.2.4. Travel Times

The distances in the two networks are presented in timesteps. They are identical for the two network layouts presented above. There are two types of trucks which can operate in the system: short-range trucks and long-range trucks. While short-range trucks can only cover journeys of 1 timestep, long-range trucks are used for journeys longer than 1 timestep. The truck travel times between nodes are presented in the Table 4.5 in timesteps. For simplicity in the strategy, road congestions and potential delays are not considered in travel times.

		End Node				
		1	2	3	4	5
Starting Node	1	1	1	2	2	4
	2	1	1	2	2	4
	3	2	2	1	1	3
	4	2	2	1	1	3
	5	4	4	3	3	1

Table 4.5: Travel times on truck networks in timesteps

Apart from the strategy presented in Section 3.2.1, in the strategy introduced in Section 3.2.2 the system operator can route the barges flexibly without complying with a schedule. For simplicity in the strategies, the barge travel time does not consider congestions on waterways, delays on locks and bridges and restricted approaches to waterways. When the system operator decides to route a barge, a prior notice to the terminal operator is not required. However, operational time for entering or leaving a terminal is considered and equals 1 timestep. This time is assumed to be sufficient for manoeuvring operations. The same barge travel times are used in Section 4.3.4 to generate an optimal barge schedule for the benchmark strategy. Barge travel times between nodes with barge connection are presented below in timesteps:

		End Node				
		1	2	3	4	5
Starting node	1	0	2	3	0	11
	2	2	0	5	0	11
	3	3	3	0	0	9
	4	0	0	0	0	0
	5	11	11	9	0	0

Table 4.6: Travel times on barge network in timestep

4.3.3. MPC Parameters

In this section, insights of the MPC planning approach are provided. One of the parameters of the MPC planning approach: the prediction horizon length is tuned by the means of numerical experiments. Eight simulation runs are executed with different Tp lengths. A trade-off between the experiment outputs and the computational time is made to select the most appropriate value.

The initial container state and the initial state of arriving container and transport vehicles is zero in all scenarios: $x_i^c(t=0)=0_{nc}$, $x_{im}^t(t=0)=0_{nc}$, $\mathrm{u}_\mathrm{i}^\mathrm{hv}(t=0)=0_{nc}$, $\mathrm{u}_\mathrm{im}^\mathrm{hs}(t=0)=0_{nc}$, $v_\mathrm{i}^\mathrm{h}(t=0)=0_{nv}$, $s_{im}^h(t=0)=0_{ns}$, $\forall_i \in N$.

4.3.3.1. Prediction Horizon (Tp) Length Calibration

The length of the prediction horizon (Tp) allows the MPC planner to capture different events and consider them. For instance, when the Tp is relatively long, the MPC planer can predict the benefits of relocating capacity to different nodes. Positioning trips of trucks and barges can be performed so when container orders enter the system, there has already been sufficient capacity to transfer them. Whereas, with a short Tp the operator can capture smaller number of events and miss the opportunity to relocate capacity in advance. The approach for defining the most appropriate length for the Prediction horizon is briefly described below:

- Prediction Horizon (Tp) Length Calibration:
    - Tp minimum length must capture the longest possible trip in the system 15 steps.
    - Testing eight values for Tp with the FBR strategy configuration on the Base Scenario
    - Trade-off between unsatisfied demand, realized costs and computational times.

Implementing longer prediction horizon has its consequences in increasing the computational time needed for finding an optimal solution. A trade-off between time spent in computation and system performance needs to be made. To define the optimal length of the Tp, eight numerical experiments are made using the Base Scenario and varying the size of the Tp. One assumption is made before the experiments. The Tp must have a minimum length of such a size which can capture the departure and arrival of trucks and barges. Thus, the MPC planner always has a perception about the transport modes which decides to route. The maximum travel time in timesteps between the most distant nodes in the network is 13, so the first experiment is done with Tp = 15 which is 15% higher than 13.

The performance of the system with different length of the Tp are presented on Figure 4.10. On the figure can be observed the realized costs for transporting all container orders and the overall computation time in seconds. Computational time is referred as the time during which the processor works. This is important as the computational force in this research is limited to the capabilities of a personal laptop.

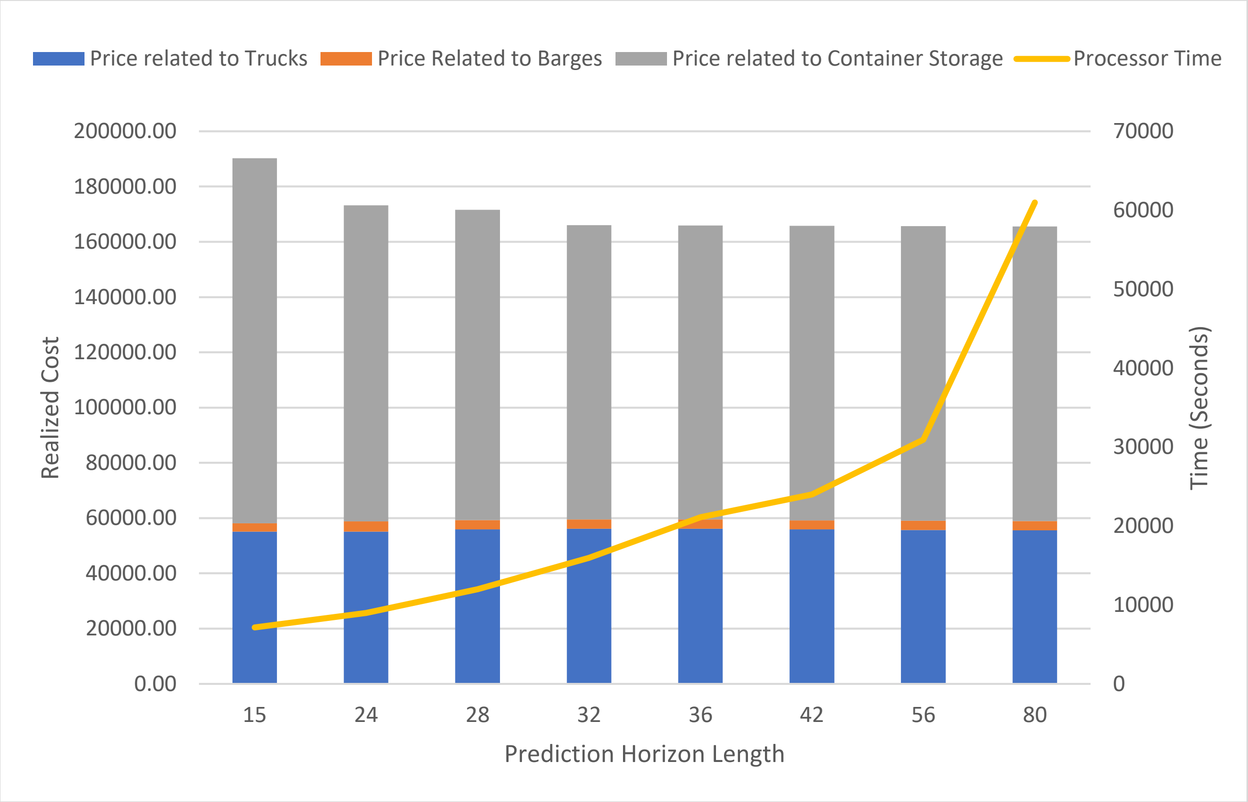


Figure 4.10: Comparison of realized costs and computational time in seconds.

The numerical experiments with the two MPC strategies are performed in MATLAB by the means of Yalmip and Gurobi. The planner can successfully transfer all container orders in the system without delays. From the results it can be observed that the longer the Tp is, the lower is the realized cost. In all experiments the realized costs related to trucks and barges do not change significantly, while the costs for storing containers at terminals decrease.

The highest operational cost is generated in the simulation run with a prediction horizon of 15 steps. This is the shortest prediction horizon length which is simulated. The following length used for the experiment is increased with 60% to 24 steps. Subsequently, the realized costs were decreased with nearly 10% while the computational time increased with 25.6% reaching the value of 9000 seconds. The next substantial reduction in realized cost is observed in the experiments of Tp = 32 steps. Compared to the results of the experiment with Tp = 24steps, the realized cost is reduced by 4.2%. However, the computational time proceed increasing to 15969 seconds which is almost double to the time of the run with Tp = 24steps.

The realized cost does not decrease significantly in the simulations with a prediction horizon greater than 32 steps, yet the computational time increases significantly. Even though, the realized cost does not drop off after the experiment with Tp = 32, the computational time doubles from Tp = 32 to Tp = 56 by reaching values higher than 80 000 seconds. Moreover, the computational time in the experiment with Tp= 80 reaches almost 17 hours, while the realized cost depreciates by the negligible 0.246 percentages. Therefore, it is assumed that the most suitable value for the prediction horizon is between the range of 32 and 56 steps.

As one step is equivalent to 1 hour, it is considered that 36 steps is a suitable period in which relevant events in the transport system are captured. The length of 36 steps is preferred over the length of 32 steps due to taken actions by the system planner. For instance, the costs for storing containers at terminals is lower in the experiment with Tp= 36 compared to the Tp = 32. Moreover, the realized cost for barge routing is nearly unchanged, while nearly 5% more containers are transported by the barge reaching an overall share of slightly over 16%. As a conclusion, a prediction horizon Tp = 36 is going to be applied further in this thesis for testing the simulation scenarios.

4.3.4. Optimal Barge Schedule

In this section, an optimal schedule for the barge routing is going to be introduced. The obtaining of a schedule is essential for the construction of a compliable configuration for the Benchmark strategy. Based on the capacity and cost parameters introduced in Section 4.3.1 and the network layout presented in Section 4.3.2.3, a simulation run is performed which output is used for the construction of the schedule. The applied approach is shortly described below:

- Obtaining Optimal Barge Schedule for the Benchmark strategy configuration:
  - Applying the FBR strategy configuration on the Base Scenario
  - No MPC planning approach: one optimization process.
  - Resulted barge routes and stays at terminals are compiled into a barge schedule.

Prior to the main simulation experiments with both strategies and the comparison of their results a schedule for the barges must be determined. For this purpose, an experiment with the FBR formulation is performed where a barge can ply between any nodes with barge connection. In the experiment the schedule is defined by solving an optimization problem with the demand profile extracted from the CTT data and presented in the Base Scenario. The problem is solved without the MPC approach with the costs and capacity parameters presented in Table 4.3 and Table 4.4. The Base Scenario is applied with the FBR strategy. The solution in obtained by a simulation experiment performed in MATLAB with Yalmip and Gurobi. An optimal solution was found in a simulation time of 55 minutes. The absolute value of the objective function is not essential in this experiment but the total amount of unsatisfied demand. In the found solution the share of unsatisfied demand is 11% which is 35 containers from the total 324. Substantial share of the unsatisfied demand is import containers heading to node 9 by a barge.

The purpose of this simulation experiment is to find the sequence of terminal visits by the barge. The results are used to define an optimal barge schedule for the configuration of the Benchmark strategy.

NODE	HANDLING ACTIVITY	TIMESTEPS								
1	Unloading	91	232	249	250	251				
	Loading	252	253							
2	Unloading	21	54	86	96	97	125	157	218	219
		237	308	341	425	454				
	Loading	218	219	238	280	309	342	426	455	
3	Unloading	225	226	243	335	347	371	395	419	
	Loading	48	60	131	163	164	192	244	336	348
		372	396							
5	Unloading	73	143	176	177	178	179	180	204	266
		294	322	323	359	383	407	439	440	466
		467	468							
	Loading	1	2	3	4	5	6	7	35	36
		72	111	144	176	177	178	180	205	267
		295	324	325	360	384	408	441		

Table 4.7: Optimal Barge Schedule applied in the Benchmark strategy configuration.

4.3.5. CTT Case: Result Expectations

In this thesis two CTT terminals are being modelled. One at Port of Rotterdam area and one at Hengelo. The terminal within the PoR area (Node 2) can be used as a dry port where import containers can be delivered from the Maasvlakte area and send to the inland terminal at Hengelo (Node 5). Furthermore, the terminal of Hengelo (Node 5) can be used as an extended gate and containers from the Maasvlakte are to be directly delivered by the barge. The truck operating in the system has shorter travel time but generates significantly higher transport costs than the barge. In both Benchmark and FBR strategies a barge which transports more than 3 containers benefits from economies of scale relative to truck transport.

However, a reference must be made to the characteristics of the included CTT terminal at PoR (Node 3). The handling and storage capacity of this terminal is substantially smaller relative to the other terminals in the area. Furthermore, terminals located at Maasvlakte have even greater available capacity (Table 4.2). Within the concept of synchromodal transport, different actors share information and infrastructural capacity. Therefore, it is assumed that there would be available storage and handling capacity at the Maasvlakte terminals. It is also assumed that the costs for these services are lower compared to Group 2 terminals due to possible economies of scale. In practice, the CTT company might use their terminal at PoR as a dry port but within above mention assumptions this might not be observed. In conditions of increased container throughput, it can be expected that the system planner is going to store incoming containers at Node 2 which represent the shared capacity of Maasvlakte Terminals. As there are port trucks which connects Node 1 and Node 2, barge routing between these two nodes might be rare.

However, the barge is expected to be routed mainly between Node 2 and Node 5 for the import containers.

For the export containers entering the system mainly from Node 5, intensive barge use is expected. As barges needs to deliver the import containers on the one leg, the export containers might be loaded on the other leg. What might be expected is the relatively high number of truck positioning trips. Due to the limitation of available parking space for trucks at Node 3 and Node 5, most of the trucks are parked at Node 2 and Node 4 at the beginning of the simulation. Therefore, it can be expected that many trucks will route empty to pick up their “first container”. What is more, the system planner has the possibility to foresee the benefits of allocating a truck at a node where capacity would be needed in future timesteps. This might increase the cost of a container per travelled distance but will decrease the overall realized costs at the system.

4.4. Summary

In this Section an answer is provided to sub-question 4 by introducing the needed variables and parameters for constructing well-founded scenarios for making a relevant performance analysis of the CTT transport system.

Firstly, this chapter introduces a Case Study on which the Benchmark and FBR strategies are going to be applied. The Case Study is built on the perspective of the CTT company which operates three container terminals in the Netherlands at Rotterdam, Hengelo, and Almelo. For the purposes of this thesis the company has provided a list of container orders with terminal origin, destination, pick up time and drop off time. The terminals within the Netherlands which operate with CTT are introduced. Terminals are grouped in three categories based on their location: 1) Group 1: Terminals located at Maasvlakte, 2) Group 2: Terminals at located at Waalhaven and 3) Group 3: CTT terminal at Hengelo and Almelo. Subsequently, an overview of the terminals located at Port of Rotterdam (Group 1) is presented.

Afterwards, a demand profile is constructed from the CTT orders list. The demand profile includes 324 orders for transport arranged for February 2019. This demand profile is used as a ground for the construction of the Base Scenario. The base demand profile is presented in Section 4.2.1. Further in the section, three additional scenarios are introduced where the demand profiles have increased volume of containers in the same number of orders compared to the Base scenario. The intention is to evaluate the operator’s actions when the demand for container transport is growing while system capacity remains unchanged. The results from testing all four scenarios are presented in the following Section 5.

Further, in the section the configuration of strategies is defined. Firstly, capacity and cost parameters are presented in Section 4.3.1 and 4.3.2. The cost and capacity parameters are compliant with actual data and characteristics of the terminals operating with CTT and found in the provided dataset. Thereafter, two network layouts are introduced each relevant to one of the strategies. The networks layouts are introduced with corresponding travel times between the nodes presented in timesteps. For the numerical experiments one timestep represents one hour.

Subsequently after the definition of input parameters and network layouts, the optimal prediction horizon length for the MPC is tuned by performing 8 numerical experiments. Tuning the value of this parameter is crucial for the decisions of the system planner. With longer prediction horizon length, the planner can cover more events and make better decisions. However, the longer the prediction horizon is, the bigger the computational time becomes. A tradeoff is made between the realized costs and computational time.

The value of 36 steps is assumed to be suitable for the MPC prediction horizon length and further applied in the actual simulation experiments.

Prior to testing different scenarios with the two strategies, final calibration of the Benchmark configuration is performed. A barge schedule is constructed by applying the FBR strategy configuration on the Base Scenario without using an MPC planning approach. The obtained barge routes are used to construct a barge schedule. This schedule is considered as optimal for the proposed parameters and network layout. Yet, by applying different configuration of the input parameters and network layout, another optimal barge schedule can be constructed for the new configuration. The optimal schedule is presented in timesteps in section 4.3.4.

5. Results

In this section the results from the numerical experiments are presented by showing different KPIs achieved with the two operational strategies at the four different scenarios presented in Section 4.2. Simulation experiments are performed in MATLAB by using Yalmip and Gurobi.

5.1. Results Overview

In Table 5.1 an overview of the results is presented. The table includes the overall amount of transported containers, computational time, realized costs, unsatisfied demand, and modal share. An additional column presents the difference between the results of the Benchmark and the FBR strategies in percentages. When the Benchmark has realized higher value of a KPI than the proposed strategy, then the difference is presented with a negative value.

Improvement in realized cost can be observed when barges are not routed on a fixed schedule. The differences in costs increase with the grow of container orders in the system. The highest reduction is observed in the Large Increase scenario being 11.2%. This marginal difference in the realized cost comes from the high amount of unsatisfied demand when applying the Benchmark strategy. The results from the FBR strategy also indicates unsatisfied demand. Yet this is a result from the insufficient capacity at Node 3 to accept all containers in the beginning of the optimization and not subject to planners' decisions.

One of the KPIs indicates the realized cost per transported container. It is obtained by dividing the total realized cost by the amount of containers in the system. An overview is presented on Figure 5.1. In the first three scenarios no delayed containers are observed. In these cases, with both the FBR and the Benchmark the cost per container decreases with the introduction of higher container volumes in scenarios. Hence, the more containers are present in the system, the lower is their routing cost. However, in all scenarios applying the FBR strategy results in a better value of this KPI compared to when the Benchmark is applied. This becomes most noticeable in the case of the Large Increase scenario when unsatisfied containers are observed. By applying the FBR strategy the operator can deliver all containers on time and benefit from economies of scale, while this is not observed with the Benchmark strategy. The value of this KPI in the Large Increase scenario is close to the one in the Base scenario. This only emphasizes the higher efficiency of the FBR to the Benchmark strategy in this KPI regardless of container volumes in the system.

An overview of the realized costs for each scenario is presented on Figure 5.2. The Base, Small Increase, Medium Increase and Large Increase scenarios are indicated on the figure respectively BS, SI, MI, and LI. The cost realized by barge routing and handling operations has the smallest share among all components and it is presented in orange. It is relatively stable with small rise in the Large Increase Scenario. The second cost which is observed only in the last scenario is the penalty for unsatisfied demand indicated in yellow. This cost has the highest coefficient compared to the others and can strongly influence the final cost. Trucks are essential part of the system operation, and this is reflected on their share on the total final costs. The expense for trucks routing is presented in blue on the figure. Analogous to barge routing, truck routing costs are close in all scenarios with light increases in the last scenario runs.

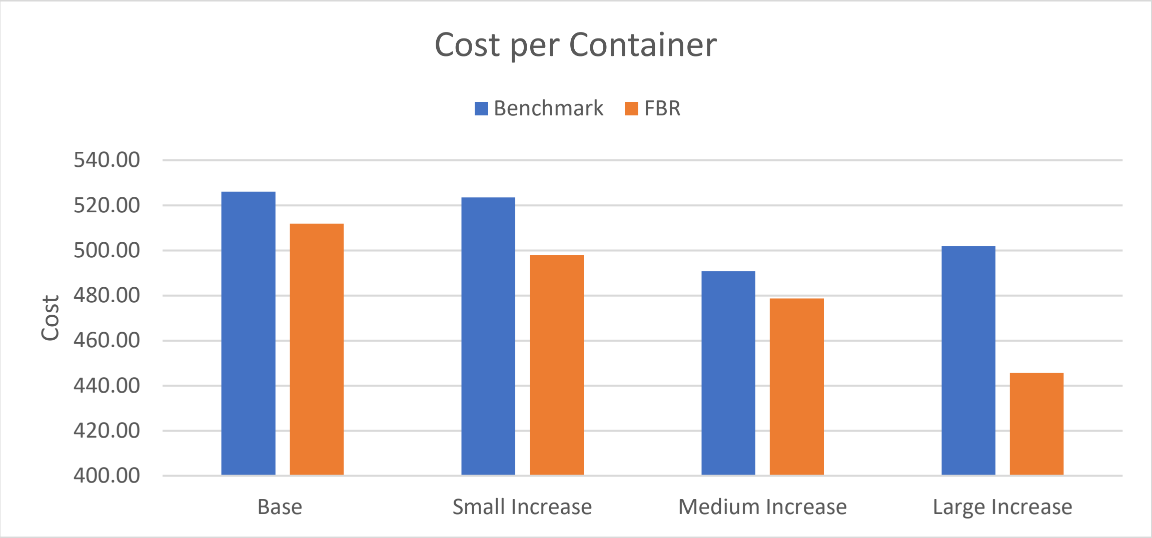


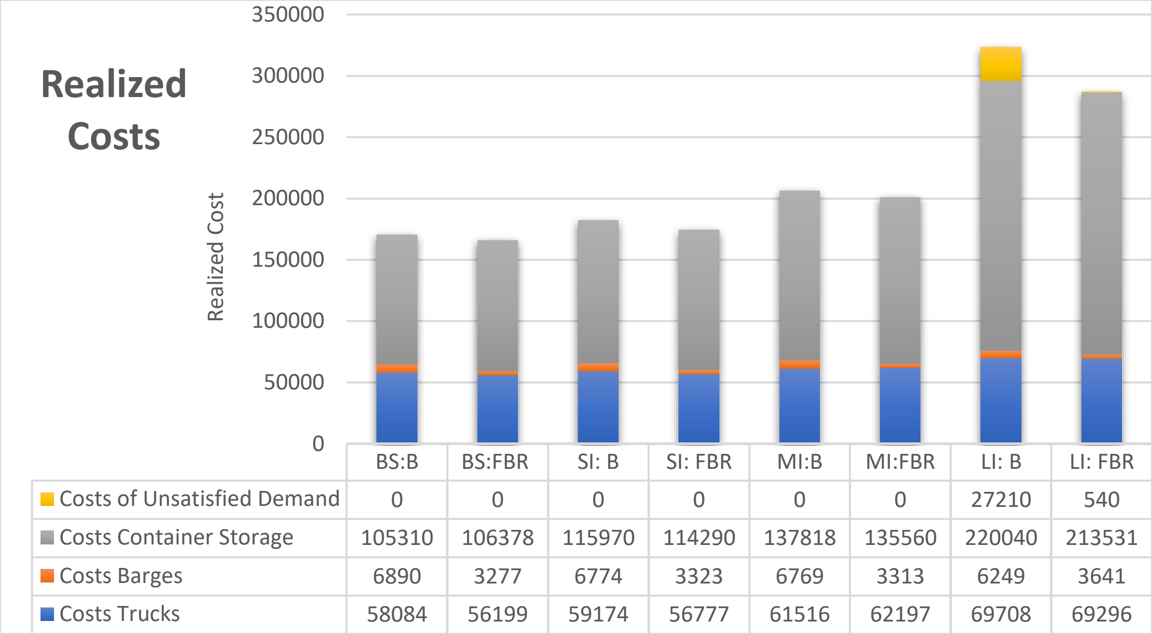
Figure 5.1: Cost per container realized in experiments.

Lastly, the cost for container storage is presented in grey color. Expectedly, this component has the highest share among the others and steadily grows with the introduction of more containers in the scenarios. Apart from barge routing cost which is double with the Benchmark strategy than with the FBR truck routing costs are relatively similar. Therefore, if there is a relation between container storage cost and routing cost it should be between storage and truck routing. However, a clear relation between these two KPIs is hard to be concluded from this figure. For instance, in the Base scenario the system planner realizes lower costs for trucks operation by applying the FBR compared to the Benchmark strategy but generates higher costs for container storage. Whereas, in the Medium Increase scenario this is inverted. Truck operational cost is higher with the FBR than with the Benchmark strategy and a reduction in storage cost is observed. In the other two scenarios, the direction of the difference between the truck operational costs in FBR and the Benchmark strategies is the identical for the storage cost. Both in the Small Increase scenario and in the Large Increase scenario with the FBR strategy the system operator can generate lower costs for trucks routing and for container storage. Eventually, it is difficult to observe a clear relation between these two costs from the figure. Thereof, this relation is going to be investigate further in this section where the results of each scenario are presented.

The number of truck trips which are realized with the two strategies does not vary considerably in all four scenarios. This can be explained with the possibility of the system operator to flexibly route trucks. In this way, available truck capacity can be allocated to the nodes where it is going to be needed in the future. Considering containers transported by barge, in the first three scenarios fewer containers are handled with the FBR compared to the Benchmark strategy. This tendency is changed in the Large Increase scenario, where the containers transported by barge in the FBR are nearly twice as much as in the Benchmark. Results indicates that with the FBR, barge capacity is used more extensively when high volume peaks occur in the system. This is illustrated below on Figure 5.3.

The modal share in scenarios is calculated by dividing the amount of moved containers by a certain transport mode to the overall number of container trips. For all scenarios, trucks have significantly greater modal share compared to barges. No decrease of truck usage is observed in all scenarios. Contrariwise, in the Large Increase scenario, the modal share of trucks reaches just under 90% with both scenarios. Yet, it is crucial to mention the tendency with containers transported by a barge. In all scenarios, except for the

Large Increase, more containers are transported by a scheduled barge than with e a flexible one. In all scenarios the containers transported by a scheduled barge are almost identical and between 119 and 130. While the amount of transport contains transported by a flexible barge with the FBR is increased considerably to 193 compared to previous scenarios where transported containers are between 102 and 110.



	BS:B	BS:FBR	SI: B	SI: FBR	MI:B	MI:FBR	LI: B	LI: FBR
🟨 Costs of Unsatisfied Demand	0	0	0	0	0	0	27210	540
◼ Costs Container Storage	105310	106378	115970	114290	137818	135560	220040	213531
🟧 Costs Barges	6890	3277	6774	3323	6769	3313	6249	3641
🟦 Costs Trucks	58084	56199	59174	56777	61516	62197	69708	69296

Figure 5.2: Realized Costs during simulation runs.

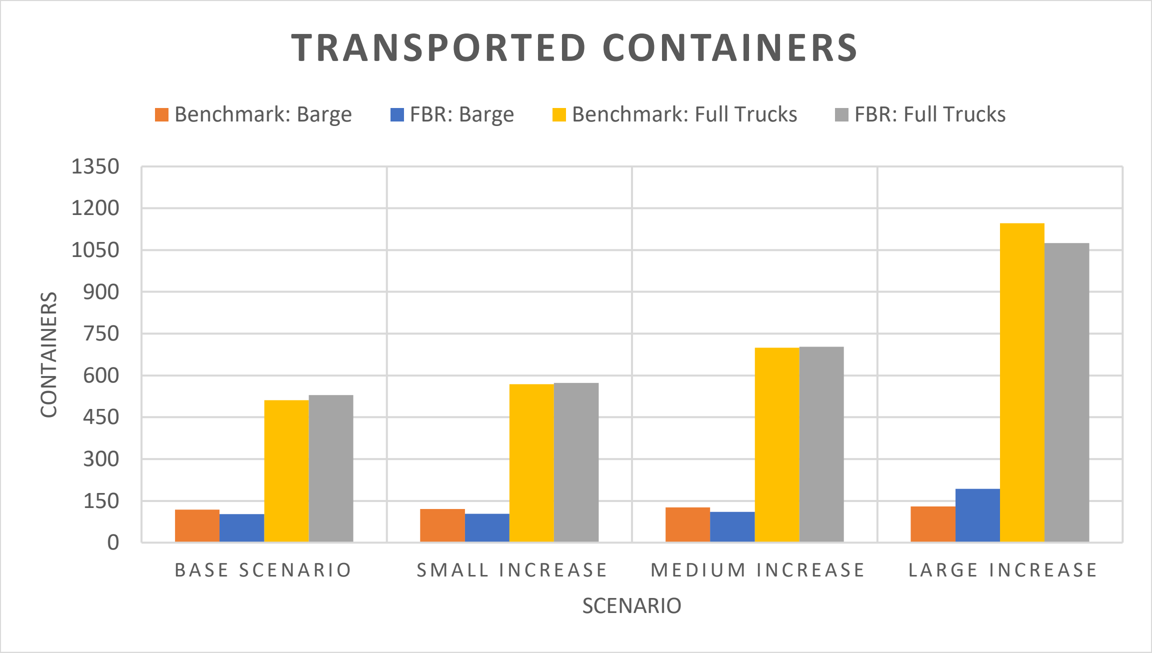


Figure 5.3: Number of containers transported by transport modes.

Scenario	**Base**			**Small Increase**			**Medium Increase**			**Large Increase**		
Strategy	*Benchmark*	*FBR*	*Diff.*	*Benchmark*	*FBR*	*Diff.*	*Benchmark*	*FBR*	*Diff.*	*Benchmark*	*FBR*	*Diff.*
Overall Volume of Containers	324	324		356	356		420	420		644	644	
Time	12790	16538	29.3%	12207	16236	33.01%	12720	16709	31.36%	12760	16078	26.00%
Unsatisfied demand	0	0		0	0		0	0		907	18	5039%
Realized Cost	170430	165850	-2.7%	186390	177270	-4.89%	206100	201070	-2.44%	323210	287010	-11.2%
Modal share Truck	81.11%	83.86%	-2.7%	82.46%	84.64%	-2.17%	84.73%	86.47%	-1.74%	89.81%	84.78%	5.03%
Modal share Barge	18.89%	16.14%	2.7%	17.54%	15.36%	2.17%	15.27%	13.53%	1.74%	10.19%	15.22%	-5.03%

Table 5.1: Results from the simulation run

5.2. Base Scenario

The previous subsection 5.1 presented an overview of system KPIs resulted from applying the two operational strategies in all four scenarios. In this chapter only the results from applying the two strategies on the Base Scenario are going to be presented. The Base Scenario is a reflection on the current performance of the CTT company. The demand profile is constructed based on their real-life data from 2019. Therefore, the results of this scenario are believed to bring more insight into the potential bottlenecks and the benefits of applying flexible barges operating in a synchromodal transport system. Additional KPIs are presented further in this subsection as utilization levels of different system resources, durations of barge stay at all terminals and the busy routes in the system.

By applying the two strategies almost identical behavior of the system operator is observed related to container routing by trucks. Containers are mainly stored at Node 2 where capacity is available and costs are lower compared to Node 1,2,3 and 4. With both strategies, the system operator extensively use the short-range trucks from Node 1 to Node 2 to transfer containers. This is expected as the travel time between the two nodes is only one timestep and the storage costs at Node 2 is 25% cheaper than at Node 1. Considering Node 5, 'the inland terminal', 97% of the departing containers are directed to Node 2. They are stored closely to Node 1, just before their due date. What is interesting, is that the same actions are applied for the containers entering the system from Node 3. The system operator firstly sends the containers to Node 2 and subsequently route them to Node 5 and Node 1.

To analyze the exploitation of system resources, Figure 5.4 presents the utilization levels of container storage, truck parking and quay berth. All utilization levels are presented in percentages. The utilization level of the storage capacity is calculated by dividing the used capacity to the available capacity during the entire optimization run. The utilization level of the truck parking is calculated in the same manner as the exploited parking capacity is divided to the overall available parking capacity. The berth utilization level expresses the share of used crane capacity over the available capacity when a barge is berthed on the quay. Therefore, it can be assumed that the presented values are average levels.

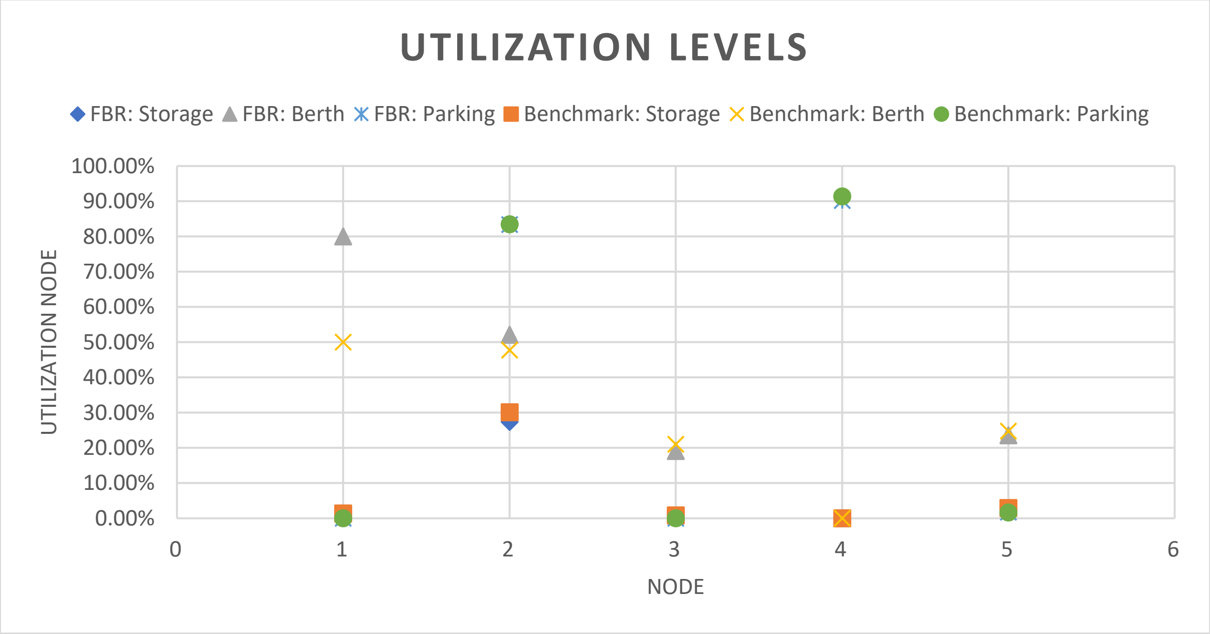


Figure 5.4: Utilization level of resources at all system nodes.

Regarding truck routing, with both strategies the operator extensively uses available trucks at Node 2. It can be observed from the figure, that parking utilization levels at Node 4 are more than 90% for both strategies while at Node 2 is 83%. This indicates that there is overcapacity of trucks in the system. For future configurations of the strategies, the truck capacity and parking spaces can be reduced in these nodes. Considering berth utilization, at Node 1 and Node 2 levels are relatively high, hence more containers are handled while the barge is berthed at these nodes. A significant difference in values between the Benchmark and FBR strategies is not observed except for node 1. When applying the FBR strategy barge stay can be assumed as more efficient since berth utilization level reaches 80% compared to just 50% with the Benchmark. As it is discussed in the paragraph above, the system operator stores containers mainly at Node 2. Expectedly, the storage utilization at this node is much higher compared to other nodes reaching nearly 30%.

The marginal difference between the two strategies is the introduction of flexible barges in the FBR. Contrary to the expectations before the runs, with the Benchmark strategy the operator routes around 14% more containers via a barge service compared to the FBR (Figure 5.3). Respectively, with the FBR the barge spends 16% less time in the terminals. The duration of the barge at the terminal quays is presented below on Figure 5.5. The outside doughnut indicates the durations in the Benchmark strategy and the inside one in the FBR.

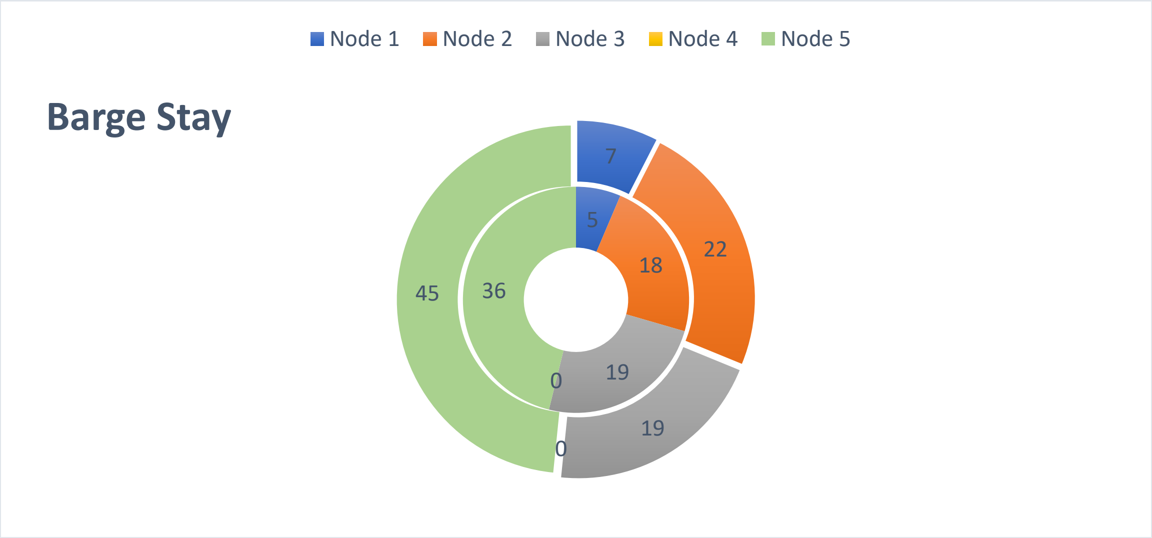


Figure 5.5: Duration of barge stay at different nodes *with* the two *strategies*.

Table 5.2 shows results from the simulation runs for each node of the network. The table contains information about the most frequent truck and barge destination. The number of trips is presented in brackets next to the destination. Two destination nodes are presented when the second has a considerable value compared to other nodes in the network.

As we discussed in Section 5.1, with both strategies the system operator can route the trucks flexibly. Therefore, the actions of the operator related to trucks routing and containers transported by trucks are almost identical. Considering barge routing, the most attractive routes in the FBR strategy coincide significantly with the barge schedule in the Benchmark approach. The barge takes the route between Node 2 and Node 5 respectively 15 times with the FBR and 14 times in the Benchmark. By introducing flexible barges in the system, the routes did not deviate from the predefined schedule. However, the realized costs for the barge operation are reduced by slightly more than 50% and the berthing time of the barge is reduced as well with 16%.

Base	**Most Frequent Truck Destination**		**Most Frequent Barge Destination**	
Strategy	*Benchmark*	*FBR*	*Benchmark*	*FBR*
Node 1	Node 2 (265)	Node 2 (259)	Node 2 (2)	Node 2,3 (2,1)
Node 2	Node 1,5 (265,145)	Node 1,5 (259,174)	Node 5,3(6,6)	Node 5,3 (7,6)
Node 3	Node 2 (63)	Node 2 (66)	Node 5,2 (6,3)	Node 5,2 (5,4)
Node 4	Node 2 (8)	Node 2,1(12,9)	N/A	N/A
Node 5	Node 2 (145)	Node 2 (163)	Node 2,3 (8,5)	Node 2,3 (8,5)

Table 5.2: Modes most frequent destinations: Base Scenario

5.3. Small Increase Scenario

In the Small Increase scenario, the volume of container orders is increased with 10% compared to the Base Scenario. The actions of the system operator led to comparable results as in the Base Scenario for both strategies. The realized costs for operating the system are lower with the FBR than with the Benchmark. Expectedly the number of truck trips and barge container movements increased due to the increased container volumes within the planning horizon. The modal share of trucks remains higher than the barge share with both strategies. Regarding container routing by barge, again the operator designates nearly 14% more containers to the barge in the Benchmark than in the FBR.

Like in the Base Scenario, with both strategies, the operator stores many of the containers at Node 2. At one timestep of the optimization, the storage space at Node 2 is utilized to 53% with the FBR and 54% with the Benchmark approach. Overall, the values of storage utilization are hardly larger than in the Base Scenario, but this can be justified with the increased container volumes in the system. Parking utilization levels at nodes 2 and 4 remains close to the Base Scenario, yet slightly lower due to the increased number of truck trips. Contrary to the results from the Base Scenario, in this scenario using the FBR does not show greater values for berth utilization levels at nodes 3 and 2. Significant decreases are observed by respectively 10% and 7% respectively. On the other hand, alike in the Base Scenario, the handling capacity is used more efficient with the FBR than with the Benchmark where the gap between the levels is increased to nearly 40%. This can be observed below on Figure 5.6.

Regarding trucks, the operator decisions are highly identical applying the two strategies due to the possibility to predict the need for truck capacity and then allocate it. The operator again uses more trucks which are located at Node 2 than at Node 4. Yet, these are the only two nodes in the system which exploits their truck parking space resulting in higher utilization levels compared to other nodes. Table 5.3 presents the most frequent destinations of trucks and barges for every node in the system. The route choices between the FBR and the Benchmark does not significantly differ in either destination or frequency. Moreover, compared to the results of the Base Scenario, the most attractive truck routes remain between node 1 and 2 for short-distance trucks and node 2 and 5 for long-distance trucks.

Regarding barge routing, with the FBR approach the system operator assigns less containers to the barge than with the Benchmark. On the other hand, the most frequent destinations of the barge deviates from the Base Scenario and the fixed schedule. Noticeable change is the concentration of journeys with origin node 5 and destination node 3 which are increased with 80% compared to the Base Scenario. Another busy route is between nodes 3 and 2 where the barge is routed 16 times. When at node 3, instead of heading the barge to the ‘inland terminal’ (node 5), the operator sends it to node 2. The completed trips on this route are doubled compared to the Base Scenario and the Benchmark. In general, the busiest barge route in this scenario is between nodes 2 and 3, followed by the routes between nodes 5 and 3, and nodes 2 and 5.

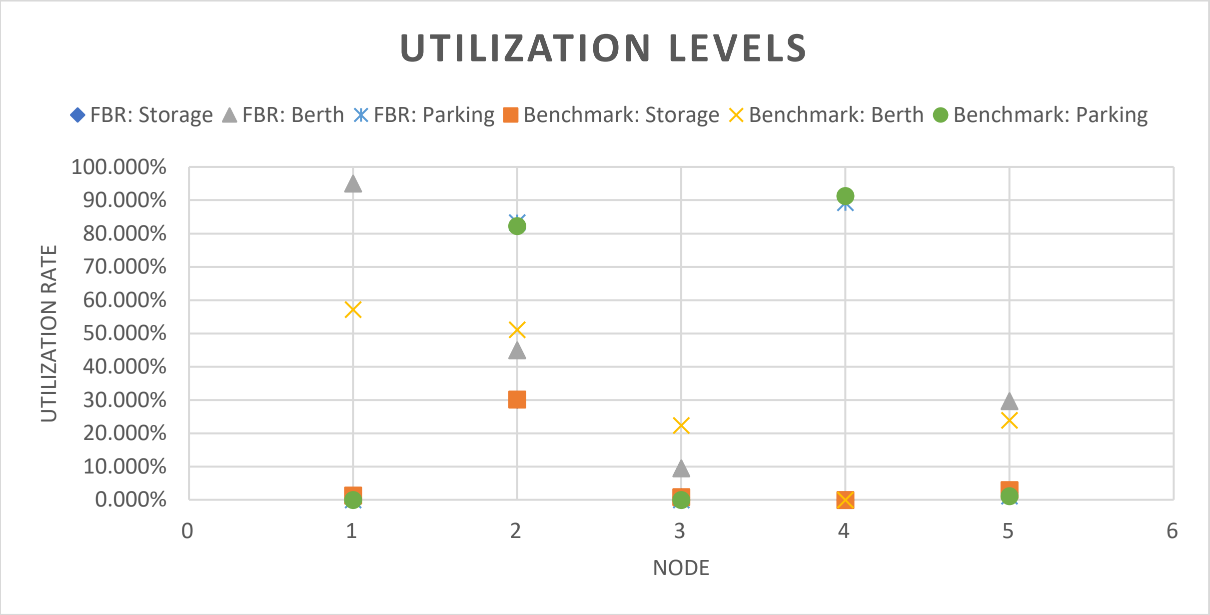


Figure 5.6: Utilization levels of resources of all network nodes

Small Increase	Most Frequent Truck Destination		Most Frequent Barge Destination	
Strategy	*Benchmark*	*FBR*	*Benchmark*	*FBR*
Node 1	Node 2 (291)	Node 2 (284)	Node 2 (2)	Node 2,5 (1)
Node 2	Node 1,5 (291, 170)	Node 1,5 (284,190)	Node 5,3(6,6)	Node 5,3 (8,6)
Node 3	Node 2 (71)	Node 2 (77)	Node 5,2 (6,3)	Node 2(10)
Node 4	Node 2 (8)	Node 2 (13)	N/A	N/A
Node 5	Node 2 (168)	Node 2 (176)	Node 2,3 (8,5)	Node 3(9)

Table 5.3: Modes most frequent destinations: Small Increase Scenario

5.4. Medium Increase Scenario

The Middle Increase Scenario has 30% more container volumes than in the Base Scenario. The total amount of containers in the system is 420. The behavior of the system operator is highly identical to the Base Scenario and Small Increase Scenario either applying the Benchmark or the FBR strategy. In this scenario as well, it is observed that the total realized cost with the FBR is lower than with the Benchmark. By the increasing the volume of containers, expectedly the number of truck trips and barge container handlings increases. With both strategies all truck trips rose with approximately 30% compared to the Base Scenario. Nevertheless, such a growth is not observed for the containers transported by the barge. Compared to the Base Scenario, the total amount of containers transported by flexible and scheduled barges has risen respectively with 8% and 6%, yet the operator still designates more containers with the

Benchmark than in the FBR approach. In this scenario, the modal share of trucks remains considerably higher than the share of the barge. This behavior has already been recognized in the simulations of the previous two scenarios.

The tendency of the system operator to store most containers at Node 2 is recognized in this scenario as well. This node has the highest level of storage utilization compared to other nodes regardless of the applied strategy. Levels observed at other nodes do not differ significantly from the levels of the Base Scenario. All nodes, except from Node 3, has lower storage utilization levels with the FBR than in the Benchmark strategy. Yet, at Node 3, the value in the FBR is insignificantly higher than in the Benchmark.

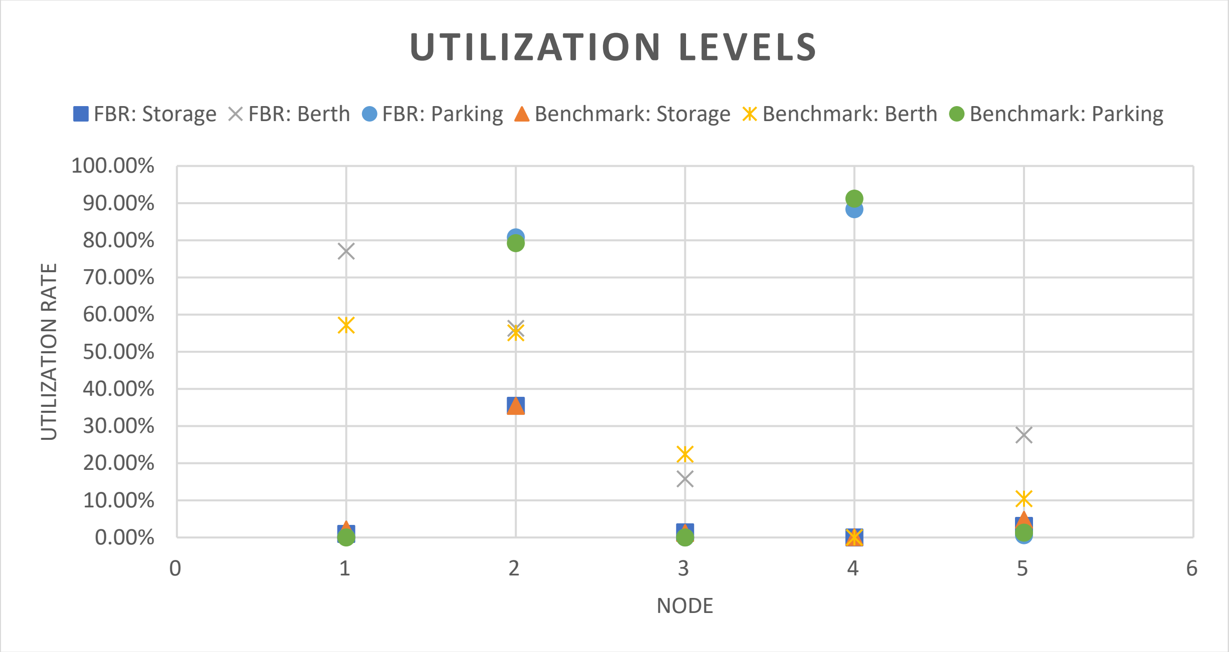


Figure 5.7: Utilization levels of system resources at all nodes

Considering truck routing, system operator decisions are almost identical to the previous two scenarios. The operator again uses more trucks which are firstly located at nodes 2 and 4. Parking utilization levels at these nodes remains close to the Base Scenario, yet slightly lower due to the increased number of truck trips.

Regarding barge operations, with the FBR approach the system operator assigns less containers to the barge than with the Benchmark. Respectively, the barge in the FBR should spends less time berthed at terminals. The duration of the barge stay from this scenario is presented in the figure above and the expectations are met. What is found interesting is that the barge spends relatively 19% less time berthed at Node 5 in this scenario compared to the Base Scenario and 35% less compared to the Benchmark. Even though, the barge spends less time at terminals with the FBR, higher utilization levels are reached for Node 1,2 and 5 than in the Benchmark strategy. This suggests that the barge stay is more effective as more containers are handled at the terminal for shorter stay. As in the Small Increase Results section, the outer doughnut contains the values resulted from the Benchmark, while the inner one contains the FBR results.

The results of Table 5.4 introduce the most frequent destinations for trucks and barges from which we can recognize the busiest routes. In this scenario as in the Base Scenario, the system operator routes the trucks on identical routes with both strategies. The only difference with the Base Scenario is the truck routing from Node 4 in the Benchmark. Instead of concentrating trucks at node 2 the operator routes the long-distance trucks between nodes 4 and 1. However, the overall number of trips is just 8 which can be assumed as negligible.

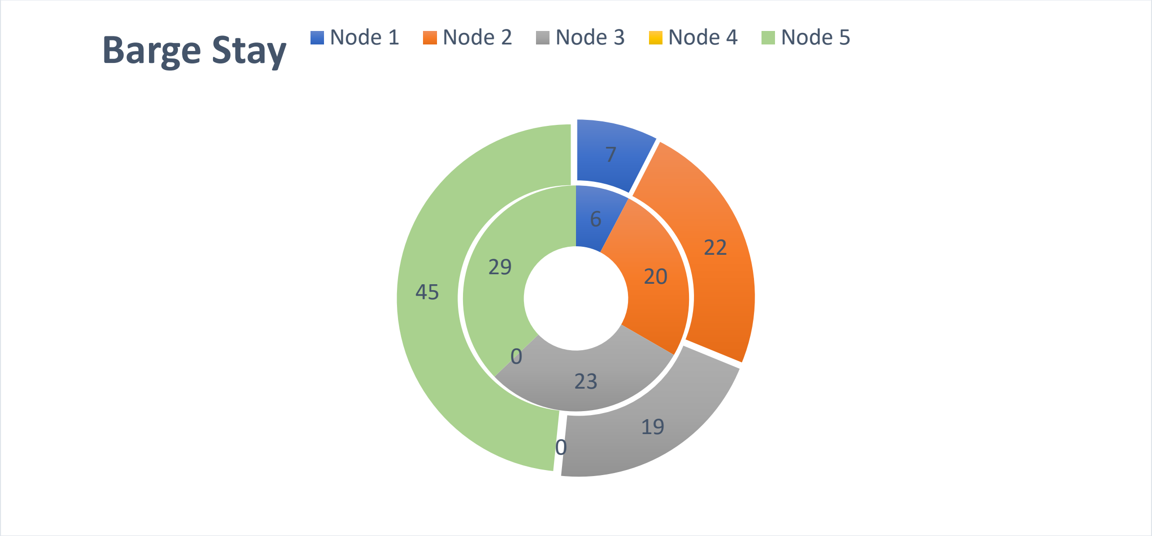


Figure 5.8: Duration of barge stay at each node in the network.

Medium Increase	**Most Frequent Truck Destination**		**Most Frequent Barge Destination**	
Strategy	*Benchmark*	*FBR*	*Benchmark*	*FBR*
Node 1	Node 2 (345)	Node 2 (333)	Node 2,5(2,1)	Node 2,3,5 (1)
Node 2	Node 1,5 (345,225)	Node 1,5 (333,251)	Node 5,3(6,6)	Node 5 (9)
Node 3	Node 2 (82)	Node 2 (81)	Node 5,2 (6,3)	Node 2 (12)
Node 4	Node 1 (8)	Node 2 (22)	N/A	N/A
Node 5	Node 2 (219)	Node 2 (231)	Node 2,3 (8,5)	Node 3 (10)

Table 5.4: Most frequent destinations by transport modes: Medium Increase Scenario

Looking over the results from the Base Scenario, the barge is mostly routed between Nodes 2 and 5. In this scenario this route takes the third place among the most used ones. The busiest barge route is now between Nodes 2 and 3 which is the same as in the Small Increase Scenario. The operator sends the barge between these nodes 16 times as opposed to just 10 times in the Base Scenario. This is evident prioritizing of the route. Moreover, the connection between 5 and 3 is now intensively used. The trips from Node 5 to 3 are doubled compared to the Base Scenario reaching the number of 10. This is the second most routed connection. As it has been mentioned already, the third busiest route is between Nodes 2 and 5. When the barge is berthed at Node 2, the operator practically always routes the barge to Node 5.

5.5. Large Increase Scenario

The Large Increase Scenario is the scenario with the highest number of containers which needs to be transported in the system. The containers in this scenario are 644. A summary of the results after applying the FBR and Benchmark strategies are presented on Table 5.1. For the first time in all simulated scenarios, there are containers which are not satisfied on time. This is observed in the results of both strategies. Yet, in the FBR the delayed containers are considerably less than in the Benchmark. Delayed containers are counted per timestep.

Figure 5.9 presents the number of unsatisfied containers in both strategies during the optimization process. Delayed containers in the FBR are presented in red dashed line, while in the Benchmark are illustrated with solid blue line. In the beginning of the optimization run, with both strategies there are 18 containers which cannot enter the system due to lack of available storage capacity at Node 3. As a result, containers must wait until capacity is released. Thereof, they are counted as delayed orders. At Node 3 storage capacity is a bottleneck but only in the first few steps of the optimization. If additional capacity is available at Node 3, this issue can be avoided. Looking further into the optimization run with the FBR strategy, delayed containers do not occur again. However, this is not observed for the Benchmark. The next moment when unsatisfied demand is observed when using the Benchmark strategy is at timestep 407 when 1 container is delayed at Node 1. Subsequently, the number of unsatisfied demands in the Benchmark dramatically escalate to 52 containers at timestep 420. Peaks of 46 and 34 delayed containers occur respectively at timestep 433 and 444. At the end of the optimization, the system has 15 containers which are yet not delivered at Node 5. Contrary to the Benchmark, with the FBR the operator successfully transports all containers on time and avoid the penalties for delays.

The vast amount of unsatisfied container orders with the Benchmark results in high realized costs due to the penalties for delays incorporated in the objective function. Unlike the Base Scenario, where the difference in the realized costs between the FBR and the Benchmark strategy is just 2.7%, hereby the difference steps up to 11.2%. The tendency of ‘cost per container’ to decrease when more containers are present in the system is observed only with the FBR approach. The magnitude of delayed containers in the FBR does not reflect on this KPI as opposed to the Benchmark. In the latter, the cost for transporting a single container rose from 490 in the Middle Increase scenario to 501 in the Large Increase Scenario.

Identically to the results from the other scenarios, the more containers are present in the system, the more trucks are routed. The containers transferred by trucks are doubled compared to the Base Scenario. Curiously, in this scenario the full truck trips in the FBR are less than in the Benchmark strategy. This result is not observed in the other three scenarios. Moreover, in this scenario for the first time the number of containers handled by barge with the FBR is higher than with the Benchmark. Comparing the results of the two operational strategies in the Base Scenario, there is a slight increase of just 11 containers transported by barge in the Benchmark. While, in the FBR the containers routed by flexible barge are nearly doubled rising from 102 in the Base Scenario to 193 in this scenario (Figure 5.3: Transported containers).

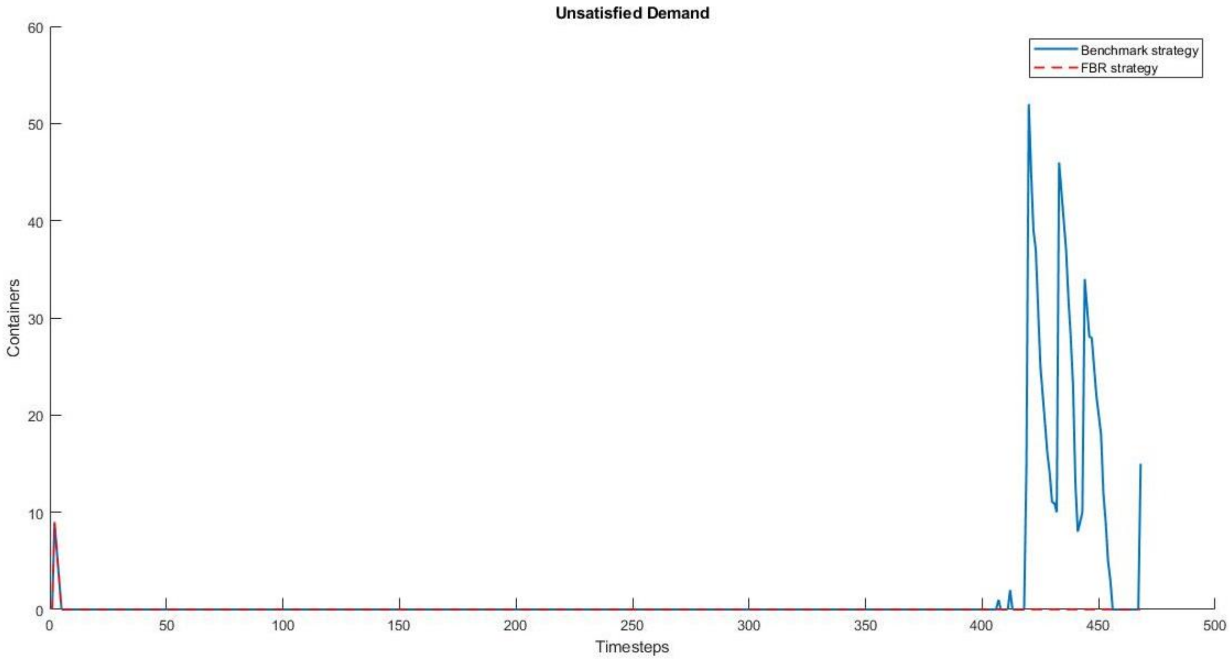


Figure 5.9*:* Unsatisfied Demand Large Increase Scenario

5.5.1. Result Details

In this subsection the results after applying the two strategies in the Large Increase Scenario are compared. The purpose is to present the differences in the operators' decisions when barges are operated in a scheduled and flexible manner. The consequences of these decisions on the system performance are briefly analysed.

The most extreme differences between the two strategies are observed in Node 1 and Node 5 where the FBR scores considerably lower values than the Benchmark. Identically to other scenarios, with both strategies the available capacity of Node 4 is not utilized, and the operator do not store containers there. In this Scenario, applying the FBR results in lower realized costs for container storage. This can be explained with the higher utilization at Node 2 and lower at Node 1 compared to the Benchmark.

Results of the Benchmark are presented in solid blue line, while results of the FBR are presented in solid red line. On the figure it is observed that progression of container storage applying both strategies is identical until timestep 148. Afterwards, the difference in storage levels firmly increases to reach its maximum of 74 containers at timestep 211. With the FBR, the highest storage level is reached at timestep 243 when 96% of the available capacity is utilized with 513 containers being stored. From this point the storage levels gently decrease until the end of the optimization run. On the contrary, with the Benchmark the absolute maximum is reached later in the optimization at timestep 271 when 468 containers are stored. This is 88% of the available capacity at Node 2. For the greatest part of the optimization run, the storage level of Node 2 with the FBR strategy is higher than with the Benchmark. However, this is changed in the final stage of the optimization run at timestep 401. This is a result of the fastest release of containers from Node 2 to their destination with the FBR. This can be observed by the slopes of both graphs on the figure. While the slope of the Benchmark is lean with a set-out at timestep 357, the slope of the FBR is steeper with a set-out at timestep 376. Eventually, it can be concluded that applying the FBR strategy storage capacity is more effectively used due to higher utilization levels reached and smaller value fluctuations.

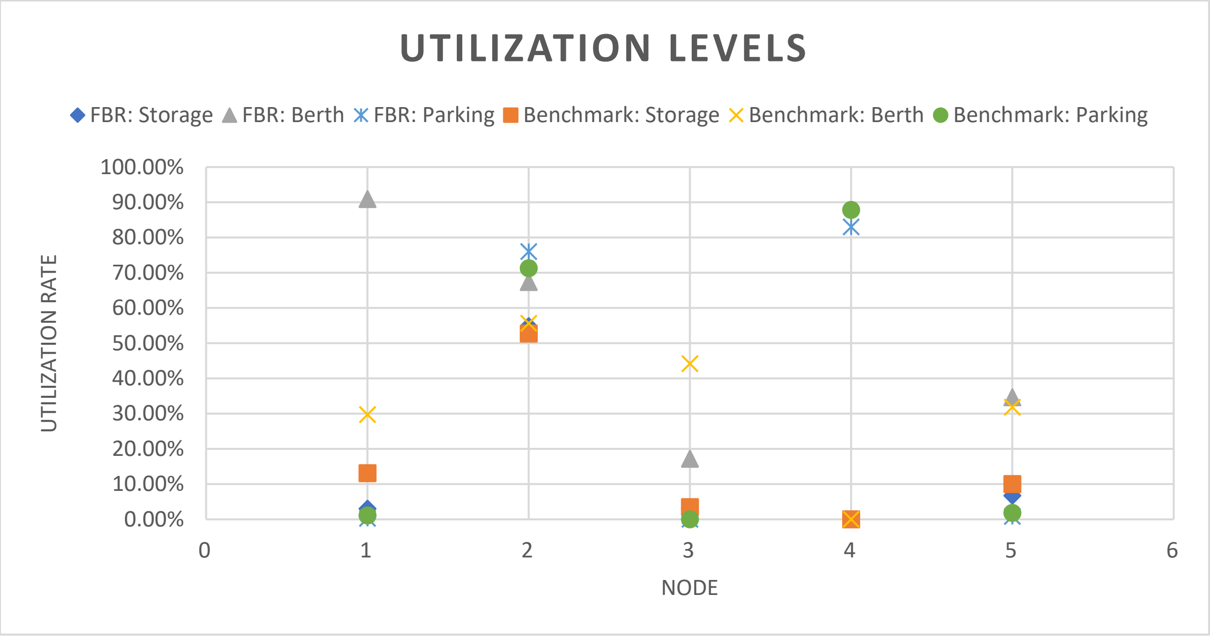


Figure *5.10*: Utilization levels of system resources at all nodes

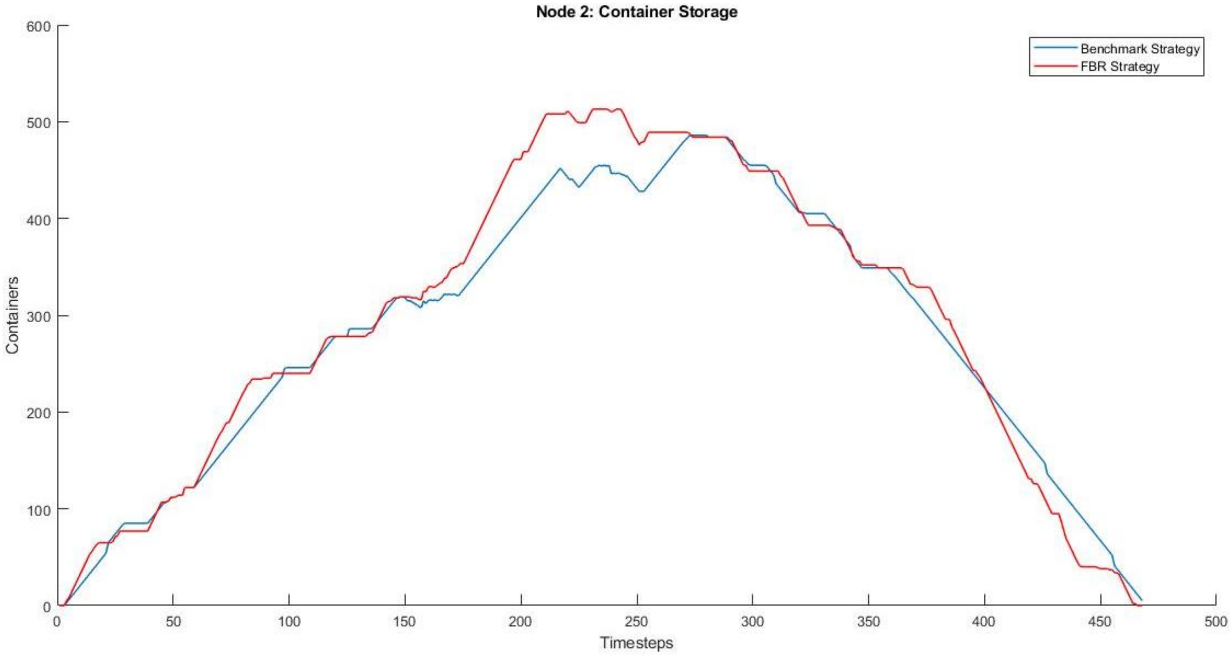


Figure 5.11: Node 2 Container Storage

Secondly, parking utilization levels are going to be analyzed. In this scenario Node 2 remains the highest utilized node in the system in terms of parking. The tendency from other scenarios is kept and the parking utilization level with the FBR is hardly greater than with the Benchmark. Figure 5.12 below illustrates the number of parked long-range trucks at Node 2 for the entire simulation run. The results of applying the Benchmark are presented in solid blue line, while those of the FBR in dotted red line. The figure indicates that in the first third of the optimization process the results for both strategies does not differ significantly. By applying both, the system operator takes almost similar decisions besides between steps 6 and 25 when less trucks are parked at Node 2 with the Benchmark. Further in the optimization process, differences in operators' actions becomes more distinct. Between timesteps 150 and 200 many long-range trucks leave node 2 notably with the Benchmark strategy. Between timesteps 200 and 388 the actions of the operator are again nearly identical. Subsequently, in the final stage of the optimization run much more trucks are routed from Node 2 with the Benchmark than with the FBR. This is expected, as the greatest container demand is in this stage of the optimization run. It is crucial that with the FBR, the available truck capacity at Node 2 is much greater compared to the other strategy. With the FBR the parking is completely full for 10 timesteps offering truck capacity for container transport. This is not observed when applying the Benchmark strategy where the maximum is 23 parked trucks for only 1 timestep. After timestep 407 the available truck capacity cannot reach this level yet decreases to 20 and 10 trucks again available for only 1 timestep. Therefore, it can be concluded that with the FBR trucks are not used as urgent available capacity as often as with the Benchmark.

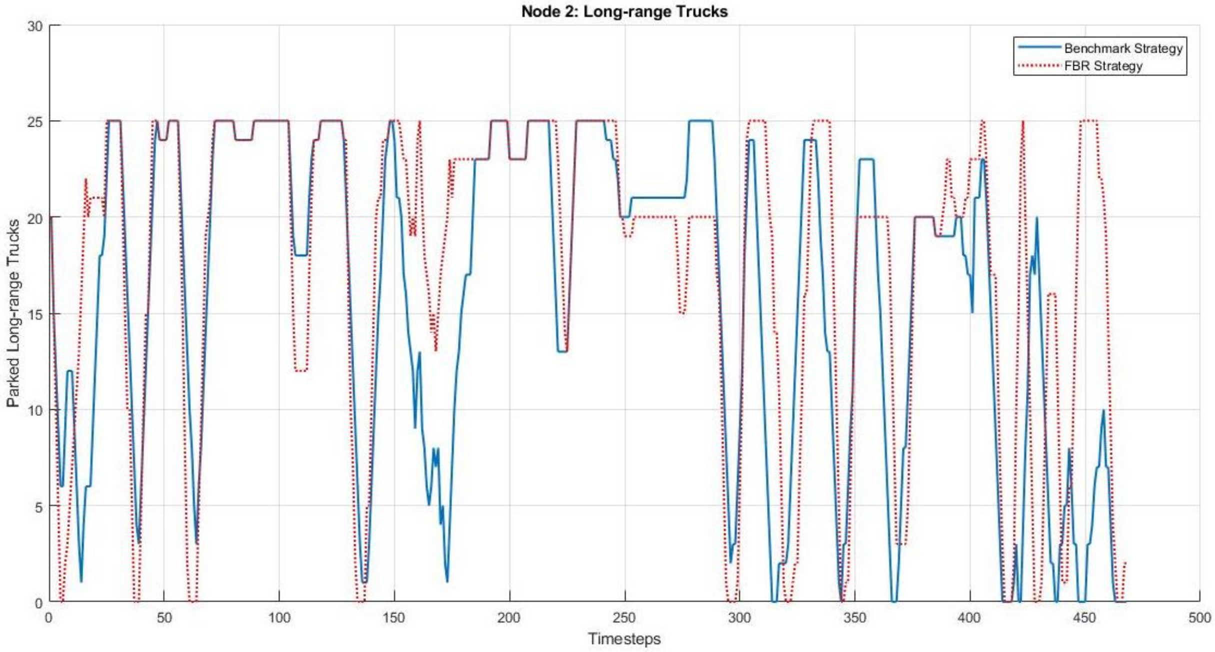


Figure 5.12: Long-Range Trucks parked at Node 2.

Considering truck routing, the system operator can flexibly allocate truck capacity within the network by applying both strategies. In other scenarios, truck routing is almost identical with both strategies. However, hereby with the FBR, the system operator routes more truck from and to Node 4. For instance, Table 5.5 shows that the operator intensively addresses trucks to Node 2 and Node 5 with origin Node 4 when the FBR is applied. The route between Node 5 and Node 4 also becomes attractive for truck routing with the FBR whereas with the Benchmark strategy, trucks are sent particularly to Node 2.

Barge operation is the distinct dissimilarity between the FBR and the Benchmark strategies. While barges in the Benchmark operates on a schedule, in the FBR the operator is free to route the barge independently between nodes. This capability of the operator in the FBR contributes for evident differences in achieved results in system performance. Not only there are considerably fewer delayed containers with the FBR than with the Benchmark strategy, but also much more containers are routed by the flexible barge.

Therefore, to realize the benefits of flexible barge routing the details of barge operations outcoming from applying both strategies are going to be briefly analysed.

Large Increase	Most Frequent Truck Destination		Most Frequent Barge Destination	
Strategy	*Benchmark*	*FBR*	*Benchmark*	*FBR*
Node 1	Node 2 (516)	Node 2 (495)	Node 2,5(2,1)	Node 2 (4)
Node 2	Node 1,5 (516, 398)	Node 1,5 (495,390)	Node 5,3(6,6)	Node 3,5 (6,5)
Node 3	Node 2 ,1(107,29)	Node 2(117)	Node 5,2 (6,3)	Node 2, 5 (6,5)
Node 4	Node 2,1 (15,9)	Node 2, 5 (36,21)	N/A	N/A
Node 5	Node 2,4 (374,14)	Node 2,4 (370,55)	Node 2,3 (8,5)	Node 3, 2 (6,5)

Table 5.5: Most frequent destinations per transport mode: Large Increase Scenario

Three of the four barge terminals in the system shows higher utilization levels with the FBR compared to the Benchmark strategy. A 30% difference is noticed at Node 1 where the utilization is respectively 90.9% and 60.7%. At node 2 and 5, the difference is slightly more than 10% in favor of the FBR. The only exception is Node 3, where the berth utilization level with the FBR is with 10% lower related to the Benchmark.

The introduction of flexible barge does not only increase the berth utilization levels but also raise the number of visited nodes in the system by the barge. Port of call is the node where the barge is plying to and is going to be berthed. While the scheduled barge has 43 ports of call, in this scenario the flexible barge has 73 ports of call. With the FBR the barge occupies all terminals for longer periods with exception of Node 5. Though, the barge spends there just one timestep less than with the Benchmark. The most prominent increase is observed at Nodes 2 and Node 3 where the barge stays respectively 27% and 26% longer. From these results, it can be concluded that even though a flexible barge could spend more time at terminals, handling capacity can be used more efficiently. These results are presented below on the figure as the results of the Benchmark are illustrated on the outer doughnut and FBR results on the inner one.

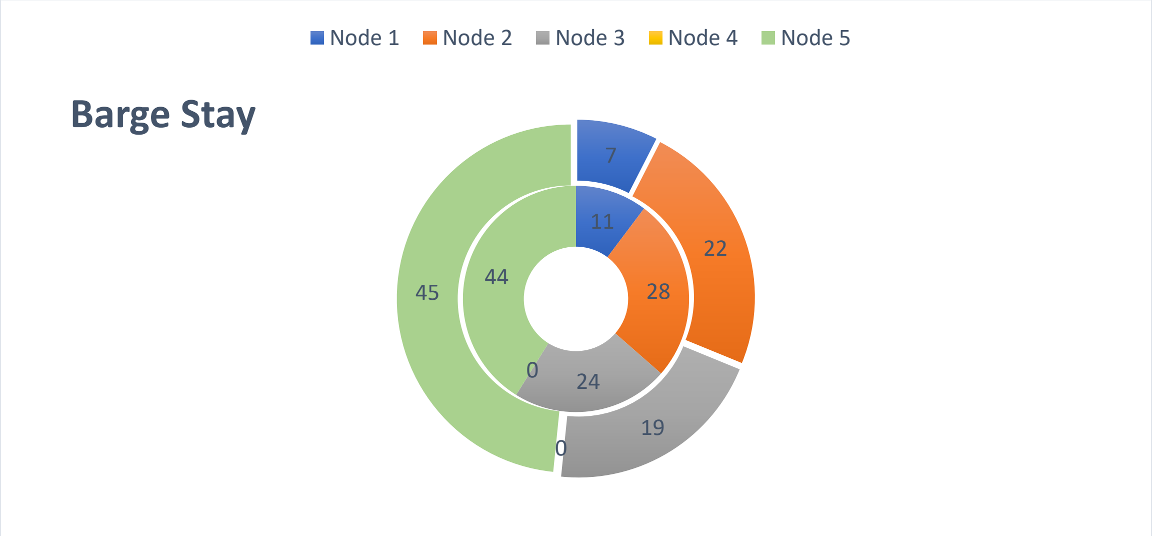


Figure *5.13*: *Duration of barge stay at terminals. Outer ring presents the Benchmark, the inner ring: FBR.*

From Table 5.5 it is easily recognized that the system operator preferences for barge routing differs with the two strategies. When applying the Benchmark, the most frequent routes are known in advance. The barge is routed most frequently between node 2 and 5 for 14 times, followed by 11 times between the pair 3 and 5 and eventually 9 times between nodes 2 and 3. Nonetheless, with the FBR the operator routes the barge in a different manner. The flexible barge is most often routed between node 2 and 3 reaching 12 times. The second most attractive route remains the pair of nodes 3 and 5 with the same number of trips between them. Relative to results from applying the Benchmark, the number of trips within nodes 2 and 5 drop off by 40% to 10 trips. What is interesting is that when the FBR is applied, the operator routes the barge 8 times between nodes 1 and 2. This behavior is unprecedented not only in this scenario, but in other scenarios as well.

The difference in routing comes along with distinct levels of capacity utilization for the barge. Figure 5.14 presents an overview of barge capacity. The capacity of the scheduled barge for the entire optimization run is presented in solid blue line while the flexible barge in dotted red line. On the figure can be easily noticed that with the FBR strategy the barge is regularly fully loaded than with the Benchmark. This is expected as 193 containers are routed by flexible barge and just 130 by the scheduled barge. During the first half of the optimization run, the payload of the scheduled barge considerably fluctuates between 10 and 20 containers. As opposed to this the payload of the flexible barge is stable on 20 containers which is indicated with long flat lines on the figure. It is essential to mention that until timestep 350 the declines of flexible barge payload correspond with those of scheduled barge besides one occasion. However, the drops in flexible barge capacity are always more distinct. From timestep 350 until the end of the optimization in the Benchmark, barge capacity gradually declines. Local maximums of 14, 12 and 8 containers are reached, but never rising to full payload again. Howbeit, the flexible barge most of the time operates on full load using its capacity more efficiently. From the figure it can be concluded that with the FBR, the system operator can reach higher utilization levels for the barge and benefit from economies of scale. This is reflected in the total amount of transported containers and realized barge operation cost.

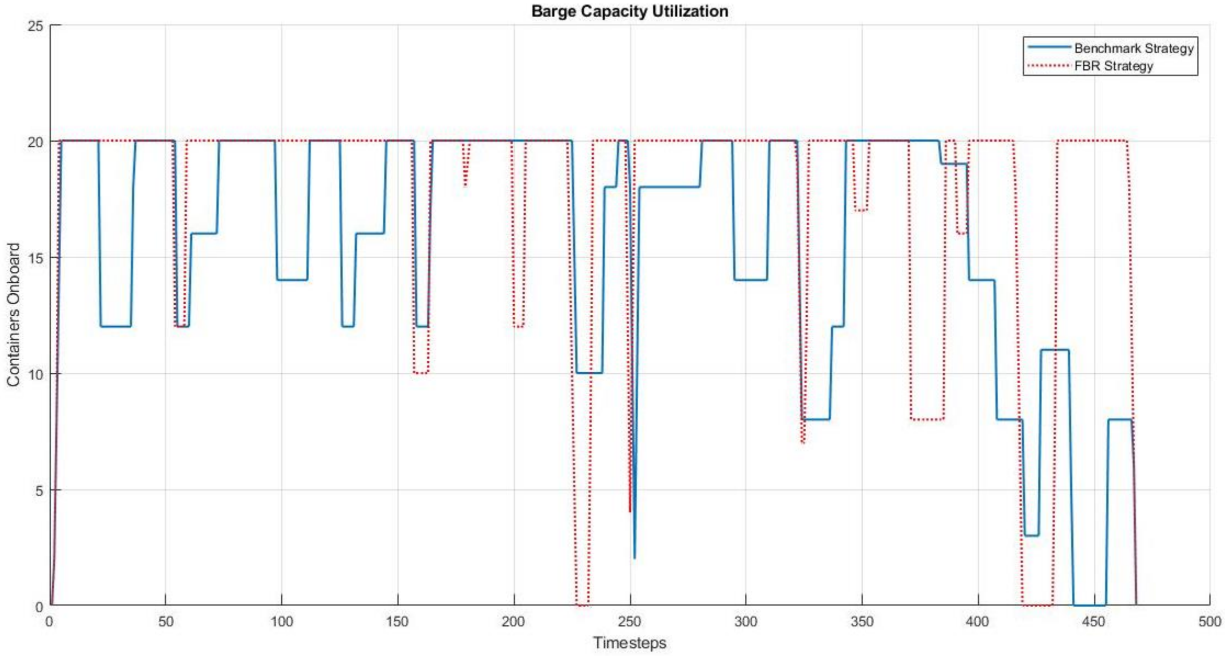


Figure 5.14: Comparison of Barge Capacity Utilization *with* both *strategies*

With applying the FBR strategy, an interesting behavior of the system operator was noticed. During the optimization frequently occurs that the operator would route a barge to a certain node without executing any handling operations at the destination. Occasions are observed when the barge even spends only one timestep at a terminal and then its routed to different node with the same payload. Figure 5.15 represent this behavior. The first graph on the figure shows the barge payload during the optimization run in solid blue line. This graph is the same as the red graph presented on Figure 5.14. The second and the third graphs represent respectively the amount of loaded and unloaded containers at terminals. The values of both graphs are presented as positive values but for better readability the graph for unloaded containers is presented with negative values.

The reason for this behavior can be a result of two factors. Either a mistake is made in the implementation of the strategy in MATLAB, or the system operator makes Illogical decisions when applying the strategy. The first possibility for an implementation mistake in the code is excluded by observing the operators' decisions at the end of the optimization. Firstly, at all nodes in the system container are being both loaded and unloaded according to crane capacity constraints. Secondly, the volume of loaded containers is equal to the unloaded containers in the complete system hence container is neither 'lost' nor 'rise' from itself. Therefore, the version of implementation mistake can be rejected. Considering the options for illogical actions of the operator, a probable reason is observed which might lead to this unexpected behavior. When applying the FBR strategy the costs for transporting containers by barge appears to be in some cases cheaper than storing the containers at a terminal. Therefore, the logic of the operator is to use the barge capacity as a cheaper capacity buffer which is regularly on the move. Yet, this behavior does not comply with the accepted practices in the shipping industry. Berthing a container barge on a terminal without executing any handling operations is very uncommon.

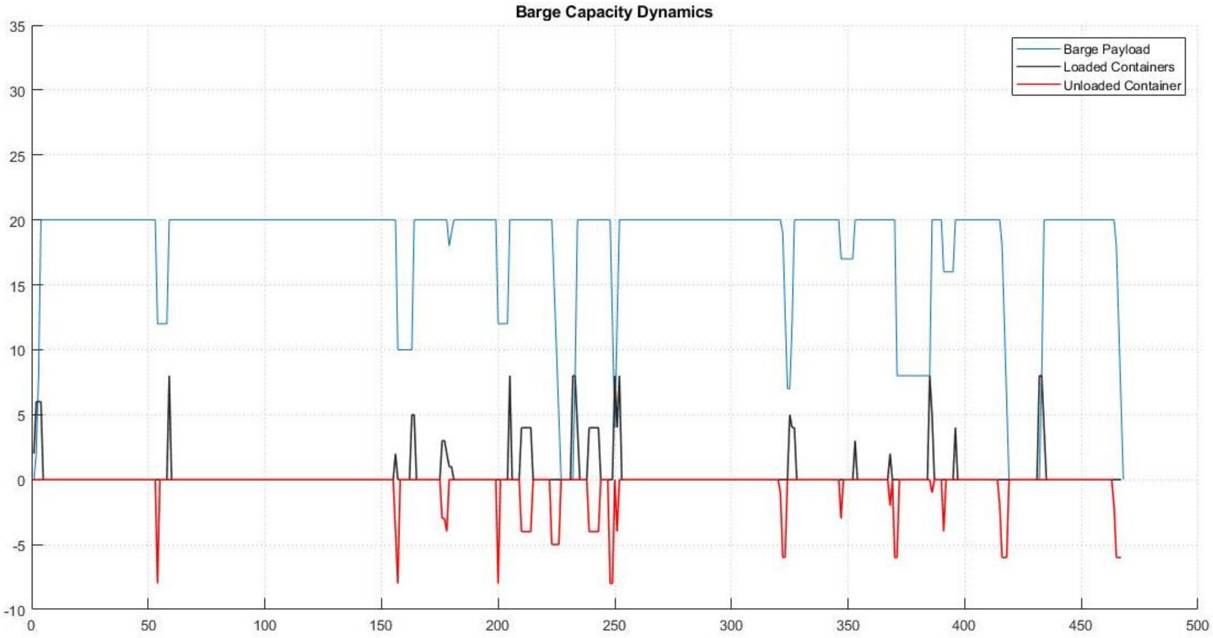


Figure 5.15: Barge Capacity dynamics in the FBR model

5.5.2. Revised Barge Schedule

For the last two decades the throughput of TEU containers in Port of Rotterdam increased more than double. The scenario discussed here is a long-term projection of the reality capturing this raise of container orders. Yet, for such an extended period it is unrealistic to assume that a transport system would not be adapted to the new conditions. From the previous section, a simple conclusion can be derived. The operator is not able to transport considerable part of the container orders on time when applying the Benchmark strategy. The operator cannot effectively use the economies of scale offered by the fixed barge service probably due to an inadequate schedule for the actual container volumes. Therefore, the configuration of the Benchmark strategy should be adapted to this amount of container orders with a new barge schedule. In this section a new barge schedule is going to be implemented and tested. The new schedule is derived using the same methodology as in Section 4.3.4.

The table below presents the timesteps at which the barge is present at a certain terminal and executes handling operations. This schedule is applied on the configuration of the Benchmark strategy. The rest of the configuration is unaltered. Then, a simulation is run with the Large Increase scenario. The purpose of this experiment is to analyze the extent to which the operator can plan and deliver all container orders on time using an up-to-date schedule.

NODE	HANDLING ACTIVITY	TIMESTEP								
1	Unloading	232	248	249	250					
	Loading	58	75	109	151	204	233	234	251	252
2	Unloading	22	53	70	104	114	115	116	117	118
		156	157	197	198	216	239	240		
	Loading	199	217	241	242	243	280	308	337	338
		353	385	425	426	456	468			
3	Unloading	64	191	210	223	224	225	226	344	345
		359	391	392	417	418	419	462		
	Loading	16	145	163	164	346	347	393		
5	Unloading	89	176	177	266	294	322	323	371	405
		440	441	442						
	Loading	1	2	3	4	36	37	38	39	90
		132	133	178	179					

Table 5.6: Updated Barge Schedule for the Benchmark strategy.

Unexpectedly, the results of the simulation run with the adapted schedule do not differ significantly from the results with the old schedule. Despite the decreased amount of delayed containers in the system, their share is still considerable. On Figure 5.16 the dynamics of the unsatisfied demand with the old and the new schedule are presented. The unsatisfied demand is presented per timestep. The results of the old schedule are presented in solid red line, while the results of the new schedule with solid blue line. It is evident that both graphs have completely identical fluctuations, yet with different magnitudes. The graph of the adapted schedule has lower local maximums and minimums. Therefore, it is assumed that to a certain extend the operator improved the performance of the system when the barge schedule is adapted. However, the number of delayed containers is still tremendous compared to the results of the FBR strategy. The results of applying the FBR strategy are presented on the figure below with a solid yellow line.

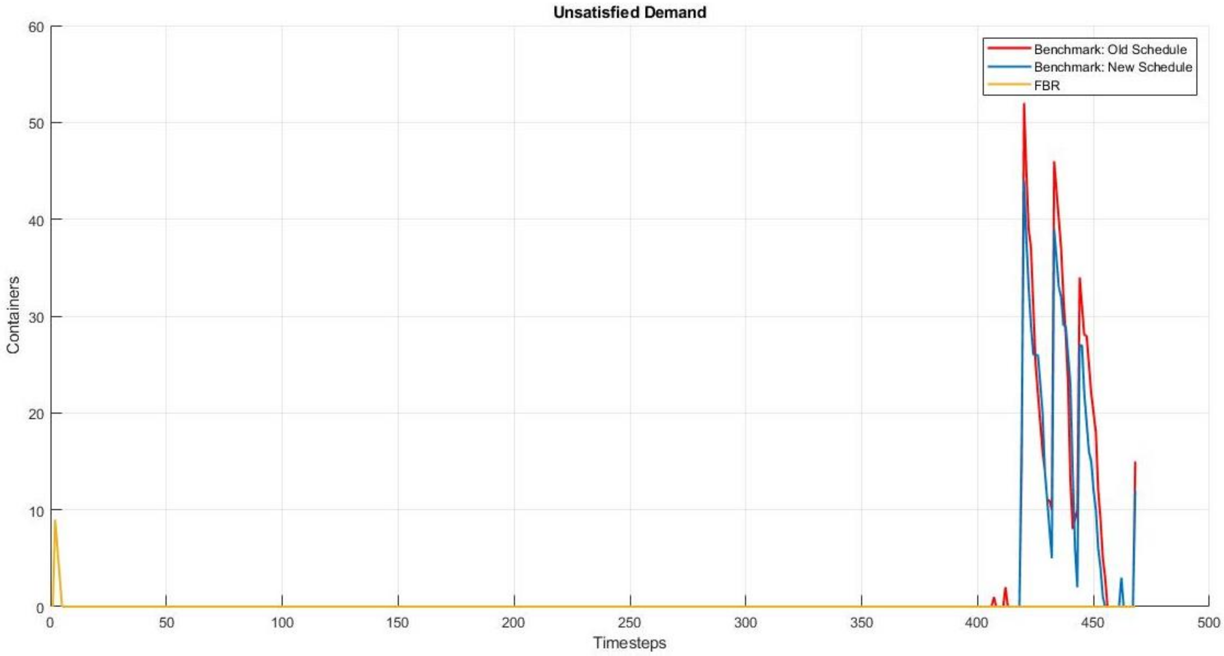


Figure *5.16*: *Unsatisfied demand of containers when the new adapted schedule is applied compared to the old schedule and the FBR* strategy*.*

On the figure below are presented the volumes of transported containers by mode. With the new configuration of the Benchmark strategy the usage of trucks remains high, but slightly lower compared to the old configuration. The updated schedule led to more containers transported by the barge which is an expected result. However, the FBR results with the highest barge share and lowest truck usage among all.

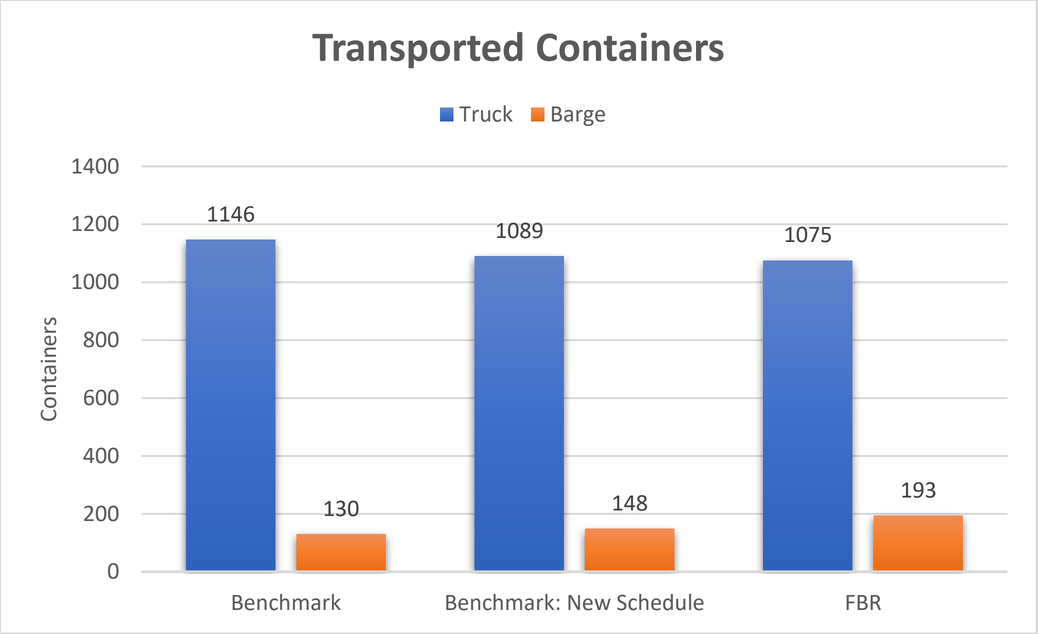


Figure 5.17: Containers transported by strategy.

Compared to the old configuration applied on the Benchmark, the system performs better based on the KPI for realized system cost and cost per container. Operators’ decisions with the updated barge schedule resulted in higher barge utilization and less containers transported by trucks. However, unsatisfied demand still occurs during the optimization and the operator cannot deliver all container orders on time. Overall, with this configuration of the Benchmark, operators' actions are better but not optimal. By applying the FBR strategy, operators' decisions can avoid the issue of delayed containers and reach the desired system performance for lower costs and less truck usage.

5.6. Summary

In this Section, the results of scenarios testing are presented. Overall, nine simulation experiments are performed in MATLAB by using Yalmip and Gurobi. Four scenarios are tested with the two strategies presented in Section 3 applying the configurations introduced in Section 4. Thereby, eight simulation experiments are executed. An additional ninth experiment is performed with an updated configuration of the Benchmark strategy introducing new barge schedule. The updated configuration is tested on the Large Increase scenario.

The results of the simulations demonstrate the ability of an MPC planner to operate a transport system and deliver container orders on time. Either applying the FBR or the Benchmark strategies, the system operator can allocate sufficient transport capacity to comply with the time windows of the orders. However, in cases with high demand for containers, the FBR strategy is recognized as more efficient. Expectedly, the tremendous volumes create bottlenecks in the system which are more ineffectively avoided with the Benchmark than with the FBR strategy.

In cases with smaller container orders, the benefits of using the FBR strategy are moderate. Small reductions in costs are observed for container storage, truck routing and cost per container. In all simulated scenarios barge routing in the FBR is considerably cheaper compared to the Benchmark. This is explained as the barge is routed only between nodes where capacity is required, so routes can be flexibly adjusted. In low demand cases this leads to shorter times of the barge being berthed in terminals which can be favored by terminal operators. However, by applying the Benchmark strategy the system operator dedicates more containers to the scheduled barge and routes less long-range trucks than with the FBR. These results do not align with the intention of terminal operators and port authorities to shift cargo from roads to alternative transport modes.

The integration of stationary and moving resources is more visible when high volumes of containers are present in the network. The FBR integrates barge routing with trucks and container routing. Due to the cheap stacking of containers at node 2 and its proximity to node1, the system operator extensively utilizes the available capacity at this node with both strategies. In cases of high demand for containers in big batches at one or several consecutive timesteps, the benefits of applying the FBR becomes more evident. With the Benchmark strategy, limited transport and handling capacity creates bottlenecks in the system so containers cannot be quickly released from highly utilized nodes. Limited number of trucks can be handled, and barge capacity is available only in fixed moments of the simulation. While with the FBR the system operator can allocate additional barge capacity to the highly utilized nodes and avoid potential order delays. In the case of the Large Increase Scenario, more containers are transported with the flexible barge than with a scheduled barge.

In a case with order delays, it is realistic to adapt the configuration of the transport system to manage the cargo flow. Therefore, in the case of the Large Increase Scenario, an updated barge schedule is introduced to the Benchmark strategy with the intention to satisfy all demand like in previous scenarios. Even though, the barge schedule is adopted to the increased demand, the system operator cannot avoid systems bottlenecks by using a schedule barge. Despite the raise of containers handled by barge and decreased trucks routing compared to the old configuration, the operator is unable to satisfy all the demand on time. To comply with time windows, additional adjustments to the configuration are required. Increase of handling capacity may favor the operator when applying the Benchmark strategy and scheduled barge.

In conclusion, operating a barge on a fixed schedule in a synchromodal network significantly shapes the optimal actions of a system operator. Inland barges are mainly operated in a linear manner, yet in cases with increased demand for containers the applied schedule becomes insufficient for favorable system performance. The proposed strategy routes barges with trucks and containers simultaneously and successfully transport all container orders within the required time windows. By integrating barge routing with truck and container routing, the available handling resources are utilized more efficiently, and capacity bottlenecks are avoided.

6. Conclusions

This thesis focusses on improving the performance of a container transport system by showing the benefits of applying different barge routing strategy. The concept of free barge routing has been proposed and investigated for use in different scenarios. This chapter presents the main conclusions made on this research and provides answers to the investigated research questions.

This thesis intends to answer the research question: **How can a decision-making strategy for flexible container and mode planning facilitate operators to achieve a desired performance of a synchromodal transport system?** To provide and answer to this question two operational strategies have been proposed. Both are presented in Section 3. One has been proposed by Larsen (2020) and the other has been developed during this work. Model Predictive Control (MPC) has been implied as an optimization strategy for obtaining optimal solutions and the desired performance for the synchromodal transport system. In this thesis, a desired performance is considered as the possibility of a system operator of a synchromodal transport system to deliver all container orders on time and successfully prevent any delays.

Following the main research question, six sub-questions were formulated in Section 1. Further in this section, answers to these sub-questions are provided.

1. *How are operations and disturbance management currently organized in a synchromodal transport system?*

The concept for Synchromodal transport was partly introduced in Chapter 1. For the purposes of this thesis the definition provided by Bart van Rissen (2015) was used: *"Synchromodality is the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provided, so that the customer (shipper of forwarder) is offered an integrated solution for his (inland) transport."*

Generally, Synchromodality is built on the theory of sharing infrastructure and capacity. One of the most distinctive features of synchromodality is the agreement made between shippers and service providers for mode-free booking. In this way, the Logistic Service Provider (LSP) has the freedom to decide how to transport the freight to its destination and provide the most efficient service to customers. By introducing mode-free booking, the LSP can also dynamically allocate transport capacity to the most necessitous places within the system if there is available transport capacity.

Other distinctive feature of synchromodality is the cooperation between actors which share not only infrastructure and services, but information as well. Distribution of information flows facilitates the system operator to adequately adapt to changes and efficiently deal with disturbances in the system. Based on frequent sharing of information the system operator can replan its decision in real-time to comply with system conditions and customer requirements. Synchromodality relies heavily on information sharing, but also on systems which support this. Intelligent systems are vital not only for data gathering, processing and distribution, but also for building trust among actors and their desire for cooperation.

2. *What are the performance indicators for hinterland container transport according to stakeholder's perspective and what are the additional performance requirements applied to synchromodal transport?*

To evaluate the performance of the thesis deliverables appropriate KPIs are defined. The KPIs focus on the dynamics of the operations in synchromodal system and aims to capture the effects of flexible planning on system performance. The trade-off between cost and quality is crucial for the system performance. Therefore, the amount of unsatisfied demand and realized operational cost are used as KPIs for the synchromodal system. How flexible planning affects the pressure in the system created by increased volumes of container demand is evaluated by looking into capacity indicators. Utilization levels of system components as storage capacity, quay terminals, handling equipment and transport modes are used as KPIs. The last KPI used in the thesis is driven by the assumption of many researchers that synchromodality is going to shift cargo to alternative transport modes which benefit from economies of scale. Hence, modal share is used as well as performance indicator for the effectiveness of the taken decisions.

In this thesis, KPIs are classified into three categories: 1) Service Quality, 2) Operational Costs, 3) Capacity Indicators. The priority of the KPIs is following the same order. Considering the term 'desired system performance' is in the main research question relevant to delivering all container orders on time, the KPI 'Service Quality' has the highest priority. Because of the important trade-off between service quality and realized costs, the KPI 'operational costs' is second after 'Service Quality'. The third category of KPIs is the most abundant including different utilization levels of system components. Although this category is considered crucial for the efficiency evaluation of taken decisions, it does not gain as much interest towards synchromodal transport as the previous two categories. Therefore, it has the lowest priority among the three categories of KPI.

3. *How can a Model predictive control (MPC) approach be implemented in a decision-making strategy for the flexible planning of containers, trucks, and barges in a synchro-modal system?*

Model Predictive Control is recognized in literature as an effective approach for handling transport operations. The most common designs found in transport literature are centralized and distributed. In this thesis a centralized MPC approach is applied with one controller which operates with the transport system. This controller represents a system operator of a synchromodal transport network. The same approach has been successfully applied in the works of Nabais (2015) and Larsen (2020) and briefly described in Section 2.4.

In Section 3 two operational strategies and MPC approach are introduced. A single layer controller is head of operations in a synchromodal system where orders of containers must be transported. Container orders are defined by destination and due time, but diverse types are not considered. Container terminals in the system can store containers and accommodate trucks and barges. There are two types of trucks which operate in the system: short and long-range. Each of the truck types can transfer only one container. Barges in the system can store more than one container and operate either on fixed schedule or are routed flexibly between nodes. Dynamics in the system are expressed in a state-space vector. Each component of the vector describes a condition of a system element at one timestep. Related to terminal dynamics the state-space vector contains information for the number of stored containers, parked trucks, and berthed barges. Related to containers, information is available for containers assigned to the available transport modes and containers approaching a destination. The state-space vector contains information about the number of vehicles and barges routed in the system either empty or full.

At each timestep the system planner optimizes an objective function considering the information stored in the state-space vector and predictions on future states. The planner defines a sequence of actions over a prediction horizon which will provide beneficial future performance of the system. However, only the sequences of actions assigned to the first timestep of the prediction horizon are implemented. Subsequently, the information in the state-space vector is updated. The operator repeats this procedure at each timestep. This approach enables the planner to dynamically utilize storage capacity, allocate containers to currently available transport capacity and re-plan decisions according to predictions. All operators' actions aim to minimize the value of the given objective function and accordingly to reduce the realized costs for operating the synchromodal system.

4. *Which transport variables and parameters should be incorporated in the design of different scenarios to have well-founded cases for making a performance analysis?*

In this thesis two operational strategy are tested in four different scenarios. The first strategy is proposed by Larsen (2020) where containers and trucks are routed simultaneously in a network with multiple origins and destinations. Barges are operated on a fixed schedule within the system. This is the Benchmark strategy. The second strategy is a built-up on the Benchmark where barges are routed with trucks and containers simultaneously instead of operating on a schedule. This operational strategy is referred as Free Barge Routing (FBR). In this manner, a system operator is introduced with more freedom for actions. For instance, barge capacity can be sent to each node in the system at anytime.

The private company of CTT has provided a list with container orders for transportation. The orders list covers the period from January 2019 to April 2019 including origins, destination, pick-up time, drop-off time and type of container. Fourteen terminals located in the Netherlands were identified in the list. Thirteen are located at Port of Rotterdam area and one terminal at Hengelo. Terminals were clustered in three groups according to their location. A demand profile was created from the orders lists with 324 containers which must be transported between the three groups of terminals. Subsequently, three additional demand profiles were created with respectively 356, 420 and 644 container orders. This increasement of orders is driven by the observed upward trend in container throughput at Port of Rotterdam for the past two decades. The main intention with these demand profiles is to evaluate the decisions of a system operator in conditions of increased demand for containers while system capacity is fixed. It was considered that the absolute volume of containers is going to be used for the demand profiles without considering one forty feet container as two twenty feet containers.

5. *To what extent can an MPC system operator handle system disturbances emerging from increased demand in container flows?*

To evaluate the decisions of a system operator and the performance of the system, four scenarios were simulated with the two operational strategies. Overall, eight simulations were executed in MATLAB, with Yalmip and Gurobi. In all tested scenarios, the operator decides to transfer most of the containers to one node and store them there until their due time. On average, 95% of all container orders were stored at this node which in turn offers the highest capacity and lowest storage cost. Further in the simulations, the system operator routes all the orders from this node to their destination.

Eventually, the high volumes of containers concentrated at one node created bottlenecks in the system. In a case when handling or storage capacity became insufficient, the application of the FBR strategy come out to be more efficient than the Benchmark strategy. This is clearly observed in the Large Increase scenario when containers at Node 2 cannot be rapidly released with the Benchmark resulting in more than 50 delayed orders at just one timestep. By using this strategy, the system operator cannot utilize barge capacity and orders are subsequently delayed. Barges are available at terminals only at certain timesteps of the optimization and trucks must compensate the lack of barge capacity. Yet, the operator cannot assign enough containers to the trucks due to the lack of sufficient truck handling capacity. On the other hand, this is not observed when the FBR strategy is applied in the Large Increase scenario. Barges are routed based on predictions instead on a fixed schedule. Eventually, there is available barge capacity when truck handling capacity is insufficient, and 193 containers are transported by barge compared to just 130 with the Benchmark strategy. Orders are loaded on the barge and then delivered at the destination on time.

Results from simulations demonstrate the ability of an operator to manage a synchromodal transport system by applying a MPC planning approach. Operators' decisions were identified to be highly dependable on three factors: 1) pattern of demand profile, 2) available capacities and costs and 3) MPC parameters. Foremost, decisions are influenced by the volume of orders which are predicted to enter or leave the system within the horizon. Subsequently, a trade-off between costs and available capacity is made and the operator decides either to route the containers or store them at a node. Lastly, it is important to mention the calibration of a MPC parameter: the prediction horizon length. Operators' actions are an outcome of the number of events covered in the prediction horizon. Therefore, with longer horizon different decisions might be considered as optimal and applied to the system. Generally, an operator of a synchromodal transport system can benefit from applying a MPC planning approach when there is a certain level of freedom in his decisions. Even though, positive effects are not explicit in all scenarios, they become so when capacity bottlenecks emerge in the system.

6. *How does short-time scheduling of barges influence the overall operational cost of a synchromodal system compared to a fixed long-term scheduling?*

The two proposed strategies in this thesis have one major distinction in the barge routing philosophy. While in the Benchmark strategy barges are routed on a fixed schedule, in the FBR they are routed flexibly between terminals without a predefined sequence. Expectedly, the implementation of the two strategies showed different sequence of actions from the system operator which respectively led to differences in the realized operational costs. Results from scenarios testing revealed an evident cut in cost per container when barges are routed simultaneously with trucks and containers. The most significant difference was observed in the Large Increase Scenario being slightly more than 11%. Moreover, scheduled barge routing turns out to generate double operational costs compared to flexible barge routing. It is also important to mention that in cases of high demand for containers as in the Large Increase scenario, the operator is unable to deliver all orders on time with a fixed scheduled barge in the system. Accordingly, penalties for delayed containers are charged and the overall operational cost escalates. With the Benchmark Scenario the penalties for delayed orders were 27210 compared to just 540 with the FBR strategy. In general, operating a barge on a short-time schedule may not only facilitate savings in operational costs, but also improve the quality of the services offered in a synchromodal transport system by significantly reducing the cases of delayed orders.

By answering the sub-questions, we can provide an answer to the main research question of this thesis. A successful strategy for operational decision-making in a synchromodal transport system must be able to capture the dynamics of such a system. This is achievable by not only taking dynamic decisions, but also by having the possibility to change them regularly. The efficiency of the strategy can be evaluated by KPIs covering the amount of satisfied demand on time and utilization levels of stationary and moving resources. The balance between service quality and cost is also recognized as crucial driver for accepting synchromodality, hence operational costs should be considered in the evaluation as well. The MPC approach has proven its potential for applicability in transport system. The single layer MPC approach is suitable for a synchromodal transport system with a centralized operator. A strategy which allows the system operator to take flexible decisions in terms of barge routing proved as an efficient concept for both reducing the operational costs of the system and improving the quality of offered services. However, the beneficial implementation of his strategy is strongly dependent on several factors as 1) cargo volumes, 2) strategy configuration and 3) MPC design and parameters.

7. Discussion

In this section, a reflection on the final conclusions is made. More insights into the results are obtained by going through the generated solutions. The deliverables and limitations of the proposed FBR strategy are discussed in this chapter. At last, the value of this research is discussed with suggestions for future improvements and research directions.

7.1. Novelty of the Research

This thesis provides useful insights about flexibility in synchromodal transport: 1) unscheduled barge routing is more cost beneficial when high volumes of cargo are routed, 2) MPC system planner can avoid capacity bottlenecks and reduce delayed containers when higher degree of decision freedom is allowed.

The added value of this research is that it shows how to improve the performance of a synchromodal transport system when flexibility is utilized to its full potential. The implementation of flexible barge routing in practice can also be beneficial for the wider acceptance of synchromodal transport concept. Yet, the most useful insight of this thesis is the laid foundation for future research on the direction of analysing the benefits of introducing more flexibility in operators’ decisions in a synchromodal transport system. In general, the synchromodal transport concept is relatively new and research in this field is gaining attention. Prior to this work, only a few studies try to capture one of the major features of synchromodality: real-time adaptation of decisions and even simulating it. As such, many knowledge gaps existed already, but many remain after this thesis as well.

The work combines various aspects of operational planning including routing of two transport modes simultaneously with containers, applying Model Predictive Control for obtaining optimal solutions and allowing for real-time changes in decisions. This thesis introduces the flexibility of barge routing into operational planning in synchromodal transport network. This is a build-up on the concept proposed by Larsen (2020) where trucks and containers are routed simultaneously, but barges are operated on a schedule. The demand profile is a realistic representation of a real-life containers flow within the Netherlands provided by the company of CTT. The novelty of this thesis includes an operational strategy which incorporates the above-mentioned concepts and simulate the operational decisions of system planner in synchromodal transport system.

7.2. Filling the Research Gap

In the literature review in Section 2, two research gaps are identified: 1) the need to design a strategy which can adapt to system changes and 2) the need to obtain optimal solutions in different scenarios. These gaps are discussed in further this subsection.

ADAPTIVE DECISION-MAKING STRATEGY

This thesis partly succeeds in filling this gap. A planning strategy is proposed which can adopt to changes in volumes of container orders and assign transport capacity for it. The strategy is flexible in terms of possibility to transship containers between transport modes and adapt the routes of transport modes. Yet, the strategy does not incorporate other possible disruption in a transport system as road and waterway congestions or handling disruptions. The precision of the proposed strategy is low in terms of barge travel times. The exact travel times are unknown due the presence of many locks and bridges which affects barge travel times. This affects the decisions of a system planner.

MPC IN OPERATIONAL PLANNING

The main reason for the application of Model Predictive Control (MPC) is because it provides the flexibility of the planner to adapt its decisions according to predictions on future states. However, with the MPC approach, the planner has a vision of a small period in the future called prediction horizon. By changing the prediction horizon length, the planner can cover different number of future events and probably take different decisions. In this thesis, the MPC parameters are aassumed optimal for the proposed configurations. Prior to this work, MPC application was rarely applied for operational planning in synchromodal transport network. We feel that with this thesis we contributed to fill this research gap and provide optimal solutions to several investigated scenarios.

The value of this thesis includes the introduction of the concept of flexible barge routing in a synchromodal transport network and measuring its impact on operational decisions. Moreover, the concept is tested on scenarios constructed from real-life data.

7.3. Values of the Deliverables

The most important deliverable of this thesis is the designed operational FBR strategy. The benefits of applying this strategy could be visible in practice, especially in areas with high demand for containers. With the constant increase of container throughput, the areas of Port of Rotterdam and the Dutch hinterland are considered as suitable.

7.3.1. Meeting the expectations

In section 4.3.5 expectations for the results of the simulated scenarios are presented. Hereby, a discussion is made to study whether these expectations are substantially met. The FBR strategy shows tendentious and predictable behaviour in some respects. For instance, the more container orders are accepted by the system planner, the lower is the realized cost per container. Therefore, the system planner successfully takes advantage of economies of scale when the strategy is applied.

As we mentioned before, the benefits of applying the proposed FBR strategy are more evident in cases of high demand. The system operator successfully recognizes one of the nodes as a hub. This behaviour of the operator meets the expectations prior to scenario testing as Node 2 offers the most attractive costs for container storage. Its proximity to Node 1 and available capacity also plays a crucial role since this the node with the greatest demand for inbound and outbound containers. The concentration of container flows at one location close to the port from which container flows are distributed to the hinterland is met in practice. This is recognized as the concept of ‘dry port’. Dry ports are used to accommodate copious quantities of containers as soon as they are unloaded on a deep-sea terminal. By applying the FBR strategy, the system planner promptly transfers the incoming containers from Node 1 to Node 2 and comply with this concept. This facilitates the acceptance of not only the strategy, but also the concept of synchromodality since the actions of a system planner are familiar with those from practice.

Considering container storage, one expectation is not met. This is the possible recognition of Node 5 as an ‘extended gate’. The Extended Gate is a concept capturing the intention of extending the delivery point from the perspective of a shipper or receiver (Veenstra et. Al. 2012). In other words, the gate of the sea terminal is moved to the inland terminal, respectively in our network layout from Node 1 to Node 5. Unfortunately, this is not observed in the actions of the system planner since all containers are stored at Node 2 which is significantly closer to Node 1 than Node 5 is.

Prior to testing scenario testing, expectations were made for the routes which would be most frequently used by a system operator to route a flexible barge. It was assumed that the busiest barge routes are going to be between nodes 2 and 5. The operator would transfer import containers in the direction of Node 2 to Node 5 and export containers in the opposite direction. This expectation is met only in the Base Scenario. Moreover, barge routes with the FBR are close to the constructed barge schedule applied in the Benchmark strategy. However, the result from other scenarios shows a clear change in operators' behavior. With an increase in container volumes in the system, the operator alters its preferences for route selection. In all other three scenarios the system operator prioritizes the route between nodes 2 and 3 and nodes 3 and 5. Even though, this behavior does not meet the expectations it shows the ability of the system operator to take decisions based on the specifics of tested scenarios.

One of the main potentials of synchromodal transport concept is the shift of cargo transportation from trucks to inland barges. However, this is not observed from the results of scenario testing with both strategies. Either with scheduled barge or flexible barge planning, trucks routing is extremely intensive. In all scenarios, more containers are transported by trucks, in all cases truck share is more than 80%. This can be partly explained with the extensive use of short-range trucks between nodes 1 and 2 which counts for more than the half of all truck trips. Despite that, long-range trucks still transport more containers than the barge in the system. These results might not be favoured by policy makers whose main intention is to reduce trucks routing in port areas and hinterland.

Integrating the philosophy of routing the barge freely within the transport system is a significant contribution to synchromodality. Operators' behaviour related to flexible barge routing partly meets the expectations. What is found intriguing in operators' behaviour is the slow increase of containers transported by barge among scenarios. Until handling capacity of trucks is sufficient in the transport system, the planner tolerates trucks routing and even a scheduled barge transports more containers by a flexible one. Yet, when trucks handling becomes a bottleneck, the operator assigns considerably more containers to the flexible barge than before and compensate for the trucks. While the scheduled barge has limited capacity potential, a flexible barge can adapt to events and avoid potential bottlenecks in the system. This can be greatly beneficial in practice for terminal operators for avoiding expensive investments in new handling equipment and storage capacity.

7.3.2. Scalability of Deliverables

The combination of the proposed FBR strategy and the MPC planning approach are feasible for all scenarios in the constructed configuration. The strategy is adaptable to different configurations in terms of cost and capacity parameters including more than one barge operating in the system. The strategy can also be applied to different network layouts. This is presented in Appendix B where small examples are solved by applying the FBR strategy. Considering the MPC approach, the prediction horizon length can be adjusted according to the available computational power and time for solving a problem. Therefore, the combination of both can be implemented in practice by different actors in a container supply chain including the company of CTT.

Moreover, with its implementation in practice, more accurate values can be used in the construction of both configuration and scenarios. This is going to not only reflect on the accuracy of the results but also indicates the possible directions for development of the operational strategy and the MPC planning approach. The possible improvements are going to be discussed further in this section in the limitations.

7.3.3. Reuse of Scenarios and Strategy Configuration

Constructed scenarios and strategy configuration are assumed accurate to a high extend. The demand profiles in different scenarios are based on real-life data from the company of CTT and statistical data on Port of Rotterdam annual container throughput. It is believed that they are suitable for implementation in future research. The configuration of the strategy can also be reused in future works as long it captures important aspects of a synchromodal transport system and its dynamics. The used network layouts consist of different points each having a dedicated purpose in the system. Yet, the construction of the parameters and travel times of transport modes is based on many assumptions due to the lack of accurate data. With accurate data the value of strategy configuration is going to be increased which itself will lead to more accurate MPC configuration.

7.4. Limitation of the Research

Main limitation of the findings in this thesis is that it indicates the possible benefits of applying flexible barge routing, but the proposed FBR strategy fails to provide consistent behaviour. For instance, it was expected for the Medium Increase scenario, the difference in realized costs between the FBR and the Benchmark strategies to increase which is observed from the Base to the Small Increase scenario. Instead, the gap between the two realized costs is reduced. Moreover, it was expected that with the FBR the number of containers transported by barge are going to rise in scenarios with higher demand for containers rather than being relatively stable. However, this is not observed until truck handling capacity becomes a bottleneck in the system and more containers are assigned to a flexible barge. This limitation can considerably hinder the implementation of the concept of flexible barge routing and synchromodal transport itself.

The operational strategy proposed in this thesis has introduced the concept of flexible barging. The made assumptions in building the strategy oversimplify some of the aspects of barge routing. Firstly, the system operator can adjust its decisions in every timestep of the optimization run. This might not be favoured from terminal operators' point of view who need some level of consistency in decisions to organise terminal operations. Secondly, it is observed that the system operator routes the barges to different terminals without executing any handling operations. This might not be appealing to terminal operators as well who would like to utilize their quay berths instead of just take up free space. Moreover, each aspect of the FBR strategy is deterministic without the possibility to adopt uncertainties in travel times which is frequent in passing through locks or congested highways.

The concept of Synchromodal transport allows the real-time adaptation of decisions which includes the transhipment of cargo on different modalities. Yet, the proposed strategy does not consider distinctive characteristics of containers like size or type and does not account for the physical constraints that shifting a container can cause. Moreover, the strategy does not cover the problem of relocating empty containers. This can be recognized as another barrier which hinders the adoptions of Synchromodal transport and flexible barge routing.

A fact must be highlighted that the proposed operational strategy is a build-up of a strategy introduced by Larsen (2020). The FBR incorporates the MPC planning approach and the concept for simultaneous planning of trucks and containers from it. Furthermore, the values for cost and capacity parameters used in this thesis are tailored to the values used in the mentioned work. Many assumptions were made for the configuration of the cost values. Only the MPC prediction horizon length is determined empirically, but it is still strongly dependent on previously assumed values for cost and capacity parameters. This is considered as a limitation of this thesis, cause the accuracy of the scenario simulation results is affected from the accuracy of the input. For instance, unexpected behavior of the system operator occurs as storing containers on barges instead at terminals due to the lower costs. Therefore, for future research, using accurate data for input is beneficial for representing valuable results and support the adoption of synchromodal transport and flexible barge routing.

7.5. Future Research

One of the important values of this thesis is providing directions for future research. Indeed, there are existing scientific gaps in implementing flexible concepts in a synchromodal transport network and creating decision-making strategies which can simulate them. There were difficulties in designing the strategy and its configurations proposed in this thesis- e.g., lack of experience and accurate data which forced several assumptions to be made. Below are presented several directions for further research in flexible barge routing and synchromodal transport.

7.5.1. Research on Flexible Barge Routing

Flexible barge routing can be beneficial to transport companies which handles large volumes of containers and operates with several terminals. It is in future research relevant to investigate how flexible inland barges can be routed not only with trucks and container but also with other transport modes. Trains also can stimulate economies of scale and the potential for combining them with flexible barges can be analysed in future. A direction for future research is investigating the effects of considering diverse types and sizes of containers in the operational strategy. Thereof, the problem of empty container allocation can be analysed so potential benefits for different actors in the system can be recognized.

In this thesis, the system operator is free to route barges to any location within the network, at any time. This assumption presents an overview of the potential of flexible barge routing but might be far from the accepted practices in the industry. The industry requires a certain level of predictability to adopt a concept and organize the accompanying operations. Therefore, a possible direction of the development of the proposed strategy is testing the level of freedom in barge routing. It is from both theoretical and practical relevance to investigate how restricted flexibility in barge routing, affects planners' decisions and system performance. Operational hours of terminals can also be introduced into the strategy to further prepare it for real world implementation.

7.5.2. Research on Synchromodal Transport and MPC

The presented MPC planning approach considers a single system operator for the entire transport network. This description might be applicable for a large-scale company with big structure and operating with many orders. For further research, the single-agent MPC approach can be adapted to a structure where many agents discuss possible actions and share information and profit. The network of agents can be either distributed or hierarchical, so different strategies for control can be tested. Showing the benefits of applying different strategies for information and profit sharing to the overall system performance can stimulate the further acceptance and development of the Synchromodal transport concept.

7.6. Difficulties

Difficulties were met during the competition. The main hurdle in this thesis was the implementation of the two investigated strategies an. Simulations were run in MATLAB by using a toolbox for modelling and optimization called Yalmip. This toolbox is used to define the variables in the models, construct the constraints, the objective functions and call an external solver. The Gurobi solver is used in this thesis to solve the simulated scenarios and find optimal solution to two mixed-integer problems. The choice of these tool

s was driven not only by their ability to simulate and solve fast mathematical problems, but also by the practical experience of supervisory team members with this tool. Their experience and advice were significantly valuable for the correct implementation of the tested strategies and scenarios.

The lack experience with MATLAB and Yalmip proved a big burden with getting to grips with the simulations. Furthermore, the lack of experience with implementing a Model Predictive Control (MPC) makes this task even more difficult. For instance, three different approaches were used before correctly defining the spaces in MATLAB for remembering the solutions. Considerable time was also spent in the correct definition and construction of variables and constraints which resulted from many hours of simulating infeasible implementations. Defying the most appropriate setting of Gurobi was also a challenge due the large scalability of the implemented problem. A wrong setting and calibration of solver parameters frequently resulted in numerical issues or extremely long time spent in solving problem. In general, much time and effort were required not only to correctly implement the proposed strategy, but also to optimize the running time of the simulations.

Other difficulty during this thesis was a rare external factor: COVID-19. An emerging global pandemic affected the possibility of investigating the topic in a suitable and productive environment. The most crucial consequence of performing a research at home was the lack of computational power and technical reliability. Personal laptop was used to simulate the experiment which resulted in longer running times and hardware issues due to overheating. The used laptop has a processor Intel® Core ™ i5- 3230M at 2.6GHz with 8GB RAM memory in a 64-bit Operating System.

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Appendix A: Scientific Paper

Centralized Operational Strategy for Container Transport in a Synchromodal Transport Network

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Abstract- In time of fast globalization and urbanization, the volumes of transported containers have significantly increased in the last decades. The challenges of operating with high volumes of containers have propagated from the deep-sea terminals into the hinterland network resulting in extensive use of road transportation, long waiting times and high carbon emissions. Synchromodal transport has addressed these challenges by promoting integration of services and real-time decisioning to increase the overall flexibility of the system. However, little is known about the effects of applying flexible concepts on operational planning decisions and whether these decisions have reflection on the performance of the system when centrally taken. This paper proposes a research for a design of an operational strategy which supports operational decisions on container routing and mode choice among trucks and barges. Model Predictive Control planning approach is applied to optimize the simultaneous routing of containers, trucks, and barges. The effectiveness the proposed strategy is evaluated in the presences of increased container volumes and compared to a Benchmark strategy by the means of simulation experiments. The impact of implementing flexible decisions on system performance and realized operational costs is investigated.

Keywords*- Synchromodality, Container routing, Centralized Model Predictive Control, Simultaneous Routing Modelling, CTT network*

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1. Introduction

Since introduction of containers in the 1960s, a revolution in transport has been observed. Nowadays, seaports not only invest in infrastructure and equipment to maintain their competitive position on the market, but also focus on the development of their connections to the hinterland network for several reasons. As part of the global supply chain, the hinterland network has the responsibility to transport the cargo in the most efficient and cost-effective manner (Behdani et al., 2020). Cheaper and faster hinterland connections are the focal point for ports in terms of their attractiveness to shippers and carriers (Konings and Priemus, 2008). Moreover, investing in reliable hinterland access may also lead to a reduction in terminal congestion and faster container release (Franc and van der Horst, 2010).

Due to the continuous growth of container volumes, the hinterland connections evolve to multi-modal transport logistic centres where high-quality and cost-efficient services are offered. Yet, the enormous increase of container throughput in seaports propagates further into the hinterland network and provokes disturbances to the entire supply chain. The hinterland transport of goods is still considered the weakest point of the chain which presents the notable 60% of the total supply chain cost (Beresford et al. 2012).

In Northwest Europe, we can observe many large deep-sea terminals and inland locations which accommodate different services and interact strongly with each other. Overall, port-hinterland dynamics are overly complicated. This complexity has driven the desire in different actors to adopt approaches which are more oriented to their supply chains. Apart from costs and capacities, more attention is given to modal-choice and routing decisions. What brings value to the competitiveness is the ability of ports to establish reliable and flexible connections with their hinterland partners in the face of inland terminals. Greater options for routing provided to shippers and logistic providers enhances the logistic attractiveness of a respective port (Noteboom and Rodrigue 2007).

Driven by the ambition to improve the performance of multi-modal networks and answer the new dynamics in transport business, many researchers have investigated the potential of a relatively new concept called “Synchromodal transport”. Synchromodality is the opportunity of logistic providers to design unique services to each of their customers. What makes this possible is the feature of synchromodal transport to integrate horizontally the transport system. ‘Horizontal integration’ is knowns the possibility to use different combinations of modalities based on their characteristics, availability in real-time, and customer requirements (Bart van Riessen, 2015).

Even though Synchromodality is a relatively new concept, there are several assumptions which hold among all research. Synchronization of “Moving Resources “and “Stationary Resources” is aimed to be achieved by implementing flexible deployment of transport modes, mode-free bookings (a-modal booking), network- wide planning and Real-time switching. The reason for all the attention which Synchromodal transport concept receives from both researchers and experts is the eventual positive effects on the supply chain performance. Synchronization of routing decisions and mode combinations is believed to increase the reliability of the supply chain and eventually reduce operational costs (Pfoser et al., 2016).

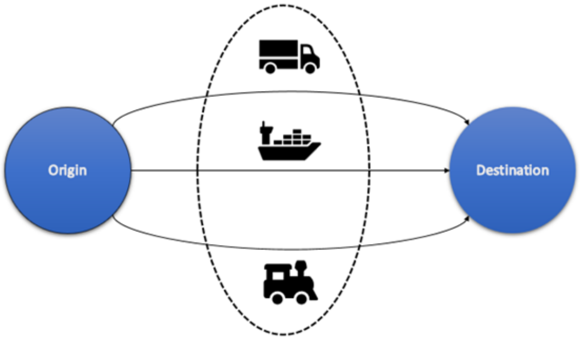


Figure 1: Horizontal integration of transport services (Bart van Riessen, 2015)

between fixed points. If barges are operated on fixed schedules, a coordinator of a synchromodal transport network is not able to efficiently utilize the additional barge capacity when its needed. Flexible routing of barges can provide more freedom to the system operator by giving him the options to route not only containers and trucks, but also to optimally route barges. Because of this, it is interesting to investigate the possibilities which open to transport operators when barge services and routing decisions are not strictly scheduled.

This paper investigates the effects of proposed planning strategy for operational decisions on container transport in a synchromodal transport network with the presence of increased demand for container flows. The strategy focuses on routing container flows in hinterland network simultaneously with different transport modes. The objective of the strategy is to facilitate a system operator in delivering container orders within given time windows and minimizing the operational costs over a given prediction horizon.

The reminder of this paper is structured as follows. The existing literature is discussed in Section 2. In Section 3, a planning strategy with a centralized MPC approach is presented. Section 4 presents a Case study and strategy configurations. In Section 5, the results from experiments are presented. In Section 6 concluding remarks are provided. Section7 introduces remarks and directions for future research.

2. Literature Review

The first definition of ‘Hinterland transport network ‘came in the beginning of the last century by Sargent et. al. (1938) as ‘the area which a port serves. Since then, hinterland transport networks have been extensively investigated by the researchers through the years in terms of its structure and internal dynamics (Sdoukopoulos and Boile, 2020). In this section studies which are related to container routing problem are divided into three categories: hinterland container transport, synchromodal transport and Model Predictive Control (MPC) implementation.

2.1. Hinterland Container Transport

Three types of decisions describe the dynamics in a hinterland transport system for container transport: strategic, tactical, and operational. Currently, the spotlight in literature is put on the strategic development of hinterland networks for container transport and the tactical design of services in it (Limbourg and Jourquin (2005), Yamada (et al., 2009)).

However, operational decisions are the focus of this paper. They have the goal to identify the optimal decisions for maintaining the designed services in the system. This includes the routing of different transport modes within the system in compliance with customer requirements. Operational decisions have the goal either to minimize the realized operational costs or maximize service profit. Fazi et al. (2015) developed a decision support system for the optimal allocation of containers in hinterland transport network with a heterogenous fleet composed of trucks and barges. The system is applied on a hub-and-spoke network with an objective to minimize the total cost of delivering all containers and routing the transport modes. Zweers et al., (2019) proposed a decision-making tool for the routing of inflow containers by trucks and barges with defined capacities. The goal of the system planner is to maximize the number of containers which are routed by barges. If barge transportation can benefit from economies of scale, Zweers (2019) believes this might result in minimal transportation costs as well. Alfandari et al. (2019) addresses a problem of optimal planning of container shipping company which operates on a linear service. The designed strategy aims to maximize a profit function by determining which containers to transport and how to route a barge fleet among predefined set of ports. Although, the above studies considered the utilization of multiple modes none of them provide a flexible approach which can adapt to any kind of changes within the network.

2.2. Synchromodal Transport

Synchromodality is the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for his (inland) transport (Bart van Riessen, 2015). The core of synchromodality is the integration of the stationary resources (e.g., roads, rails, navigable waterways, terminals, and transshipment hubs) and moving resources (e.g., trucks, trains, and barges) which are constantly aligned with the requirements of the customers (Behdani et., al., 2014). Synchromodal transport planning is dynamic incorporating real-time data, decisions, and system states. Pfoser et. al., (2016) defines seven crucial success factors (CSF) which are necessary for a functional synchromodal transport chain. Operational strategy needs to consider the dynamical allocation of available resources, forecasting and dynamical switching of decisions to model a well-organized synchromodal system.

In the literature, Jin et al. (2018) proposed a design for feeder services in a network where feeders visit port terminals on fixed schedules. The main goal of the paper is to synchronize the transshipment of containers between large sea vessels and feeder vessels within a terminal hence the schedules of both are adjusted optimally and terminal congestions are avoided. A direction of research in literature is found to be the comparison between intermodal and synchromodal transport. Zhang & Pel (2016) used a capacitated schedule-based assignment algorithm applied on the Rotterdam hinterland network to explore the potential impact of synchromodal transport on hinterland distribution compared to the traditional intermodal freight transport. The effects of the routing decisions on the robustness and reliability of the system are not fully captured as service variations and disruptions are not considered in the model. Qu, et al (2019) refers to the need of adequate changes in pre-designed schedules of hinterland transport systems when system disturbances are presence. Accordingly, the paper proposes a mixed integer problem formulation under the concept of synchromodality to deal with rerouting of shipment flows and replanning of terminal operations and services including transshipments. The model is tested on dealing with cases of late release of shipments, volume fluctuations and latency of barge and train services in the Rotterdam hinterland transport network. Rivera & Mes, (2017) investigated the problem of scheduling drayage request by the means of trucks. Drayage operations are the transportation stages of pre and end-haulage. The work introduced an approach which makes dynamic decisions about the assignment of terminals, the routing of containers and trucks**.** The outcome of their model is a schedule for the drayage requests as the schedule can be changed in relation to a new incoming request. Modeling operational decisions in a synchromodal transport network can be challenging in terms of computational power and time. A research from Xu et al. (2015) proposes an algorithm for container allocation with random freight demands aiming for improved computational performance.

2.3. Model Predictive Control Implementation

The concept of synchromodality gives more freedom to operators and broadens the scope of actions and decisions which can be taken. This freedom and the increasing amount of freight volumes which needs to be transported has motivated the introduction of control methods. Model predictive control (MPC) is recognized in literature as an effective approach to address container routing problems. The most common designs of MPC found in transport literature are centralized and distributed. The centralized MPC structure is managed by a single agent who has access and control over the complete system. More information about the concept of MPC can be found in the work of Negenborn et al., (2010, p. 14). An interest for the purposes of this paper is the applications of centralized control on transport system which can be found in the existing literature.

Nabais et al. (2015) investigates the problem of increasing volumes of containers and the need of their on-time delivery. A centralized controller algorithm is designed for assigning containers to transport modes in the perspective of a terminal operator. The main goal of the controller is to assign the cargo to available transport capacity and delivered it to the desired destination on time. The solution of the formulated optimization function is an optimal sequence of actions over a prediction horizon which provides the most suitable predicted performance. The controller implements only the first sequence of actions until the beginning of the next timestep of the horizon when a new optimization problem is solved based on the current state, available information, and goals. The proposed approach is applied on a network with a single origin node and multiple destinations. The available routes between the nodes are pre-defined. Barges and trains operate on a scheduled service with predefined frequencies and capacities. The results of the numerical experiments indicate that the performance of the model is highly dependable on the network configuration, the length of the prediction horizon, and the demand patterns.

In comparison to Nabais (2015), a centralized MPC approach was proposed by Larsen et al., (2020) which combine the routing of containers and trucks. Both are routed simultaneously as truck operate in a flexible manner. Hence, the controller of the system can reposition empty trucks to nodes of the network where they will be needed in future timesteps. Trucks are not considered to be constantly available to the needs of the controller and the size of the fleet is also defined. The proposed model is applied on a network with multiple origin and destination nodes. To test the effects of routing simultaneously trucks and containers, the approach was tested under conditions of uncertainty of truck travel times. The results indicate that the proposed MPC is encouraged to transport containers only when the deadline for a shipment is approaching, but also when an empty truck is available at the appropriate location.

Instances for distributed MPC applied on transport problem also can be found in literature as well. Di Febbraro et al. (2016) investigates the problem of container transportation by decomposing it into a set of sub-problems, each representing the operations of an actor which are connected by a negotiation scheme.

2.4. Contributions

In the literature there are vast amount of works which investigate problems in various aspects of transportation and supply chain. Many decision-making tools have been proposed to route various compositions of fleets in different network configurations. However, there is a scarce number of models and operational strategies which consider dynamical switching of modes and real-time changes of routing decisions in terms of disruptions in the system. In this manner the full potential in terms of synchromodal flexibility is barely investigated.

With this paper we would like to propose an operational strategy for routing decisions which can reflect on the robustness and reliability of a multi-modal transport network with the presence of increased demand for container flows. The proposed approach needs to have the possibility to readapt its routing decisions according to current state of a synchromodal transport system. Furthermore, by the means of a Model Predictive Control (MPC), the strategy will have the ability to perform optimal decisions based on predictions of future states of the system. In this manner we believe we are going to contribute for the fulfilment of the identified gap.

3. Operational Strategy: Concept and Formulation

To evaluate the consequences of taking real-time routing decisions for inland barges in a synchromodal transport network, one operational strategy is created and a second is going to be used as a Benchmark. The Benchmark is an operational strategy previously introduced by Larsen (2020). The Benchmark is used as a basis for the design of the proposed strategy, which in turn is referred as Free Barge Routing (FBR).

In the Benchmark strategy trucks and containers are routed simultaneously while inland barges are operated according to a fixed schedule. In contrast, the proposed FBR, determines the optimal routes of barges together with truck and container routes. Both strategies use a centralized Model Predictive Control (MPC) planning approach which enables the operator of the synchromodal network to take decisions based on the latest available information.

3.1. Benchmark Strategy

A strategy proposed by Larsen (2020) is used as a Benchmark Strategy. The research of Larsen, (2020) introduces a Model Predictive Control (MPC) for a multimodal transport system. The system in accommodates flexible trucks and scheduled barge and train services. Commodity flows are containers of a single size. They are modelled as continuous variables. Flexible trucks are implemented in the same manner as well. Both containers and trucks are coupled by a constraint that containers can only flow on an arc if there is at least the same number of trucks moving on this arc.

3.2. FBR Strategy Formulation

To handle increased demand for container flows, an operational strategy with flexible routing of barges is proposed. The FBR strategy is a continuation of the strategy introduced by (Larsen 2020). Table 1 in the Appendix presents all notations used in this paper. In this section we present a mixed integer linear programing for the representation of the FBR strategy.

Most of the variables in the strategy formulation are vectors. The vector $\mathrm{u}_{\mathrm{i}}^{\mathrm{hm}}(k)$ is used to keep a record of the incoming containers to node *i* by all truck types at timestep *k*. This is necessary to represent the travel time of trucks τ_{ij} in the truck network as a delay. The formulation of the delay is:

$$\mathrm{u}_{\mathrm{i}}^{\mathrm{hv}}\ (\mathrm{k}) = \left[u_{ji}^{v1}(k-1) \dots u_{ji}^{v1}\left(k-\tau_{ji}\right) \dots u_{j'i}^{v_{nv}}(k-1) \dots u_{j'i}^{v_{nv}}\left(k-\tau_{j'i}\right)\right],\ \{j,\dots,j'\} \in \mathrm{T_i},\ \{v1,\dots,v_{nv}\} = [1,nv],$$

where $u_{ji}^{v}(k-1)$ is the number of containers on all types of trucks sent to node *i*. Respectively, the record of the vehicles approaching node *i* is:

$$v_i^h(k) = \left[v_{ji}(k-1) \dots v_{ji}\left(k-\tau_{ij}\right) \dots v_{j'i}(k-1) \dots v_{j'i}\left(k-\tau_{ji}\right)\right], \{j,\dots,j'\} \in \mathrm{T_i}$$

The vector $\mathrm{u}_{\mathrm{im}}^{\mathrm{hs}}(k)$ is used to keep a record of the incoming containers send to quay *m* of node *i* by all type of barges at timestep *k*. This is necessary to represent the travel time of barge φ_{imjn} and the operational time within ports ω_{im} in the barge network as a delay. The formulation of the barge delay is:

$$\begin{aligned}\mathrm{u}_{\mathrm{im}}^{\mathrm{hs}}(k) = \Big[&u_{jnim}^{s_1}(k-1) \dots u_{jnim}^{s_1}\big(k-\omega_{jn}-\ \varphi_{jnim} \\ &-\omega_{im}\big) \dots u_{j'n'im}^{s_{nb}}(k-1) \dots u_{j'nim}^{s_{nb}}\big(k-\ \omega_{j'n'} \\ &-\varphi_{j'n'im}-\omega_{im}\big)\Big], \qquad m \in Q_i, \\ &\{j \dots j'\}\ \in \mathrm{B_i},\ \ \{s1 \dots s_{nb}\}, \qquad \{n \dots n'\} \in Q_j, \\ &s \in [1,\mathrm{ns}]\end{aligned}$$

Here, the u_{ji}^{s1} is the number of containers of each type send to node *i* from node *j*. Following the same the delay of barges is constructed as well:

$$\begin{aligned}\mathrm{s}_{\mathrm{im}}^{\mathrm{h}}(k) = \big[&s_{jnim}(k-1) \dots s_{jnim}\big(k-\omega_{jn}-\varphi_{jnim} \\ &-\omega_{im}\big) \dots s_{j'n'im}(k-1) \dots s_{j'n'im}\big(k-\omega_{j'n'} \\ &-\varphi_{j'n'im}-\omega_{im}\big)\big],\ \ m \in Q_i, \\ &\{j \dots j'\}\ \in \mathrm{B_i}, \qquad \{n \dots n'\} \in Q_j,\end{aligned}$$

Each node of the network can be described with a state which is measured at every timestep *k* of the prediction horizon. The initial states of each node *i* are the number of stored containers, the number of parked vehicles, the number of vehicles approaching the network node *i*, the number of vehicles on their way to node *I*, the number of containers which are ready to be transported by barges and the number of barges which are present at a node at each timestep (*k*). The state of every network node is completed with the delays presented above.

Each node of the network can be described with a state which is measured at every timestep *k* of the prediction horizon. The initial states of each node *i* are the number of stored containers, the number of parked vehicles, the number of vehicles approaching the network node *i*, the number of vehicles on their way to node *I*, the number of containers which are ready to be transported by barges and the number of barges which are present at a node at each timestep (*k*). The state of every network node is completed with the delays presented above.

$$x_i(k) = \begin{bmatrix} x_i^c(k) \\ x_i^v(k) \\ x_{im}^b(k) \\ x_{im}^t(k) \\ u_i^{hv_1}(k) \\ \vdots \\ u_i^{hv_{nv}}(k) \\ u_{im}^{hs_1}(k) \\ \vdots \\ u_{im}^{hs_{ns}}(k) \\ v_i^h(k) \\ s_{im}^h(k) \end{bmatrix}, \qquad (1)$$

Containers enter and leave the system through the virtual destination nodes (VDs). Therefore, VDs are considered as the origins and destinations for each container type. There are no capacity constraints on the arcs connecting a VD node and its adjacent network node and the travel time between them is set to zero. For this reason, dynamics of virtual destination (VD) nodes differs from the dynamics of the network nodes. The equation defining the dynamics is:

$$x_i^d(k+1) = x_i^d(k+1) - uid(k) +\ uid(k) + d_i(k), \qquad (2)$$

The terms *incoming* and *outgoing* demand are used in this strategy. The term *incoming* is used when node *i* is the destination of commodities and *outgoing* when node *i* is their origin. Here, the incoming and outgoing demand $d_i(k)$ serve as a disturbance to the state of the system. Container types are defined according to the available VDs in the system. Hence, if there are three VDs in the system there are three container types. An instance for demand for 1 outgoing container of type 2 at node 1 at timestep 1 is formulated as $d_1(1) = (0; 1; 0)$, while the demand for 1 incoming container of type 1 at node 1 at timestep 5 is formulated as $d_1(5) = (1; 0; 0)$. In this way both incoming and outgoing containers are formulated as positive values.

The network node dynamics describe the number of containers which are stored at a network node and the amount of truck vehicles which are parked there. The number of containers is related to the new incoming demand and the container used to satisfy the outgoing demand to the destination nodes.

$$
\begin{aligned}
x_i^c(k+1) = x_i^c(k) &+ \sum_{v\,\in[1,nv]} \sum_{j\,\in\,T_i} \left(u_{ji}^v(k-\tau_{ji}) - u_{ij}^v(k)\right) \\
&+ \sum_{m\,\in\,O_i} \left(u_{mi}^u(k) - u_{im}^l(k)\right) \\
&+ \sum_{d\,\in\,D_i} u_d^i(k) - u_i^d(k)\ , \qquad (3)
\end{aligned}
$$

The variable $x_i^v(k)$ describes the number of trucks of each type which are parked at node *i* at timestep *k*. The dynamics of this variable are described by the equation:

$$
\mathrm{x_i^v(k+1) = x_i^v(k)} + \sum_{\mathrm{j\,\in T_i}} (v_{ji}(k-\tau_{ji}) - v_{ij}(k)), \qquad (4)
$$

The subsequent Equation (5) defines the number of barges which are present at a quay in node *i* and can be processed by the gantry cranes:

$$
\begin{aligned}
&\mathrm{x_{im}^b(k+1) = x_{im}^b(k)} \\
&+ \sum_{j\in \mathrm{B_i}} \sum_{n\in Q_j} \Big(s_{jnim}(k - \omega_{jn} - \varphi_{jnim} - \omega_{im}) \\
&- s_{imjn}(k)\Big), \qquad (5)
\end{aligned}
$$

The state $\mathrm{x_{im}^t}$, aims to reflects on these differences and represent the number of containers which are transported from the main stacking area and subsequently loaded on a barge at timestep *k*. The containers which are unloaded from a barge follows the same steps but in opposite direction. They are considered as well in the dynamics of this state. The following equation describes the number of containers which are assigned to barges:

$$
\begin{aligned}
\mathrm{x_{im}^t}(k+1) &= x_{im}^t(k) + u_{im}^l(k) \\
&- u_{mi}^u(k) +, \sum_{j\in B_i} \sum_{n\in \mathrm{Q_j}} \sum_{s\,\in S} (u_{jnim}^s(k - \omega_{jn} \\
&- \varphi_{jnim} - \omega_{im}) - u_{imjn}^s(k))\,, \qquad (6)
\end{aligned}
$$

In the strategy containers and trucks are routed simultaneously. This gives the opportunity for the system operator to send empty vehicles to nodes where there are going to be needed in the future. Yet, this does not count for containers and there should not be any container routing in the network without being assigned to a truck. The following constrain hinders the routing of containers without the presence of a truck if they are transported on a truck arc:

$$
\sum_{m\,\in[\,1,\mathrm{nv}]} [1\boldsymbol{nc}] * \mathrm{u_{ij}^{\mathit{v}}}(k) \le [\boldsymbol{1nc}] * v_{ij}(k), \qquad \forall j \in \mathrm{T_i}, \qquad (7)
$$

In Eq. (7) $\boldsymbol{1nc}$ represents a row vector of ones with a size of nc. The following set of constraints define the network capacities:

$$
1nc * x_i^c(k) \le c_i^c, \qquad i \in N, \qquad (8)
$$

Eq. (8) defines the maximum number of containers which can be stored at node *I* per timestep(*k*). The following Eq. (9) defines the maximum number of vehicles which can be parked at node *i* at timestep *k*:

$$
x_i^v(k) \le c_i^v, \qquad i \in N, \qquad (9)
$$

The following two equations Eq. (10) and Eq. (11) concerns the amount of container which pass through a node without being unloaded from their vehicle:

$$
z_i^v(k) \le \sum_{j\in \mathrm{T_i}} u_{ij}^v(k)\,, \qquad \forall i \in N, \qquad \forall v \in [1, nv], (10)
$$

$$
\mathrm{z}_i^v(\mathrm{k}) \le \sum_{j\in \mathrm{T_i}} u_{ji}^v(k-\tau_{ji})\,, \forall i \in N, \qquad \forall v \in [1, \mathrm{nv}], (11)
$$

With the introduction of $\mathrm{z}_i^v(\mathrm{k})$ the crane capacity can be formulated as a linear constraint and the containers which leave on the same vehicle, they arrived with do not count for a crane move:

$$
\sum_{v\,\in[1,nv]} \sum_{j\in T_i} \left(u_{ij}^v(k) + u_{ji}^v(k-\tau_{ji})\right) - 2 * \mathrm{z}_i^v(\mathrm{k}) \le c_i^t,
$$
$$
\forall i\ \in N, \qquad (12)
$$

The following constraints considers the network capacity and the terminals capacities. Equation (13) limits the available space for barges at node *i*:

$$
[1\boldsymbol{ns}] * x_{im}^b(k) \le c_{im}^b, \qquad \forall i\ \in N, \qquad (13)
$$

Further, the number of containers which are assigned to barges are limited to the capacity of the present barges at node *i*. This is described in Eq. (14):

$$
[1\boldsymbol{nc}] * x_{im}^t(k) \le Cap * [1\boldsymbol{ns}] * x_{im}^b(k), \qquad \forall i\ \in N,\ \ m \in O_i,
$$
$$
(14)
$$

Variables $u_{im}^l(k) \in \mathrm{R}_{\ge 0}^{nc}$ and $u_{mi}^u(k) \in \mathrm{R}_{\ge 0}^{nc}$ represent volumes of containers moved to and from the main stacking area of a terminal in handling operations of barges. Such movements are restricted by the productivity of quay gantry cranes and their speed. The next equation constraints the capacity of handling operations according to the crane's capabilities:

$$
[1\boldsymbol{nc}] * \mathrm{u_{im}^l}(k) + [1\boldsymbol{nc}] * u_{mi}^u(k) \le c_i^s * x_{im}^b(k), \qquad \forall i\ \in N,
$$
$$
\forall\, m \in Q_i, \qquad (15)
$$

In the strategy it is assumed that a barge cannot transport containers to the same node which she is currently in.

$$
\mathrm{u_{ii}^s}(k) = 0, \qquad \forall i\ \in N, \qquad i\ \in Q_i, \qquad \forall s\ \in S\ \ (16)
$$

Once the containers are ready and loaded on barges, they are assigned on a barge arc, and they can leave the terminal. Eq. (17) ensures that the assigned containers on a barge link does not exceed the capacity of the barges which is assigned to the same barge link:

$$[1\boldsymbol{nc}] * \sum_{j \in B_i} \sum_{n \in Q_i} \sum_{s \in S} u^{s}_{imjn} \leq Cap * s_{imjn}(k) \;\; \forall i \; \in N, \quad \forall m \; \in Q_i, (17)$$

The consistency of barges is ensured by Eq. (18), so the number of barges assigned to journeys does not exceed the total number of barges operating in the network. The following Eq. (19) allows a barge journey only if the barge is currently berthed at the origin node of the journey:

$$\sum_{i,j \in N} \sum_{m \in Q_i} \sum_{n \in Q_j} s_{imjn}(k) \leq [1\boldsymbol{ns}], \quad (18)$$

$$\sum_{j \in B_i} \sum_{n \in Q_j} s_{imjn}(k) \leq [1\boldsymbol{ns}] * x^{b}_{im}(k), \qquad \forall i \; \in N, \quad \forall m \; \in Q_i, \quad (19)$$

By applying the MPC planning approach, the system operator can make decisions which results are observed within the prediction horizon. Thus, the operator can send vehicles to a node only if the vehicles can arrive to their destination by the end of the prediction horizon. The same logic is followed for the barges.

$$v_{ij}(k) = 0, \qquad \forall i \; \in N, \forall j \; \in T_i, \forall k > Tp - \tau_{ji}\,, \qquad (20)$$

$$s_{imjn}(k) = 0, \qquad \forall i \in \; N, \qquad \forall m \; \in Q_i, \qquad \forall j \in B_i, \quad \forall n \in Q_j, \quad \forall k \geq Tp - \omega_j - \; \varphi_{ji} - \omega_i, \qquad (21)$$

The operator is not allowed to start loading a barge if the barge cannot arrive to its destination until the end of the prediction horizon:

$$u^{l}_{im}(k) = 0, \qquad \forall i \in \; N, \qquad \forall m \; \in Q_i, \qquad \forall j \in B_i, \quad \forall n \in Q_j, \quad \forall k \geq Tp - \omega_j - \; \varphi_{ji} - \omega_i, \qquad (22)$$

The following constraints define the positivity of the action variables and the states of the nodes:

$$v_{ij}(k) \geq 0, \qquad \forall i \; \in N, \qquad \forall j \; \in T_i, \qquad \forall v \in [1, nv], \quad \forall k \leq Tp - \tau_{ji}, \qquad (23)$$

$$u^{v}_{ij}\,(k) \geq 0, \qquad \forall i \; \in N, \qquad \forall j \; \in T_i, \qquad \forall v \in [1, nv]\,, \quad \forall k \in [0, Tp - 1], \qquad (24)$$

$$z^{v}_{i}\,(k) \geq 0, \qquad \forall i \; \in N, \qquad \forall v \in [1, nv], \quad \forall k \in [0, Tp - 1], \qquad (25)$$

$$s_{imjn}(k) \; \in \; \{0,1\}, \qquad \forall i \in \; N, \qquad \forall m \; \in Q_i, \qquad \forall j \in B_i, \quad \forall n \in Q_j, \qquad \forall k \; \in [0, Tp - 1], \qquad (26)$$

$$u^{s}_{imjn}(k) \geq 0, \qquad \forall i \in \; N, \qquad \forall m \; \in Q_i, \qquad \forall j \in B_i, \quad \forall n \in Q_j, \qquad \forall k \; \in [0, Tp - 1], \qquad (27)$$

The operator solves an optimization problem at every timestep *k* and measures the state of every node *i Eq.*(28). For the optimization process at the following timestep *k+1*, the operator considers the measured state $y_i(t)$, as an initial condition of the system.

$$x_i(k = 0) = y_i(t), \qquad \forall i \; \in N, \;\; \forall k \; \in [0, Tp - 1], \;\; (28)$$

The decision vector U contains all inputs to system: $u^{v}_{ij}(k)$, $u^{s}_{imjn}(k)$, $u^{l}_{im}(k)$, $u^{u}_{mi}(k)$, $v_{ij}(k)$, $s_{imjn}\,(k)$, $u_{id}(k)$ and $u_{di}(k)$for all $i, j \in N, m \; \in Q_i$, $n \in Q_j$, $s \; \in \mathrm{S}$, $d \in VD_i$, $k \in \; [0, Tp - 1]$. The optimization problem is solved at each timestep k by the operator. The aim is to minimize an objective function Eq (29)

$$\min \sum_{k=0}^{Tp} \Bigg(\sum_{i \in N} \Bigg(M^{c}_{i} x^{c}_{i}(k) + \; M^{bc}_{im} \Bigg(\sum_{m \in Q_i} x^{t}_{im}(k) \Bigg) + M^{v}_{i} x^{v}_{i}(k) + M^{b}_{im} x^{b}_{im}(k) + \sum_{j \in T_i} M^{v}_{ij} v_{ij}(k) + \sum_{j \in B_i} M^{tb}_{ij} \Bigg(\sum_{m \in Q_i} \sum_{n \in Q_j} s_{imjn} \Bigg) + \sum_{v \in [1,nv]} M^{lv}_{i} \Bigg(\sum_{j \in T_i} (u^{v}_{ji}\big(k - \tau_{ji}\big) + u^{v}_{ij}(k)) - 2 z^{v}_{i}(k) \Bigg) + \Bigg) + \Bigg), \quad (29)$$

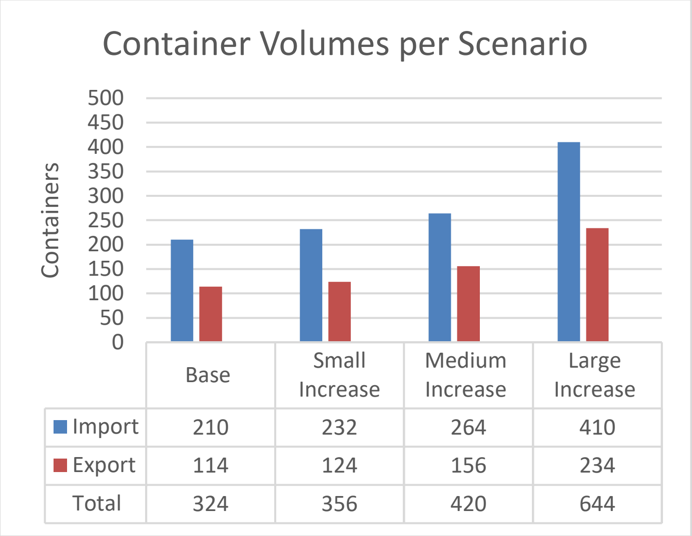
4. Case Study

In this Section, a case study is introduced. The case is based on the perspective of the Combi Terminal Twente (CTT) company which is involved in the container transport business in the Netherlands and internationally. The case is focused on the activity of the company within the Netherlands and specifically with Port of Rotterdam. The company provided a data set of orders for container transport for the period of 03.01.2019 to 07.04.2019. From the order list is derived that the CTT company is operating with 14 terminals within the territory of the Netherlands. Three terminals are owned by CTT located at Rotterdam, Hengelo, and Almelo. Eleven terminals located at Port of Rotterdam (Maasvlakte, Waalhaven and Eemshaven) are operating with CTT. Table 2 in the Appendix presents characteristics of all terminals.

4.1. Simulation Scenarios

To evaluate the effects of applying flexible barge routing in a synchromodal transport network, four scenarios are proposed. The four scenarios which are going to be tested are derived from data provided by the company of CTT in addition to the container activity in the past 10 years at Port of Rotterdam. Each Scenario has unique demand profile with certain volumes of containers presented on Figure 2.

Demand profiles of the four scenarios share identical characteristics of the orders in terms of origin, destination, and due times. The uniqueness in each demand profile is arise from the volumes of containers in each order. Demand profiles are constructed by considering three Virtual Destination (VD) nodes. Containers are distributed between these VDs. Each VD node in the system is a representation of a geographical group of terminals. Two groups represent the terminals at the area of Port of Rotterdam. Group 1 represent container terminals at Maasvlakte and Group 2 at Waalhaven. Group 3 is a representation of the CTT terminal at Hengelo and Almelo. A demand profile is constructed by counting the transport orders which must be routed between terminals of two separate groups. Thus, orders for container transport between terminals within the Maasvlakte area or Waalhaven area are not counted. The constructed demand profile is unbalanced in terms of export and import orders. Almost twice more containers are directed to deep-sea terminals compared to inland terminals. The profiles used in the four scenarios are presented on Figure 3 in the Appendix.



	Base	Small Increase	Medium Increase	Large Increase
🟦 Import	210	232	264	410
🟥 Export	114	124	156	234
Total	324	356	420	644

Figure2: Container volumes in each scenario

With the four scenarios, the effect of greater container volumes on the system performance can be analyzed. It is expected that the operational strategy with scheduled services is going to struggle with satisfying the demand on time. As barge capacity cannot be relocated it is also expected that more extensive use of trucks is going to be observed. This will lead to lower utilization of terminal truck parking but also to higher realized costs for operating the system. Moreover, a container delay is going to reflect on the delay of other containers which is going to increase the number of containers being stacked at terminals. This is going to result in higher utilization levels of stacking areas in different nodes of the network.

The FBR strategy with flexible barge services is expected to perform better than the Benchmark strategy in a way to satisfy more container orders on time. As the control agent can send the barge capacity to any point of the network, more available capacity can be relocated to a node where it is going to be needed. The utilization level of stacking areas is expected also to grow as the available transport capacity is limited and containers need to wait to be picked up. It is interesting to observe the share of empty and full truck trips when the demand is bigger and the utilization level of terminal quays for barges. Barges are expected to spend more time at terminals to load and unload larger batches of containers.

4.2. Strategy Configuration

In this section, configurations of parameters, network layouts and MPC parameters for the Benchmark and FBR strategies are presented. The configurations for the two strategies have several similar components. For instance, the cost and capacity parameters have identical values. The purpose of this is to highlight the impact of flexible barge routing in the output of the simulation runs. Moreover, parameter values of the MPC planning approach are also identical for the two strategies. A sequence of numerical experiments is executed to define suitable value for the crucial Tp (prediction horizon length) parameter. The experiments are performed in MATLAB, using Yalmip and Gurobi.

4.2.1. Scenario Parameters

The selection of costs and capacity parameters has significant impact on the choices made by the system operator. The proposed costs are based on several assumptions. The costs to berth and handle a barge at nodes representing CTT terminals is lower than at the other terminals. It is not cheaper to park a truck or store a container at CTT terminals due to the smaller available space. It is assumed that there are two nodes in the network, one for each group of terminals, which represent multimodal hubs with greater stacking space. These nodes offer lower costs for storage, parking, and handling services. The costs are formulated in a way which encourages the movement of containers and trucks. Stacking and parking costs are relatively high compared to transport costs except at the hub nodes where costs are lower. The cost for unsatisfied demand is assumed to appropriate to be nearly 10 times higher than the most expensive container stacking area. This price is not deriver empirically and can be a topic for a further research in the synchromodal literature. All costs are presented on Table 1.

The construction of the capacity parameter values is also based on real-life assumptions. The nodes which represent Maasvlakte terminals have significantly higher storage and parking capacities. Furthermore, the crane speed capacity there is also higher compared to other terminals. For simplicity, it is assumed that only one barge can be berthed at a terminal, but this can be easily extended by adding additional quay nodes to the network. All capacity parameters are presented on Table 2.

4.2.2. Network Layout

The network of long-range trucks is illustrated with solid gray lines. The second network layout for the FBR strategy introduces an additional graph with four fully connected additional nodes. The number of VD nodes and terminals remains the same. The layout is presented on Figure 5. The network layout is extended by a fully connected graph with four additional nodes which represent terminal quays called “barge nodes”. Each barge node is adjacent to one “terminal node” and connected via a black dotted link. There is no travel time applied on these black dotted links, but there is a capacity limitation which represents the gantry crane speed. It is assumed that each of the new nodes can accommodate one barge. The network of solid green lines is used by the barges.

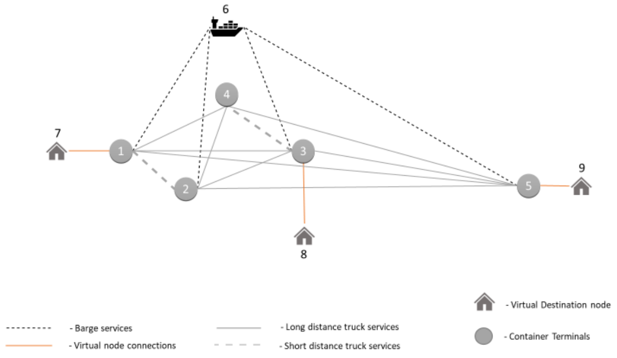


Figure 4: CTT Network with scheduled barge service (Benchmark Strategy)

The distances between the nodes in the two layouts are measured in travel times presented in timesteps. The configuration of the travel times is the same for the two strategies. For simplicity in the strategy, road congestions and potential delays are not considered in travel times. Table 3 and Table 4 present the travel times of trucks and barges. For simplicity in the strategies, the barge travel time does not consider congestions on waterways, delays on locks and bridges and restricted approaches to waterways. When the system operator decides to route a barge, a prior notice to the terminal operator is not required. However, operational time for entering or leaving a terminal is considered and equals 1 timestep. This time is assumed to be sufficient for maneuvering operations.

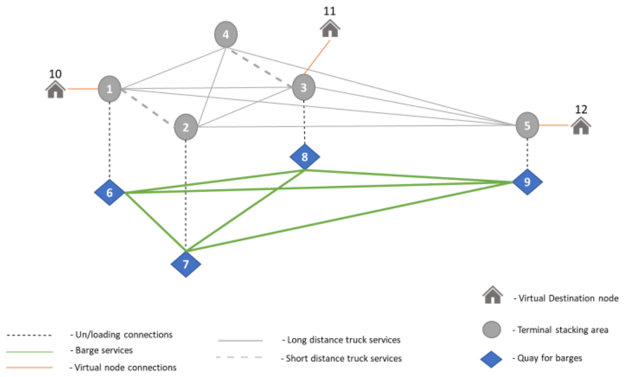


Figure 5: CTT network with flexible barge services (FBR Strategy)

1.1.1. MPC Parameters

. The initial container state and the initial state of arriving container and transport vehicles is zero in all scenarios: $x_i^c(t=0)=0_{nc}$, $x_{im}^t(t=0)=0_{nc}$, $\mathrm{u}_{\mathrm{i}}^{\mathrm{hv}}(t=0)=0_{nc}$, $\mathrm{u}_{\mathrm{im}}^{\mathrm{hs}}(t=0)=0_{nc}$, $v_{\mathrm{i}}^{\mathrm{h}}(t=0)=0_{nv}$, $s_{im}^h(t=0)=0_{ns}$, $\forall_i \in N$.

One of the parameters of the MPC planning approach: the prediction horizon length is tuned by the means of numerical experiments. The length of the prediction horizon (Tp) allows the MPC planner to capture different events and consider them. The longer the Tp is, the better the predictions of the system planer are expected to be. Implementing longer prediction horizon has its consequences in increasing the computational time needed for finding an optimal solution. A trade-off between time spent in computation and system performance needs to be made. To define the optimal length of the Tp, eight numerical experiments are made using the Base Scenario and varying the size of the Tp. One assumption is made prior to the experiments that the Tp must have a minimum length of such a size which can capture the departure and arrival of trucks and barges. Thus, the MPC planner always has a perception about the transport modes which decides to route. The maximum travel time in timesteps between the most distant nodes in the network is 13, so the first experiment is done with Tp = 15 which is 15% higher than 13. It is considered that 36 steps are a suitable period for the further numerical experiments. Figure 6 presents a comparison of system performance with the different values for Tp.

Table 1: Cost Parameters

Cost Parameters	
$\boldsymbol{M_1^c = 2 * 1nc}$	$M_1^v = 2 * \boldsymbol{1nv}$
$\boldsymbol{M_2^c = 1.5 * 1nc}$	$M_2^v = 1.5 * \boldsymbol{1nv}$
$\boldsymbol{M_3^c = 4 * 1nc}$	$M_3^v = 3 * \boldsymbol{1nv}$
$\boldsymbol{M_4^c = 3 * 1nc}$	$M_4^v = 1.5 * \boldsymbol{1nv}$
$\boldsymbol{M_5^c = 2.5 * 1nc}$	$M_5^v = 2 * \boldsymbol{1nv}$,
$\boldsymbol{M_6^b = 3 * 1nc}$	$M_8^b = 1 * \boldsymbol{1nc}$
$\boldsymbol{M_7^b = 2 * 1nc}$	$M_9^b = 1 * \boldsymbol{1nc}$
$\boldsymbol{M_{ij}^{tv} = \tau_{ij} * 4.5 * 1nc,}$ $\forall \boldsymbol{i,j \in [1,5], i \neq j}$	$M_{ii}^{tv} = \tau_{ii} * 9 * \boldsymbol{1nc}, \forall i \in [1,5]$
$\boldsymbol{M_{ij}^{tb} = (\omega_{im} + \varphi_{imjn} + \omega_{jn}) * 5.5 * 1nc,}$ $\forall \boldsymbol{i,j \in [1,2,3,5],}$ $\forall \boldsymbol{m,n \in [6,7,8,9]}$	$M_1^{ls} = 2 * 1\boldsymbol{nc}$
$\boldsymbol{M_i^{lv} = 3 * 1nc}, \forall \boldsymbol{i \in [1,3,5]}$	$M_2^{ls} = 1.5 * 1\boldsymbol{nc}$
$\boldsymbol{M_i^{lv} = 2 * 1nc,} \quad \forall \boldsymbol{i \in [2,4]}$	$M_i^{ls} = 1 * 1\boldsymbol{nc}, \quad \forall i \in [3,5]$
$\boldsymbol{M_6^{bc} = 0.7}$	$M_7^{bc} = 0.6$
$\boldsymbol{M_i^{bc} = 0.5,} \quad \forall \boldsymbol{i \in [8,9]}$	$M_i^d = 30, \ \forall i \in [10,11,12]$

Table 2: Capacity parameters

Capacity Parameters	
$\boldsymbol{c_1^c = 130}$	$c_1^v = [15\ 5]^T$
$\boldsymbol{c_2^c = 530}$	$c_2^v = [15\ 25]^T$
$\boldsymbol{c_3^c = 30}$	$c_3^v = [15\ 5]^T$
$\boldsymbol{c_4^c = 120}$	$c_4^v = [15\ 20]^T$
$\boldsymbol{c_5^c = 50}$	$c_5^v = [0\ 10]^T$
$\boldsymbol{c_{im}^b = 1}, \forall \mathbf{i} \in \boldsymbol{[1,2,3,5]}, \forall \mathbf{m} \in \boldsymbol{[6,7,8,9]}$	$Cap = 20$
$\boldsymbol{c_i^t = 5}, \forall \mathbf{i} \in \boldsymbol{[1,2,4,5]}$	$c_i^s = 8, \forall \mathrm{i} \in [1,2]$
$\boldsymbol{c_3^t = 3}$	$c_3^s = 5$
$\boldsymbol{x_i^v(0) = [\,0\ 0]^T} \ \forall \mathbf{i} \in \boldsymbol{[1,3]}$	$c_5^s = 6$
$\boldsymbol{x_2^v(0) = [\,15\ 20]^T}$	$x_4^v(0) = [\,15\ 16]^T$
$\boldsymbol{x_5^v(0) = [\,0\ 4]^T}$	

Prior to the main simulation experiments with both strategies and the comparison of their results a schedule for the barges must be determined. For this purpose, an experiment with the FBR formulation is performed where a barge can ply between any nodes with barge connection. In the experiment the schedule is defined by solving an optimization problem with the demand profile extracted from the CTT data and presented in the Base Scenario. The problem is solved without the MPC approach with the costs and capacity parameters presented in Table 1 and Table 2. The Base Scenario is applied with the FBR strategy. The solution in obtained by a simulation experiment performed in MATLAB with Yalmip and Gurobi. The absolute value of the objective function is not essential in this experiment but the total amount of unsatisfied demand. In the found solution the share of unsatisfied demand is 11% which is 35 containers from the total 324. Substantial share of the unsatisfied demand is import containers heading to node 9 by a barge.

5. Results

In this section the results from the numerical experiments are presented by showing different KPIs achieved with the two operational strategies at the four different scenarios presented in Section 4.2. Simulation experiments are performed in MATLAB by using Yalmip and Gurobi.

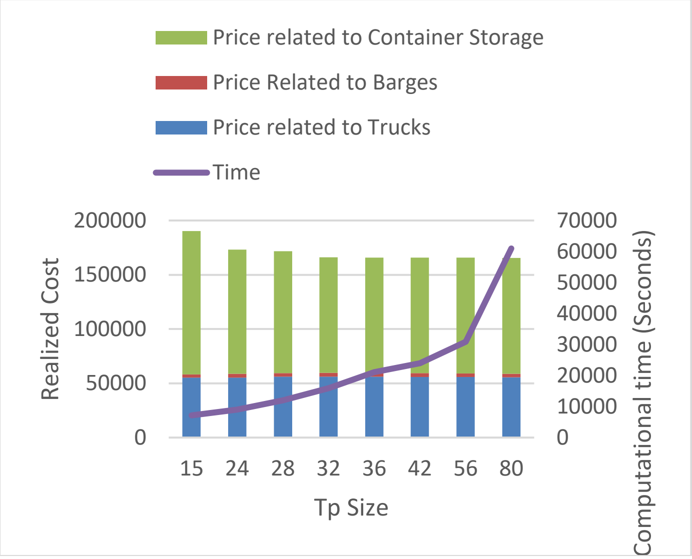


Figure 6: Comparison of realized costs and computational time in seconds.

5.1. *Results Overview*

In Table 5 an overview of the results is presented. The table includes the overall amount of transported containers, computational time, realized costs, unsatisfied demand, and modal share. An additional column presents the difference between the results of the Benchmark and the FBR strategies in percentages. When the Benchmark has realized higher value of a KPI than the proposed strategy, then the difference is presented with a negative value.

Improvement in realized cost can be observed when barges are not routed on a fixed schedule. The differences in costs increase with the grow of container orders in the system. The highest reduction is observed in the Large Increase scenario being 11.2%. This marginal difference in the realized cost comes from the high amount of unsatisfied demand when applying the Benchmark strategy. The results from the FBR strategy also indicates unsatisfied demand. Yet this is a result from the insufficient capacity at Node 3 to accept all containers in the beginning of the optimization and not subject to planners' decisions.

The realized cost per transported container is obtained by dividing the total realized cost by the amount of containers in the system. An overview is presented on Figure 7. In all scenarios applying the FBR strategy results in a better value of this KPI compared to when the Benchmark is applied. This becomes most noticeable in the Large Increase scenario when unsatisfied containers are observed. By applying the FBR strategy the operator can deliver all containers on time and benefit from economies of scale, while this is not observed with the Benchmark strategy. This only emphasizes the higher efficiency of the FBR to the Benchmark strategy in this KPI regardless of container volumes in the system.

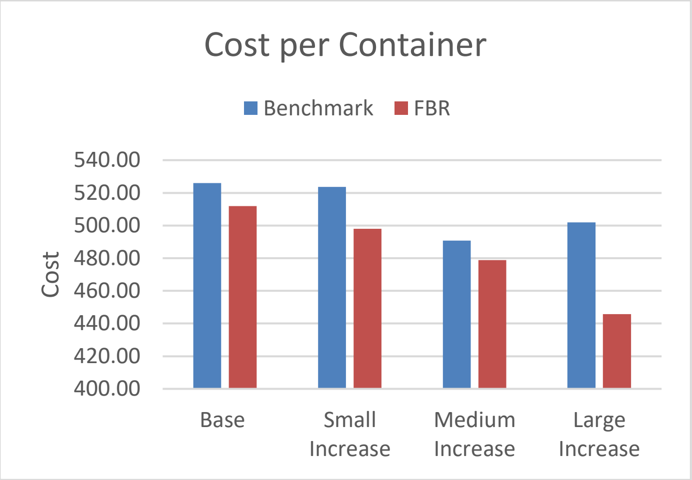


Figure 7: Cost per container realized in experiments.

An overview of the realized costs for each scenario is presented on Figure 8. The Base, Small Increase, Medium Increase and Large Increase scenarios are indicated on the figure respectively BS, SI, MI, and LI. The cost realized by barge routing and handling operations has the smallest share among all components. It is relatively stable with small rise in the Large Increase Scenario. The second cost which is observed only in the last scenario is the penalty for unsatisfied demand. This cost has the highest coefficient compared to the others and can strongly influence the final cost. Trucks are essential part of the system operation, and this is reflected on their share on the total final costs. Analogous to barge routing, truck routing costs are close in all scenarios with light increases in the last scenario runs. The cost for container storage has the highest share among other costs and steadily grows with the introduction of more containers in the scenarios. Apart from barge routing cost which is double with the Benchmark strategy than with the FBR truck routing costs are relatively similar. Therefore, if there is a relation between container storage cost and routing cost it should be between storage and truck routing. However, a clear relation between these two KPIs is hard to be concluded from this figure.

The number of truck trips which are realized with the two strategies does not vary considerably in all four scenarios. This can be explained with the possibility of the system operator to flexibly route trucks. In this way, available truck capacity can be allocated to the nodes where it is going to be needed in the future. Considering containers transported by barge, in the first three scenarios fewer containers are handled with the FBR compared to the Benchmark strategy. This tendency is changed in the Large Increase scenario, where the containers transported by barge in the FBR are nearly twice as much as in the Benchmark. Results indicates that with the FBR, barge capacity is used more extensively when high volume peaks occur in the system. This is illustrated on Figure 9. The modal share in scenarios is calculated by dividing the amount of moved containers by a certain transport mode to the overall number of container trips. For all scenarios, trucks have significantly greater modal share compared to barges. No decrease of truck usage is observed in all scenarios. Contrariwise, in the Large Increase scenario, the modal share of trucks reaches just under 90% with both scenarios. Yet, it is crucial to mention the tendency with containers transported by a barge. In all scenarios, except for the Large Increase, more containers are transported by a scheduled barge than with e a flexible one.

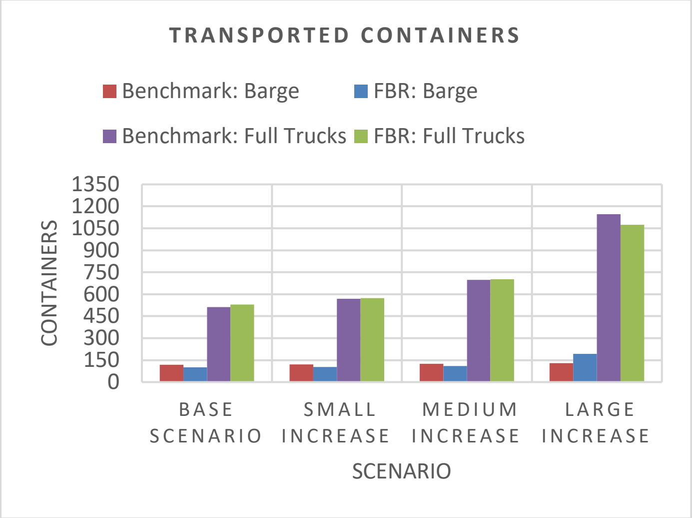


Figure 9: Number of containers transported by transport modes.

1.1. *Large Increase Scenario*

The Large Increase Scenario is the scenario with the highest number of containers which needs to be transported in the system. The containers in this scenario are 644. This is the only scenario containers are not satisfied on time. This is observed in the results of both strategies. Yet, with the FBR strategy the delayed containers are considerably less than in the Benchmark. Delayed containers are counted per timestep.

Figure 10 presents the number of unsatisfied containers in both sstrategies during the optimization process. Delayed containers in the FBR are presented in red dashed line, while in the Benchmark are illustrated with solid blue line. In the beginning of the optimization run, with both strategies there are 18 containers which cannot enter the system due to lack of available storage capacity at Node 3. Unsatisfied demand is observed again at timestep 407 when using the Benchmark strategy. Subsequently, the unsatisfied demands dramatically escalate to 52 containers at timestep 420 followed by peaks of 46 and 34 at timestep 433 and 444. At the end of the optimization, the system has 15 containers which are yet not delivered at Node 5. Contrary to the Benchmark, with the FBR the operator successfully transports all containers on time and avoid the penalties for delays. The vast amount of unsatisfied container orders with the Benchmark results in high realized costs due to the penalties for delays incorporated in the objective function.

Identically to the results from the other scenarios, the more containers are present in the system, the more trucks are routed. The containers transferred by trucks are doubled compared to the Base Scenario. Curiously, in this scenario the full truck trips in the FBR are less than in the Benchmark strategy. This result is not observed in the other three scenarios. Moreover, in this scenario for the first time the number of containers handled by barge with the FBR is higher than with the Benchmark. Either applying the FBR or the Benchmark strategy, Node 2 remains the place where the most containers are stored. Figure 11 presents an overview. When applying the FBR strategy, storage capacity is more effectively used. With the FBR, the highest storage level is reached at timestep 243 when 96% of the available capacity is utilized with 513 containers. From this point the storage levels gently decrease until the end of the optimization run. On the contrary, with the Benchmark the absolute maximum of 88% is reached later in the optimization at timestep 271 when 468 containers are stored. In the final stage of the optimization run, containers are released from Node 2 towards their destinations. With the Benchmark strategy this process commences earlier and takes longer compared to the FBR strategy. This can be observed by the slopes of both graphs on the figure. While the slope of the Benchmark is lean with a set-out at timestep 357, the slope of the FBR is steeper with a set-out at timestep 376.

In this scenario Node 2 remains the highest utilized node in the system in terms of parking. Figure 12 illustrates the number of parked long-range trucks at Node 2 for the entire simulation run. Looking into the final stage of the optimization run when is the highest demand for containers more trucks are routed with the Benchmark strategy than with the FBR. It is crucial that with the FBR, the available truck capacity at Node 2 is much greater. The parking is completely full for 10 timesteps offering capacity for container transport. This is not observed with the Benchmark strategy where the maximum is 23 trucks for only 1 timestep. Available truck capacity reaches peaks to 20 and 10 trucks again but for only 1 timestep. Therefore, with the FBR trucks are not used as urgent available capacity as often as with the Benchmark.

Figure 10: Unsatisfied Demand in the Large Increase Scenario

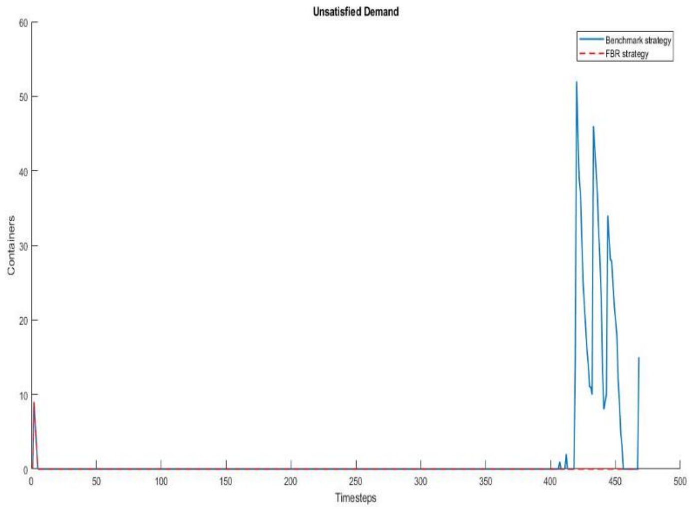
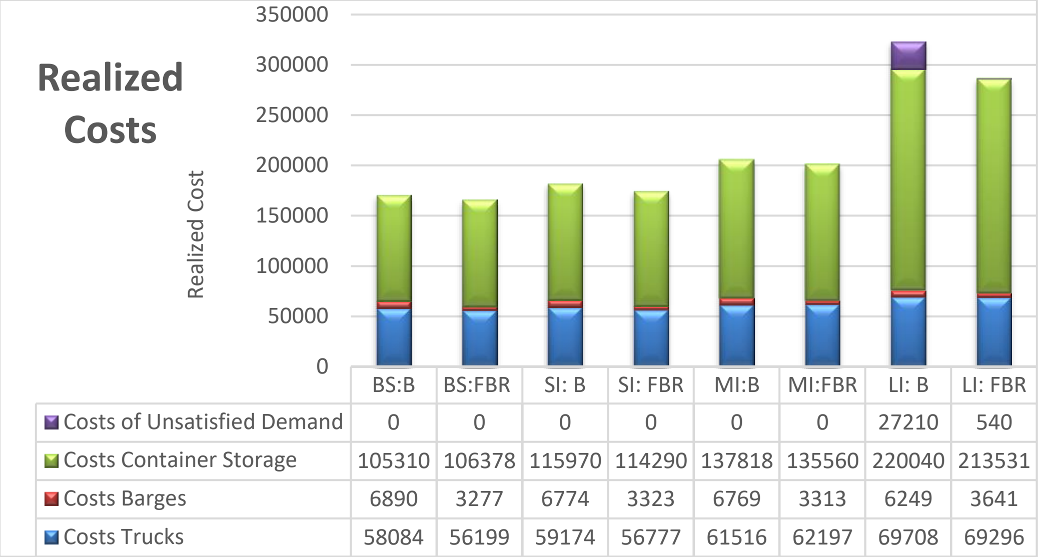


Figure 8*:* Realized Costs during simulation runs.



	BS:B	BS:FBR	SI: B	SI: FBR	MI:B	MI:FBR	LI: B	LI: FBR
🟪 Costs of Unsatisfied Demand	0	0	0	0	0	0	27210	540
🟩 Costs Container Storage	105310	106378	115970	114290	137818	135560	220040	213531
🟥 Costs Barges	6890	3277	6774	3323	6769	3313	6249	3641
🟦 Costs Trucks	58084	56199	59174	56777	61516	62197	69708	69296

Table 5: Results from the simulation runs.

Scenario	Base			Small Increase			Medium Increase			Large Increase		
Strategy	Bench mark	*FBR*	*Diff.*	Bench mark	*FBR*	*Diff.*	Bench mark	*FBR*	*Diff.*	*Bench mark*	*FBR*	*Diff.*
Container Volumes	324	324		356	356		420	420		644	644	
Time	12790	16538	29.3%	12207	16236	33.01%	12720	16709	31.36%	12760	16078	26.00%
Unsatisfied demand	0	0		0	0		0	0		907	18	5039%
Realized Cost	170430	165850	-2.7%	186390	177270	-4.89%	206100	201070	-2.44%	323210	287010	-11.2%
Modal share Truck	81.11%	83.86%	-2.7%	82.46%	84.64%	-2.17%	84.73%	86.47%	-1.74%	89.81%	84.78%	5.03%
Modal share Barge	18.89%	16.14%	2.7%	17.54%	15.36%	2.17%	15.27%	13.53%	1.74%	10.19%	15.22%	-5.03%

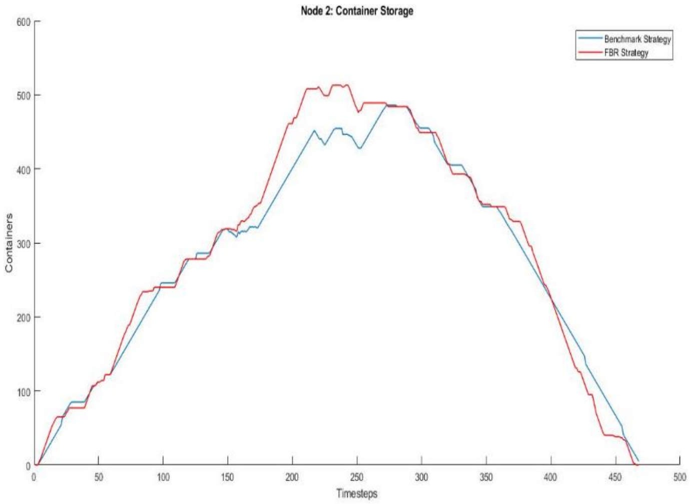


Figure 11: Node 2 Container Storage

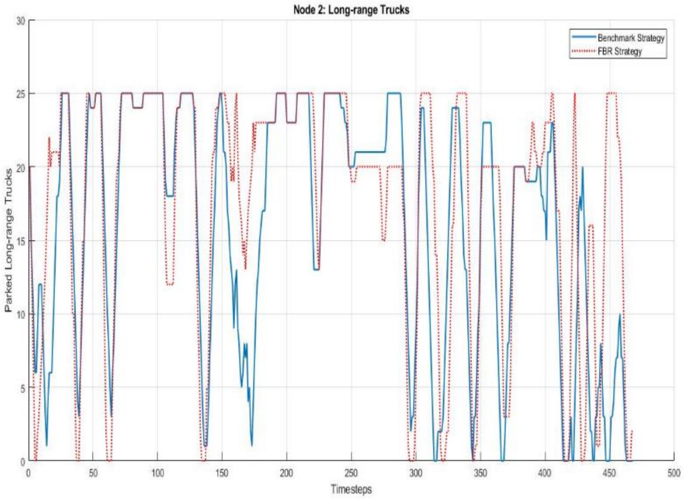


Figure 12: Long-Range Trucks parked at Node 2.

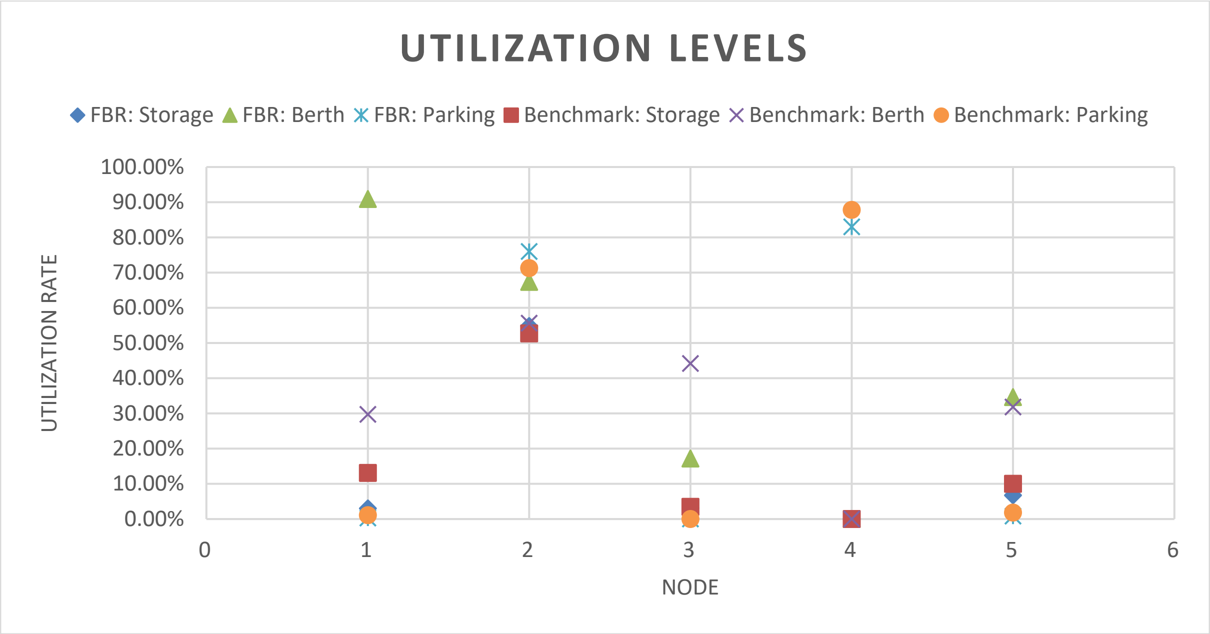


Figure 13: Utilization levels of system resources at all nodes

Barge operation is the distinct dissimilarity between the FBR and the Benchmark strategies. While barges in the Benchmark operates on a schedule, in the FBR the operator is free to route the barge independently between nodes. This capability of the operator in the FBR contributes for evident differences in achieved results in system performance. Considering terminal operations, three of the four barge terminals in the system shows higher utilization levels with the FBR compared to the Benchmark strategy. A 30% difference is noticed at Node 1 where the utilization is respectively 90.9% and 60.7%. At node 2 and 5, the difference is slightly more than 10% in favor of the FBR. The only exception is at Node 3, where the berth utilization level with the FBR is with 10% lower related to the Benchmark. Figure 13 presents different utilization levels of system resources in this Scenario.

The introduction of flexible barge does not only increase the berth utilization levels but also raise the number of visited nodes in the system by the barge. While the scheduled barge has 43 ports of call, in this scenario the flexible barge has 73 ports of call. Respectively, with the FBR strategy the barge spends more time at terminals increasing the utilization of barge handling capacity. Barge routing differs with the two strategies. With the FBR strategy shorter routes become the most attractive. The routes between nodes 2 and 3 and nodes 2 and 1 are frequently used by the system operator. Compared to the fixed schedule, the trips of the flexible barge between the most distinct nodes 2 and 5 drops with 40%.

The difference in routing comes along with distinct levels of capacity utilization for the barge. Figure 14 presents an overview of barge capacity with the two strategies. With the FBR strategy the barge is regularly fully loaded than with the Benchmark. This is expected as 193 containers are routed by flexible barge and just 130 by the scheduled barge. It is essential to mention that until timestep 350 the declines of flexible barge payload correspond with those of scheduled barge besides one occasion. However, the drops in flexible barge capacity are always more distinct. From timestep 350 until the end of the optimization in the Benchmark, barge capacity gradually declines. Howbeit, the flexible barge most of the time operates on full load using its capacity more efficiently. With the FBR, the system operator can reach higher utilization levels for the barge and benefit from economies of scale. This is reflected in the total amount of transported containers and realized barge operation cost.

Large Increase Scenario	Most Frequent Truck Destinations		Most Frequent Barge Destinations	
Strategy	*Benchmark*	*FBR*	*Benchmark*	*FBR*
Node 1	Node 2 (516)	Node 2 (495)	Node 2,5 (2,1)	Node 2 (4)
Node 2	Node 1,5 (516, 398)	Node 1,5 (495,390)	Node 5,3 (6,6)	Node 3,5 (6,5)
Node 3	Node 2,1 (107,29)	Node 2(117)	Node 5,2 (6,3)	Node 2,5 (6,5)
Node 4	Node 2,1 (15,9)	Node 2,5 (36,21)	N/A	N/A
Node 5	Node 2,4 (374,14)	Node 2,4 (370,55)	Node 2,3 (8,5)	Node 3,2 (6,5)

Table 6: Most frequent destinations per transport mode: Large Increase Scenario

With applying the FBR strategy, an interesting behavior of the system operator was noticed. During the optimization frequently occurs that the operator would route a barge to a certain node without executing any handling operations at the destination.
Occasions are observed when the barge even spends only one timestep at a terminal and then its routed to different node with the same payload. When applying the FBR strategy the costs for transporting containers by barge appears to be in some cases cheaper than storing the containers at a terminal. Therefore, the

logic of the operator is to use the barge capacity as a cheaper capacity buffer which is regularly on the move. Yet, this behavior does not comply with the accepted practices in the shipping industry. Berthing a container barge on a terminal without executing any handling operations is very uncommon.

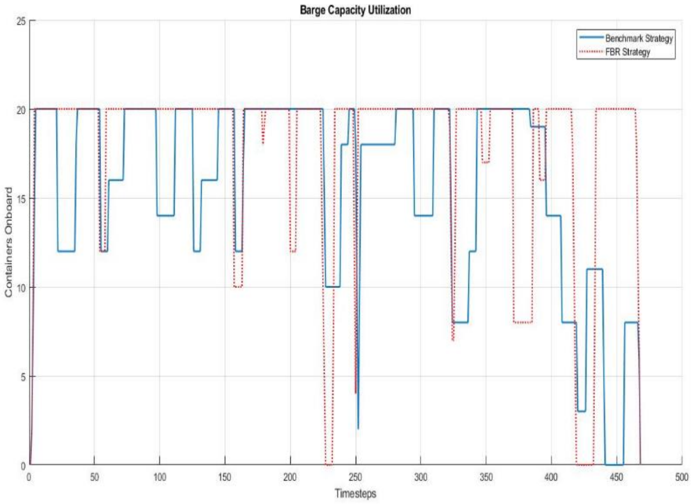


Figure 14: Comparison of Barge Capacity Utilization with both strategies

5.1.1. Revised Barge Schedule

The Large Increase Scenario is a long-term projection of the reality capturing this raise of container orders. Yet, for such an extended period it is unrealistic to assume that a transport system would not be adapted to the new conditions. From the previous section it can be concluded that the system operator is not able to transport considerable part of the container orders on time when applying the Benchmark strategy. This is might a consequence of an inadequate schedule for the actual container volumes. Therefore, the configuration of the Benchmark strategy should be adapted to this amount of container orders with a new barge schedule. The revised schedule is derived as described in Section 4.2.4. Table 7 in the Appendix introduce the new schedule.

Unexpectedly, the results of the simulation run with the adapted schedule do not differ significantly from the results with the old schedule. Despite the decreased amount of delayed containers in the system, their share is still considerable. On Figure 15 the dynamics of the unsatisfied demand with the old and the new schedule are presented. It is evident that the graphs have completely identical fluctuations, yet with different magnitudes. The graph of the adapted schedule has lower local maximums and minimums. Therefore, it is assumed that to a certain extend the operator improved the performance of the system when the barge schedule is adapted. However, the number of delayed containers is still tremendous compared to the results of the FBR strategy.

6. Conclusions

This paper focusses on improving the performance of a container transport system by showing the benefits of applying different barge routing strategy. The concept of free barge routing has been proposed and investigated for use in different scenarios.

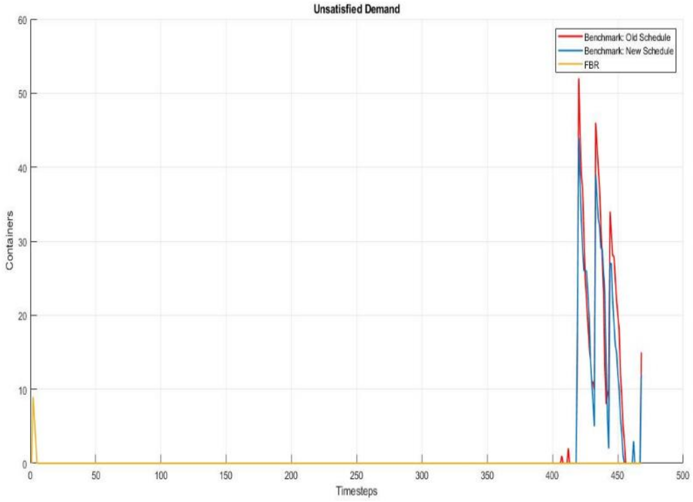


Figure 15: Unsatisfied demand of containers when the new adapted schedule is applied compared to the old schedule and the FBR strategy.

Generally, Synchromodality is built on the theory of sharing infrastructure and capacity. One of the most distinctive features of synchromodality is the agreement for mode-free booking. Other distinctive feature of synchromodality is the cooperation between actors which share not only infrastructure and services, but information as well. Based on frequent sharing of information the system operator can replan its decision in real-time to comply with system conditions and customer requirements.

A centralized MPC approach is applied with one controller which operates with the transport system. A single layer controller is head of operations in a synchromodal system where orders of containers must be transported. Dynamics in the system are expressed in a state-space vector. Each component of the vector describes a condition of a system element at certain point of the time. At each timestep the system planner optimizes an objective function considering the information stored in the state-space vector and predictions on future states. The planner defines a sequence of actions over a prediction horizon which will provide beneficial future performance of the system. Only the sequences of actions assigned to the first timestep of the prediction horizon are implemented. Subsequently, the information in the state-space vector is updated.

In this paper two operational strategy are tested in four different scenarios. The first strategy is proposed by Larsen (2020) where containers and trucks are routed simultaneously in a network with multiple origins and destinations. Barges are operated on a fixed schedule. This is the Benchmark strategy. The second strategy is a built-up on the Benchmark where barges are routed with trucks and containers simultaneously instead of operating on a schedule. This operational strategy is referred as Free Barge Routing (FBR). How flexible planning affects the pressure in the system created by increased volumes of container demand is evaluated by looking into the level of service quality, realized operational costs and capacity indicators of different system resources.

The private company of CTT has provided a list with container orders for transportation. A demand profile was created from the orders lists with 324 containers. Subsequently, three additional demand profiles were created with respectively 356, 420 and 644 container orders. This pattern of increasement of orders is driven by the observed upward trend in container throughput at Port of Rotterdam for the past two decades.

To evaluate the decisions of a system operator and the performance of the system, four scenarios were simulated with the two operational strategies. Overall, eight simulations were executed in MATLAB, with Yalmip and Gurobi. In all tested scenarios, the operator decides to transfer most of the containers to one node and store them there until their due time. Eventually, the high volumes of containers concentrated at one node created bottlenecks in the system. In a case when handling or storage capacity became insufficient, the application of the FBR strategy come out to be more efficient than the Benchmark strategy. By using the Benchmark strategy, the system operator cannot utilize barge capacity and orders are subsequently delayed resulting in lower service quality and higher operational costs. This is not observed with the proposed FBR strategy.

Expectedly, the implementation of the two strategies showed different sequence of actions from the system operator which respectively led to differences in the realized operational costs. Results from scenarios testing revealed an evident cut in cost per container when barges are routed simultaneously with trucks and containers. Scheduled barge routing turns out to generate double operational costs compared to flexible barge routing. Operating a barge on a flexible schedule may not only facilitate savings in operational costs, but also improve the quality of the services offered in a synchromodal transport system by significantly reducing the cases of delayed orders.

Overall, a successful strategy for operational decision-making in a synchromodal transport system must be able to capture the dynamics of such a system. This is achievable by not only taking dynamic decisions, but also by having the possibility to change them regularly. The balance between service quality and cost is recognized as crucial. The single layer MPC approach is suitable for a synchromodal transport system with a centralized operator. A strategy which allows the system operator to take flexible decisions in terms of barge routing proved as an efficient concept for both reducing the operational costs of the system and improving the quality of offered services. However, the beneficial implementation of his strategy is strongly dependent on several factors as 1) cargo volumes, 2) strategy configuration and 3) MPC design and parameters.

7. Discussion and future research

In this section, a reflection on the final conclusions is made. More insights into the results are obtained by going through the generated solutions. The deliverables and limitations of the proposed FBR strategy are discussed.

This paper provides useful insights about flexibility in synchromodal transport: 1) unscheduled barge routing is more cost beneficial when high volumes of cargo are routed, 2) MPC system planner can avoid capacity bottlenecks and reduce delayed containers when higher degree of decision freedom is allowed. This research shows how to improve the performance of a synchromodal transport system when flexibility is utilized to its full potential. Yet, the most useful insight of this thesis is the laid foundation for future research on the direction of analyzing the benefits of introducing more flexibility in operators' decisions in a synchromodal transport system.

A planning strategy is proposed which can adopt to changes in volumes of container orders and assign transport capacity for it. The strategy is flexible in terms of possibility to transship containers between transport modes and adapt the routes of transport modes. The benefits of applying this strategy could be visible in practice, especially in areas with high demand for containers. With the constant increase of container throughput, the areas of Port of Rotterdam and the Dutch hinterland are considered as suitable.

The research in this paper has its limitations. The made assumptions in building the FBR strategy oversimplify some of the aspects of barge routing. Firstly, the system operator can adjust its decisions in every timestep of the optimization run. This might not be favored from terminal operators' point of view who need some level of consistency in decisions to organize terminal operations. Secondly, it is observed that the system operator routes the barges to different terminals without executing any handling operations. This might not be appealing to terminal operators as well who would like to utilize their quay berths instead of just take up free space. Moreover, each aspect of the FBR strategy is deterministic without the possibility to adopt uncertainties in travel times which is frequent in passing through locks or congested highways. The FBR strategy does not consider distinctive characteristics of containers like size or type and does not account for the physical constraints that shifting a container can cause.

The values for cost and capacity parameters used in this thesis are tailored to the values used in the work of Larsen (2020). Many assumptions were made for the configuration of the cost and capacity values. Only the MPC prediction horizon length is determined empirically, but it is still strongly dependent on previously assumed values for cost and capacity parameters. This is considered as a limitation of this research, cause the accuracy of the numerical experiments is affected from the accuracy of the input.

One of the important values of this thesis is providing directions for future research. It is in future research relevant to investigate how flexible inland barges can be routed not only with trucks and container but also with other transport modes. Trains also can stimulate economies of scale and the potential for combining them with flexible barges can be analyzed in future. A direction for future research is investigating the effects of considering diverse types and sizes of containers in the operational strategy. Thereof, the problem of empty container allocation can be analysed so potential benefits for different actors in the system can be recognized. A possible direction of the development of the FBR strategy is testing the level of freedom in barge routing. It is from both theoretical and practical relevance to investigate how restricted flexibility in barge routing, affects planners' decisions and system performance. Operational hours of terminals can also be introduced into the strategy to further prepare it for real world implementation.

For further research, the single-agent MPC approach can be adapted to a structure where many agents discuss possible actions and share information and profit. The network of agents can be either distributed or hierarchical, so different strategies for control can be tested.

Appendix A: Notations in the paper

Table1: Notations used in this paper.

Sets	**Description**
N	Set of nodes in the network
VD	Set of Virtual demand nodes
$\mathrm{T_i}$, $\mathrm{i} \in \mathrm{N}, \mathrm{T_i} \in \mathrm{N}$	Set of nodes with a truck connection to node *i*
B_i, $\mathrm{i} \in \mathrm{N}$	Set of nodes with barge connection
Q_i, $\mathrm{i} \in \mathrm{N}$	Set of quay nodes connected to node *i* where barges can be accommodated
V	Set of truck types
S	Set of barge types

Costs	**Description**	**Units**
M_i^c	Cost for storing a container at node *i*.	_$*Timestep_
M_i^v	Cost for parking a truck at node *i*.	_$*Timestep_
M_{im}^{b}	Cost for berthing a barge at a quay m of node *i*.	_$*Timestep_
M_{im}^{bc}	Cost of booking a container spot on a barge at quay *m* at node *i*.	_$*Timestep_
M_{ij}^{tv} $i \in N, j \in \mathrm{T_i}$	Cost of a truck trip from node *i* to node *j*	_$*Travel Time ($*Timesteps)_
M_{ij}^{tb} $i \in N, j \in B_\mathrm{i}$	Cost of a barge journey between port *i* and port *j*	_$*Travel Time ($*Timesteps)_
M_i^{lv}	Operational cost for moving a container from a stack to a truck	_$_
M_i^{ls}	Operational cost for moving a container from a stack to a barge	_$_
M_i^d	Cost of unsatisfied demand at Virtual Demand node *i*	_$*Timestep_

Parameters	**Description**	**Units**
nc	Number of container types according to the possible destination	_Container Units_
nv	Types of trucks operating in the system	_Port Truck_ _Long-distance Trucks_
$ns \in Z$	Types of barges operating in the system	
Cap	Capacities of barges operating in the network	_Container Units_
τ_{ij}, $i \in \mathrm{N}, j \in \mathrm{T_i}$	Truck Travel time between node *i* and node *j*	_Timesteps_
φ_{imjn} , $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j$	Barge Travel Time between node *i* and node *j*	_Timesteps_
ω_{im} $i \in \mathrm{N}, m \in Q_i$	Operational Barge Time need by a barge to leave or enter quay m of port *i*	_Timesteps_
$d_i \in \mathrm{R}_{\geq 0}^{nc}$, $i \in VD$	Amount of incoming and outgoing demand which can be satisfied during at Virtual destination node *i* during timestep (*k*)	_Container Units_
$K_{max} = \{1,2, \ldots k\_max\}$	Horizon length	_Timesteps_
Tp $Tp \geq 0$	Prediction Horizon length	_Timesteps_

Capacity Parameters	**Description**	**Units**
$\boldsymbol{c_i^c} \in \mathbf{R}^{\mathbf{nc}}_{\geq 0}$	Maximum number of containers of each kind which can be stored node *i*	*Container Units*
$\boldsymbol{c_i^v} \in \mathbf{R}^{\mathbf{nv}}_{\geq 0}$	Maximum number of trucks of each kind which can be parked at node *i*	*Trucks per type*
$\boldsymbol{c_{im}^b} \in \mathbf{R}^{\mathbf{ns}}_{\geq 0}$	Maximum number of barges of each kind which can be berthed at quay *m* at node *i*	*Barges*
$\boldsymbol{c_i^t}$	Crane capacity operating with containers and trucks.	*Container Units/Timestep*
$\boldsymbol{c_i^s}$	Crane capacity operating with containers and barges.	*Container Units/Timestep*
Node States	**Description**	**Units**
$x_i^c(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N$	Number of containers of each type parked at a node *i* at timestep *k*	*Container Units*
$x_i^d \in \mathrm{R}^{\mathrm{nc}}_{\geq 0}$ $i \in \mathrm{VD}$	Number of unsatisfied demands at virtual destination node *i* which is penalized	*Container Units*
$x_i^v(k) \in \mathrm{R}^{nv}_{\geq 0}$ $i \in N$	Number of trucks of each type parked at a node *i* at timestep *k*	*Trucks per type*
$x_{im}^b(k) \in \mathrm{R}^{ns}_{\geq 0}$ $i \in \mathrm{N}, \quad m \in Q_i$	Number of barges of each type berthed at quay *m* of node *i* at timestep *k*	*Barges per type*
$x_{im}^t(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in \mathrm{N}, \quad m \in Q_{\mathrm{i}}$	Number of containers which are present on a barge berthed at quay *m* at node *i* at timestep *k*	*Container Units*
$\mathrm{u}_{\mathrm{i}}^{\mathrm{hv}}(k)$ $i \in N$	Number of containers approaching node *i* by trucks of all types at timestep *k*	*Container Units*
$\mathrm{u}_{\mathrm{im}}^{\mathrm{hs}}(k)$ $i \in N$	Number of containers approaching quay *m* of node *i* by barges of all types at timestep *k*	*Container Units*
$v_{\mathrm{i}}^{\mathrm{h}}(k)$ $i \in N$	Number of trucks approaching node *i* at timestep *k*	*Trucks per type*
$s_{im}^h(k)$ $i \in N$	Number of barges approaching quay *m* of node *i* at timestep *k*	*Barges per type*
Actions Variables	**Description**	**Units**
$u_{ij}^v \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad j \in T_i, \quad v \in M$	Number of containers send from node *i* to node *j* by truck type *m*	*Container Units*
$u_{imjn}^s \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j, \quad s \in \mathrm{S}$	Number of containers send from quay *m* of node *I* to quay *n* of node *j* by a barge of type *s*	*Container Units*
$v_{ij} \in \mathrm{R}^{nv}_{\geq 0}$ $i \in \mathrm{N}, \quad \mathrm{j} \in \mathrm{T_i}$	Number of trucks of each type send from node *I* to node *j*	*Trucks per type*
$s_{imjn} \in \{0; 1\}^{ns}_{\geq 0}$ $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j$	Binary variable indicating if a barge of each type is sent from the quay *m* of node *i* to the quay *n* node *j*	
$u_{im}^l(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad m \in Q_i$	Number of containers being loaded on a barge berthed at quay *m* of node *I* from the stack at node *i*	*Container Units*
$\mathrm{u}_{\mathrm{mi}}^{\mathrm{u}}(k) \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad j \in Q_i$	Number of containers being unloaded from a barge berthed at quay *m* of node *i* to the stack of node *i*	*Container Units*
$\mathrm{u}_{\mathrm{i}}^{\mathrm{d}} \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad d \in VD$	Containers used to satisfy the incoming demand form network node *i* to virtual destination node *d* at timestep *k*	*Container Units*
$\mathrm{u}_d^i \in \mathrm{R}^{nc}_{\geq 0}$ $i \in N, \quad d \in VD_i$	Containers used to satisfy the outgoing demand form network node i to virtual destination node d at timestep k	*Container Units*
$z_i^v \in \mathrm{R}^{nc}_{\geq 0},$ $i \in N, \quad v \in V$	The number of containers which leaves from node *i* to node *j* at timestep *k* on the same truck which they arrived with and have not been unloaded from	*Container Units*

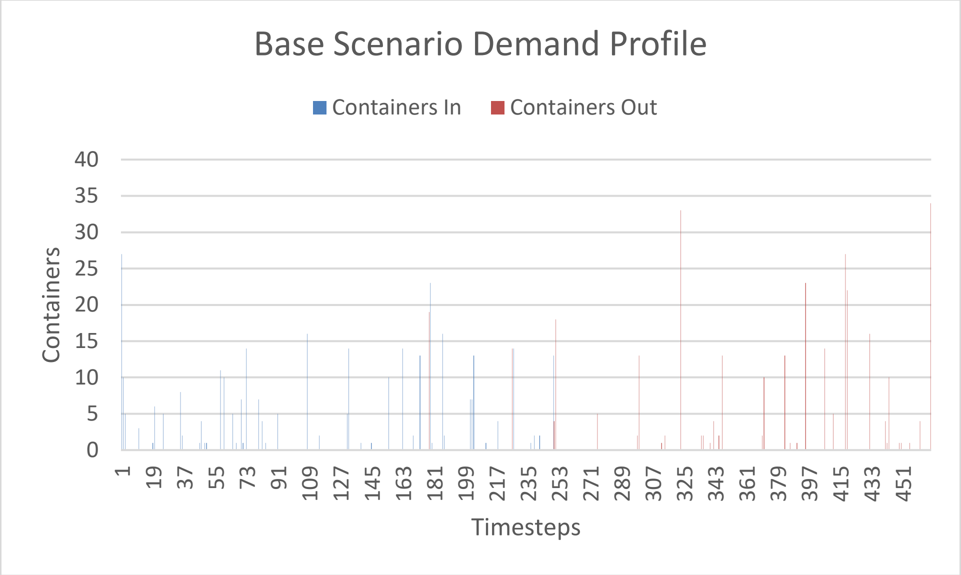
Appendix B: Terminal Characteristics

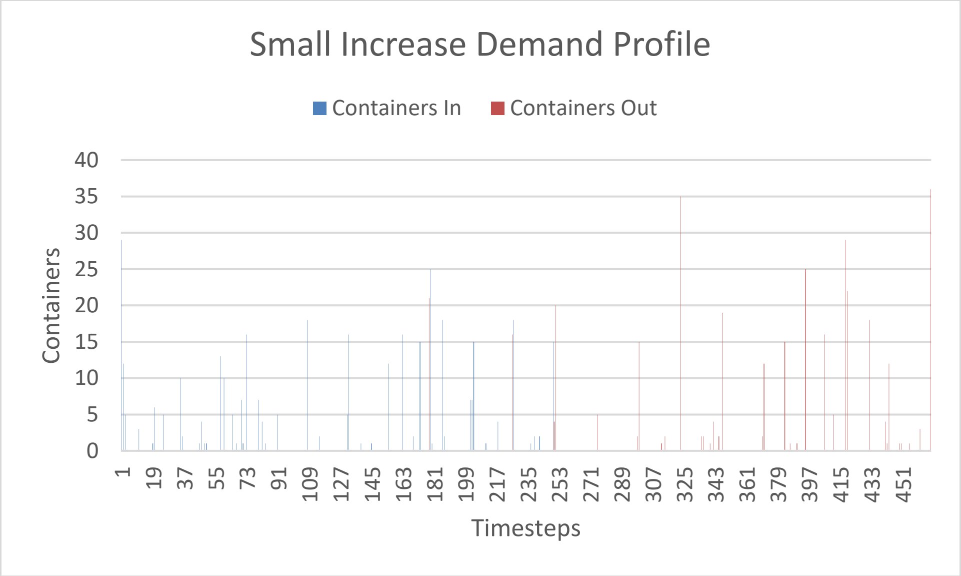
Table 2: Characteristics of container terminals at Port of Rotterdam and CTT terminal at Hengelo (*Container Port of Europe*, 2020)

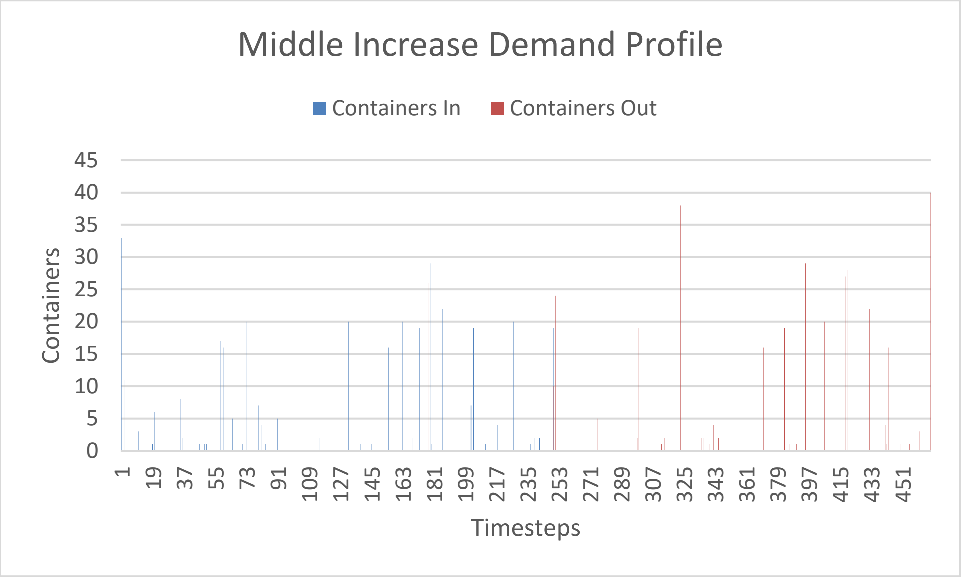
Terminals	Capacity (TEU)	Quay length (m)	Type of vessels (Ds/B)	Plot Area (ha)
Maasvlakte				
APM	3350000	1600	DS	100
APM2	2700000	1500/500	DS/B	86
Rotterdam World Gateway	2350000	1700/550	DS/B	108
ECT Euromax	*3000000*	1500	DS	84
ECT Delta	*5000000*	3600	DS	272
ECT Delta Barge	*100000*	890	B	7.5
Delta Container Services	*50000*	260	B	2.5
Rotterdam Container Terminal	500000	400	B	17
Waalhaven and Eemshaven				
CTTROT	240000	150	B	8
Matrans Rotterdam Terminal	300000	1180	DS/B	34
Rotterdam Short Sea Terminals	1400000	1800	DS/B	46
Uniport Multipurpose Terminals	1200000	2400	DS/B	54
Barge Center Waalhaven	200000	225	B	6.4
Hengelo				
CTT Hengelo	***400000***	400	B	12.5

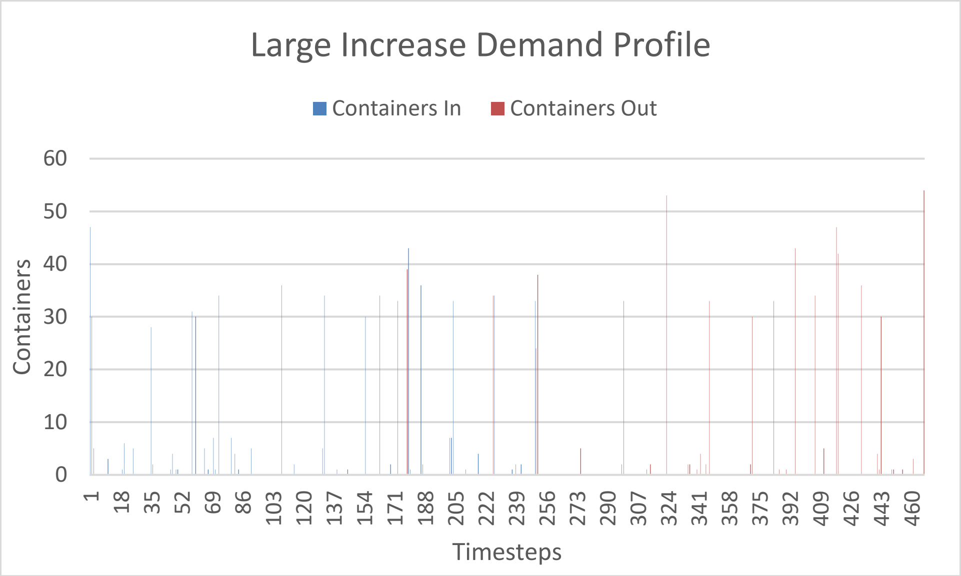
Appendix C: Demand Profiles

Figure 3: Demand profiles of all Scenarios






Middle Increase Demand Profile
🟦 Containers In
🟥 Containers Out
Containers
45
40
35
30
25
20
15
10
5
0
1
19
37
55
73
91
109
127
145
163
181
199
217
235
253
271
289
307
325
343
361
379
397
415
433
451
Timesteps


Large Increase Demand Profile
🟦 Containers In
🟥 Containers Out
Containers
60
50
40
30
20
10
0
1
18
35
52
69
86
103
120
137
154
171
188
205
222
239
256
273
290
307
324
341
358
375
392
409
426
443
460
Timesteps

Appendix D: Travel Times

		End Node				
		1	2	3	4	5
Starting Node	1	1	1	2	2	4
	2	1	1	2	2	4
	3	2	2	1	1	3
	4	2	2	1	1	3
	5	4	4	3	3	1

Table 3: Truck Travel Times

		End Node				
		1	2	3	4	5
Starting node	1	0	2	3	0	11
	2	2	0	5	0	11
	3	3	3	0	0	9
	4	0	0	0	0	0
	5	11	11	9	0	0

Table 4: Barge Travel Times

Appendix E: Barge Schedules

Table 5: Optimal Barge Schedule applied in the Benchmark strategy configuration.

Node	**Handling Activity**	**Timesteps**								
1	Unloading	91	232	249	250	251				
	Loading	252	253							
2	Unloading	21	54	86	96	97	125	157		
		218	219	237	308	341	425	454		
	Loading	218	219	238	280	309	342	426	455	
3	Unloading	225	226	243	335	347	371	395	419	
	Loading	48	60	131	163	164	192	244	336	
		348	372	396						
5	Unloading	73	143	176	177	178	179	180	204	
		266	294	322	323	359	383	407	439	
		440	466	467	468					
	Loading	1	2	3	4	5	6	7	35	
		36	72	111	144	176	177	178	180	
		205	267	295	324	325	360	384	408	441

Table 7: Updated barge schedule for the Benchmark Strategy

Node	Handling Activity	Timesteps								
1	Unloading	232	248	249	250					
	Loading	58	75	109	151	204	233	234	251	252
2	Unloading	22	53	70	104	114	115	116	117	118
		156	157	197	198	216	239	240		
	Loading	199	217	241	242	243	280	308	337	338
		353	385	425	426	456	468			
3	Unloading	64	191	210	223	224	225	226	344	345
		359	391	392	417	418	419	462		
	Loading	16	145	163	164	346	347	393		
5	Unloading	89	176	177	266	294	322	323	371	405
		440	441	442						
	Loading	1	2	3	4	36	37	38	39	90
		132	133	178	179					

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Appendix B: Test Runs

Test Run 1

Hereby, a test run of the proposed MPC planning approach is presented. The length of the experiment is 20 timesteps (k_max = 25) with a prediction horizon of 20 timesteps (Tp = 20). This test run has the purpose to test the container routing and the assignment of container orders to transport modes.

NETWORK

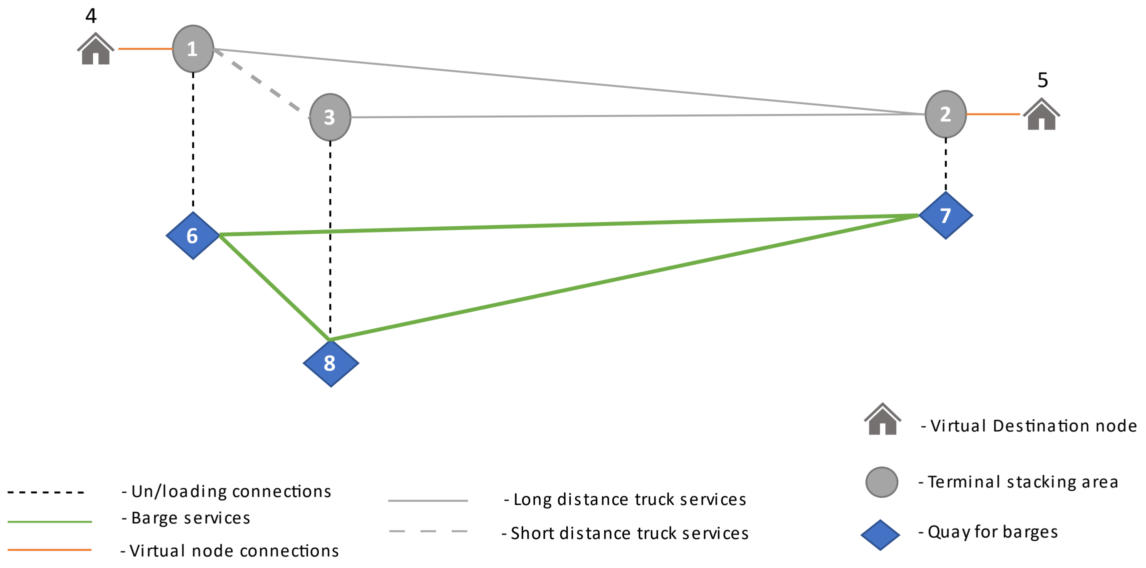

Figure A.TR1.1: Network Layout

The network consist of two virtual nodes, three terminals and three terminal quays. The network has both truck and barge connections.

PARAMETER VALUES

CAPACITY PARAMETERS

$\boldsymbol{c^c_1 = 25}$	$c^v_1 = [5\ 5]^T$
$\boldsymbol{c^c_2 = 25}$	$c^v_2 = [5\ 5]^T$
$\boldsymbol{c^c_3 = 30}$	$c^v_3 = [10\ 10]^T$
$\boldsymbol{c^b_{im} = 1}$ $\boldsymbol{\forall i \in [1,2,3], \quad \forall m \in [6,7,8]}$	$Cap = 20$

$c_i^t = 5$ $\forall \mathrm{i} \in [1,2,4,5]$	$c_i^s = 8$ $\forall \mathrm{i} \in [1,2,3]$
$x_i^v(0) = [\,0\ 1]^T$ $\forall \mathrm{i} \in [1,3]$	$x_3^v(0) = [\,1\ 0]^T$
$x_{16}^b(0) = 1$	

Table A.TR1.1: Capacity Parameters

COST PARAMETERS

$M_1^c = 3 * 1\mathrm{nc}$	$M_1^v = 2 * 1nv$
$M_2^c = 3 * 1\mathrm{nc}$	$M_2^v = 2 * 1nv$
$M_3^c = 1 * 1\mathrm{nc}$	$M_3^v = 1 * 1nv$
$M_6^{\mathrm{b}} = 3 * 1nc$	$M_1^{ls} = 2 * 1nc$
$M_7^{\mathrm{b}} = 1 * 1nc$	$M_2^{ls} = 1.5 * 1nc$
$M_8^{\mathrm{b}} = 3 * 1nc$	$M_3^{ls} = 1 * 1nc$
$M_{ij}^{tv} = \tau_{ij} * 4.5 * 1nc$ $\forall i,j \in [1,3], i \neq j$	$M_i^{lv} = 3 * 1nc$ $\forall i \in [1,3]$
$M_{ii}^{tv} = \tau_{ii} * 9 * 1nc$ $\forall i \in [1,3],\ \ i = j$	$M_i^{lv} = 2 * 1nc$ $\forall i \in [2]$
$M_{ij}^{tb} = (\omega_{im} + \varphi_{imjn} + \omega_{jn}) * 5.5 * 1nc$ $\forall i,j \in [1,2,3], \quad \forall m,n \in [6,7,8]$	$M_6^{bc} = 1$
$M_i^d = 30$ $\forall i \in [4,5]$	$M_8^{bc} = 1$
	$M_7^{bc} = 1$

Table A.TR1.2: Cost Parameters

TEST DEMAND PROFILE

For the purposes of this experiment 21 containers are going to be transported within the network. From Node 1, 20 containers are going to enter the system with a direction of Node 2. Respectively, one container is going to enter the system from Node 2 and sent to Node 1. The batch of 20 containers has long lead team while the 1 container order has a short lead time. The purpose of this is to analyze whether the big batch will be sent by the barge and the single container by truck.

TRAVEL TIMES

- Barge Travel Times in timesteps

		End Node		
		1	2	3
Starting Node	1	0	2	3
	2	2	0	5
	3	3	3	0

Table A.TR1.3: Barge Travel Times

- Truck Travel Times in timesteps

		End Node		
		1	2	3
Starting Node	1	1	5	2
	2	5	1	6
	3	2	6	1

Table A.TR1.4: Truck Travel Times

RESULTS

After the completion of the simulation run, the experiments for container and barge routing are met. The big batch of containers is loaded on the barge and sent to their destination Node2. Respectively, the single container from Node 2 is routed to Node 1 by a long-distance truck. All containers are delivered on time.

Test Run 2

Hereby, a test run of the proposed MPC method is presented. The length of the experiment is 20 timesteps (k_max = 25) with a prediction horizon of 20 timesteps (Tp = 20). This test run has the purpose to test the routing of transport modes. The simulation experiment is run without container orders in the system. The expected behaviour from the system planner is to route all transport vehicles to a hub node where the cost for parking is the lowest.

NETWORK

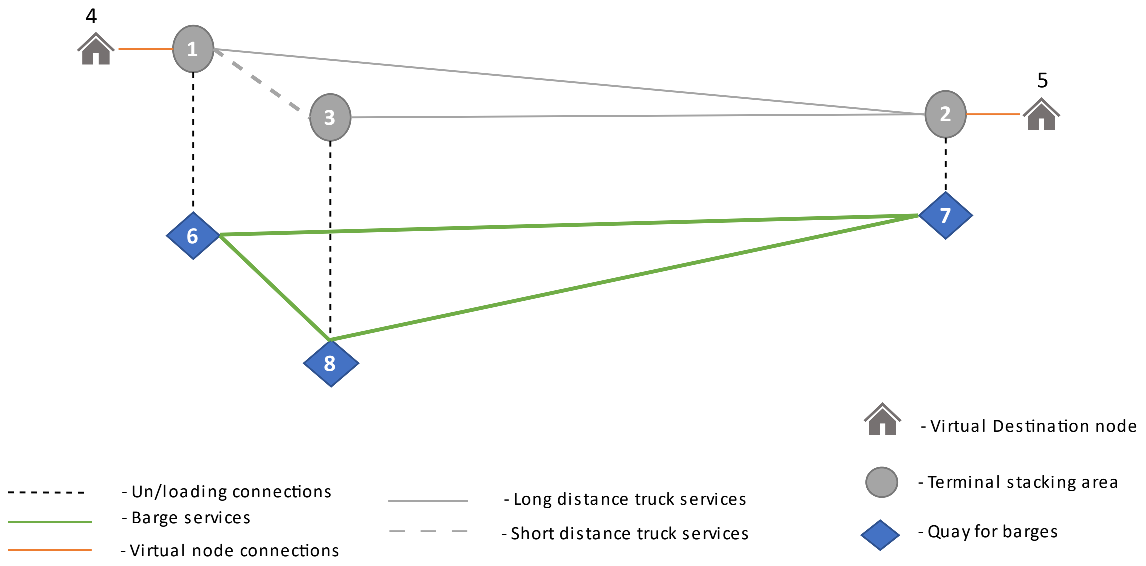

Figure A.TR2.1: Network Layout

The network consist of two virtual nodes, three terminals and three terminal quays. The network has both truck and barge connections.

PARAMETER VALUES

CAPACITY PARAMETERS

$\boldsymbol{c_1^c = 25}$	$c_1^v = [5\ 5]^T$
$\boldsymbol{c_2^c = 25}$	$c_2^v = [5\ 5]^T$
$\boldsymbol{c_3^c = 30}$	$c_3^v = [10\ 10]^T$
$\boldsymbol{c_{im}^b = 1,}$ $\forall \mathbf{i} \in [\mathbf{1,2,3}], \qquad \forall \mathbf{m} \in [\mathbf{6,7,8}]$	$Cap = 20$

$c_i^t = 5 \quad \forall i \in [1,2,4,5]$	$c_i^s = 8 \quad \forall i \in [1,2,3]$
$x_i^v(0) = [\,0\ 1]^T \quad \forall i \in [1,3]$	$x_3^v(0) = [\,1\ 0]^T$
$x_{16}^b(0) = 1$	

Table A.TR2.1: Capacity Parameters

COST PARAMETERS

$M_1^c = 3 * 1nc$	$M_1^v = 4 * 1nv$
$M_2^c = 3 * 1nc$	$M_2^v = 4 * 1nv$
$M_3^c = 1 * 1nc$	$M_3^v = 1 * 1nv$
$M_6^b = 3 * 1nc$	$M_1^{ls} = 2 * 1nc$
$M_7^b = 1 * 1nc$	$M_2^{ls} = 1.5 * 1nc$
$M_8^b = 3 * 1nc$	$M_3^{ls} = 1 * 1nc$
$M_{ij}^{tv} = \tau_{ij} * 4.5 * 1nc, \quad \forall i,j \in [1,3], i \neq j$	$M_i^{lv} = 3 * 1nc, \quad \forall i \in [1,3]$
$M_{ii}^{tv} = \tau_{ii} * 9 * 1nc, \quad \forall i \in [1,3], \ i = j$	$M_i^{lv} = 2 * 1nc, \quad \forall i \in [2]$
$M_{ij}^{tb} = (\omega_{im} + \varphi_{imjn} + \omega_{jn}) * 5.5 * 1nc, \quad \forall i,j \in [1,2,3], \forall m,n \in [6,7,8]$	$M_6^{bc} = 1$
$M_i^d = 30, \ \forall i \in [4,5]$	$M_8^{bc} = 1$
	$M_7^{bc} = 1$

Table A.TR2.2: Cost Parameters

TEST DEMAND PROFILE

For the purposes of this experiment 0 containers are going to be transported within the network. There is one barge operating in the system which is berthed at node 1. There is one short range truck which is parked at node 3. Furthermore, there are total 2 long range trucks in the system as 1 truck of this type is parked respectively at Node 1 and 2. As there are not going to be any container orders within the system in this simulation run, it is expected from the system planner to route all transport vehicles to Node 3. Node 3 is modelled as a hub with the lowest costs for vehicle parking. Therefore, the barge is expected to be routed from Node 1 to Node 3 together with all long-range trucks, while the short-range truck parked at Node 3 should not be routed.

TRAVEL TIMES

- Barge Travel Times in timesteps

		End Node		
		1	2	3
Starting Node	1	0	2	3
	2	2	0	5
	3	3	3	0

Table A.TR2.3: Barge Travel Times

- Truck Travel Times in timesteps

		End Node		
		1	2	3
Starting Node	1	1	5	2
	2	5	1	6
	3	2	6	1

Table A.TR2.4: Truck Travel Times

RESULTS

According to the expectations, the planner sent all transport vehicles to Node 3. This node is modelled as a multimodal hub where parking and berthing is significantly cheaper compared to other nodes. Therefore, this experiment shows that the planners' actions are following the objective of minimizing the overall operational costs of the system.

Test Run 3

Hereby, a test run of the proposed MPC method is presented. The length of the experiment is 20 timesteps (k_max = 25) with a prediction horizon of 20 timesteps (Tp = 20). This test run has the purpose to test the actions of the planner when there is intensive demand for container orders and a shortage of a capacity.

NETWORK

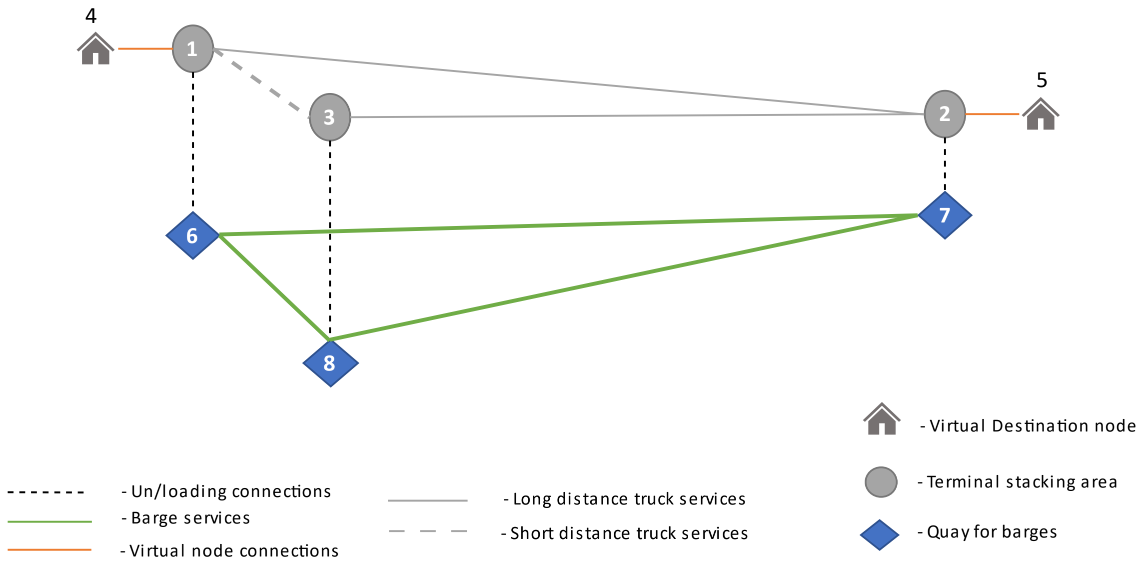

Figure A.TR3.1: Network Layout

The network consist of two virtual nodes, three terminals and three terminal quays. The network has both truck and barge connections.

PARAMETER VALUES

CAPACITY PARAMETERS

$\boldsymbol{c_1^c = 25}$	$c_1^v = [5\ 5]^T$
$\boldsymbol{c_2^c = 25}$	$c_2^v = [5\ 5]^T$
$\boldsymbol{c_3^c = 30}$	$c_3^v = [10\ 10]^T$
$\boldsymbol{c_{im}^b = 1,}$ $\forall \mathbf{i} \in [\mathbf{1}, \mathbf{2}, \mathbf{3}], \quad \forall \mathbf{m} \in [\mathbf{6}, \mathbf{7}, \mathbf{8}]$	$Cap = 20$
$\boldsymbol{c_i^t = 5}$ $\forall \mathbf{i} \in [\mathbf{1}, \mathbf{2}, \mathbf{4}, \mathbf{5}]$	$c_i^s = 8$ $\forall \mathbf{i} \in [\mathbf{1}, \mathbf{2}, \mathbf{3}]$

$x_i^v(0) = [\,0\ 1]^T$ $\forall \mathrm{i} \in [1, 3]$	$x_3^v(0) = [\,1\ 0]^T$
$x_{16}^b(0) = 1$	

Table A.TR3.1: Capacity Parameters

COST PARAMETERS

$M_1^c = 3 * 1\mathrm{nc}$	$M_1^v = 2 * 1nv$
$M_2^c = 3 * 1\mathrm{nc}$	$M_2^v = 2 * 1nv$
$M_3^c = 1 * 1\mathrm{nc}$	$M_3^v = 1 * 1nv$
$M_6^{\mathrm{b}} = 3 * 1nc$	$M_1^{ls} = 2 * 1nc$
$M_7^{\mathrm{b}} = 1 * 1nc$	$M_2^{ls} = 1.5 * 1nc$
$M_8^{\mathrm{b}} = 3 * 1nc$	$M_3^{ls} = 1 * 1nc$
$M_{ij}^{tv} = \tau_{ij} * 4.5 * 1nc, \quad \forall i, j \in [1, 3], i \neq j$	$M_i^{lv} = 3 * 1nc, \quad \forall i \in [1,3]$
$M_{ii}^{tv} = \tau_{ii} * 9 * 1nc, \quad \forall i \in [1, 3], \ i = j$	$M_i^{lv} = 2 * 1nc, \quad \forall i \in [2]$
$M_{ij}^{tb} = (\omega_{im} + \varphi_{imjn} + \omega_{jn}) * 5.5 * 1nc,$ $\forall i, j \in [1, 2, 3], \forall m, n \in [6, 7, 8]$	$M_6^{bc} = 1$
$M_i^d = 30, \ \forall i \in [4, 5]$	$M_8^{bc} = 1$
	$M_7^{bc} = 1$

Table A.TR3.2: Cost Parameters

TEST DEMAND PROFILE

For the purposes of this experiment 120 containers are going to be transported within the network. This is 20% bigger than the overall capacity offered by the system. In the system there is static capacity of 80 containers. The static capacity is the storage available at terminals where containers can be stored. The other type of capacity is moving and is the storage available at operating barges and trucks. In the experiment there is one barge with a capacity of 20 containers and three trucks which can carry one container each. Therefore, the entire system has an overall capacity of 103 containers.

The container orders enter the system in batches of 20 containers every 5 steps through Node 1 and 2. The lead time of each container in a batch is 10 timesteps which is equal to the barge travel time between Node 1 and Node 2. The expectations from this simulation run are that there are going to be significant amount of unsatisfied container orders on time. The barge is expected to be routed on maximum capacity and all trucks to be routed in every step. This includes also the short-range truck parked at Node 3. It is expected that the planner is going to store the container orders which cannot be delivered on time at Node 3 due to the cheapest storage cost.

TRAVEL TIMES

- Barge Travel Times in timesteps

		End Node		
		1	2	3
Starting Node	1	0	2	3
	2	2	0	5
	3	3	3	0

Table A.TR3.3: Barge Travel Times

- Truck Travel Times in timesteps

		End Node		
		1	2	3
Starting Node	1	1	5	2
	2	5	1	6
	3	2	6	1

Table A.TR3.4: Truck Travel Times

RESULTS

The results of the simulation run are according to the expectations. Half of the container orders do not enter the system and vast majority of the delivered orders do not satisfy the lead time requirements. The barge is routed between the nodes at full capacity and trucks are in constant movement. One fifth of the containers which entered the system are stored at the hub node and transported by the short-range truck between Node 1 and 3. At the end of the run, the barge is berthed at the hub loaded with containers at its limit.

Test Run 4

Hereby, a test run of the proposed MPC method is presented. The length of the experiment is 20 timesteps (k_max = 25) with a prediction horizon of 20 timesteps (Tp = 20). This test run has the purpose to test the actions of the planner when it must route only one container within the truck network. To compare the actions of the planner, the example is solved by applying the Shortest Path Algorithm.

NETWORK

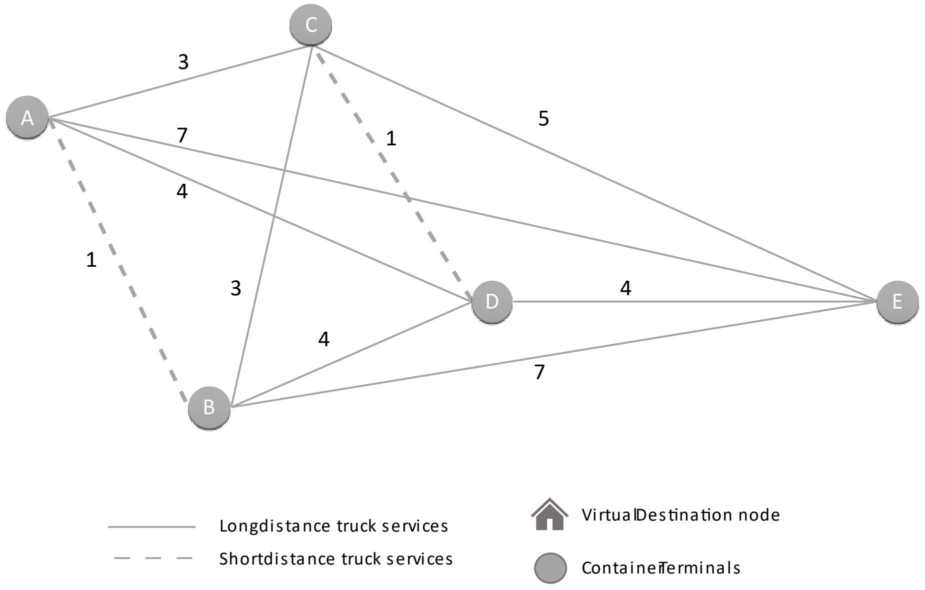

Figure A.TR4.1: Network Layout

The network consist of 5 nodes which are connected by two types of truck routes. The connection presented by a dashed line is a short distance which is operated by port trucks. The solid lines represent long-distance routes which are routed by long-distance trucks. The travel times between the nodes are presented on the Figure above. The travel times are equivalent to the transport cost for routing the container order. For the purposes of this example, one container must be transported from Node A to Node E for the lowest possible cost.

GENERATED SOLUTION

A solution is generated by applying the Shortest Path Algorithm. The approach of obtaining a solution is presented below in the table. According to it, the cheapest route to deliver the container order is to take the connection from Node A to Node E. The cost to deliver the container is 7. The example is run in MATLAB to check whether the planner of the system is going to route the container the same way.

n	Solved Nodes Directly Connected to Unsolved Nodes	Closest Connected Unsolved Node	Total Distance Involved	*n*th Nearest Node	Minimum Distance	Last Connection
1	A	B	1	B	1	AB
2	A	C	3	C	3	AC
	B	C	1+3=4			
3	A	D	4	D	4	AD
	B	D	1+4=5			
	C	D	3+1=4	D	4	CD
4	A	E	7	E	7	AE
	B	E	1+7=8			
	C	E	3+5=8			
	D	E	4+4=8			

Table A.TR4.1: Hand Generated solution

SIMULATION RUN SOLUTION

The results of the simulation run comply with the results generated by the Shortest Path Algorithm. The actions of the system planner are to route the container by using the connection from Node A to Node E and generate a cost of 7 (which is equal to the travel time between the two nodes). This experiment verifies the operator’s behavior and generated results.

List of Tables

List of Figures