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*

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).

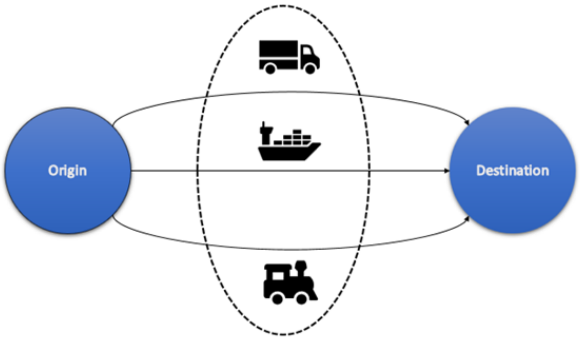


Figure 1: Horizontal integration of transport services (Bart van Riessen, 2015)

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. 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 X 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:

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

, 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:

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

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:

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

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:

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

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.

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

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:

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

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:

$$\mathrm{x}_\mathrm{im}^\mathrm{b}(\mathrm{k}+1) = \mathrm{x}_\mathrm{im}^\mathrm{b}(\mathrm{k}) + \sum_{j\in\mathrm{B_i}}\sum_{n\in Q_j}\left(s_{jnim}(k-\omega_{jn} - \varphi_{jnim} - \omega_{im}) - s_{imjn}(k)\right), \qquad (5)$$

The 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:

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

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:

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

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:

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

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):

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

Variables $u_{im}^l(k)\in\mathrm{R}_{\ge0}^{nc}$ and $u_{mi}^u(k)\in\mathrm{R}_{\ge0}^{nc}$ 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:

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

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

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

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:

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

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:

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

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

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.

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

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

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:

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

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

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

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

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

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

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

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.

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

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 optimization problem is solved at each timestep k by the operator. The aim is to minimize an objective function Eq (29)

$$\min \sum_{k=0}^{Tp}\left(\sum_{i\in N}\left(M_i^{c}x_i^{c}(k) + M_{im}^{bc}\left(\sum_{m\in Q_i} x_{im}^{t}(k)\right) + M_i^{v}x_i^{v}(k) + M_{im}^{b}x_{im}^{b}(k) + \sum_{j\in T_i} M_{ij}^{v}v_{ij}(k) + \sum_{j\in B_i} M_{ij}^{tb}\left(\sum_{m\in Q_i}\sum_{n\in Q_j} s_{imjn}\right) + \sum_{v\in[1,nv]} M_i^{lv}\left(\sum_{j\in T_i}(u_{ji}^{v}(k-\tau_{ji}) + u_{ij}^{v}(k)) - 2z_i^{v}(k)\right) + \right) + \right), \quad (29)$$

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.

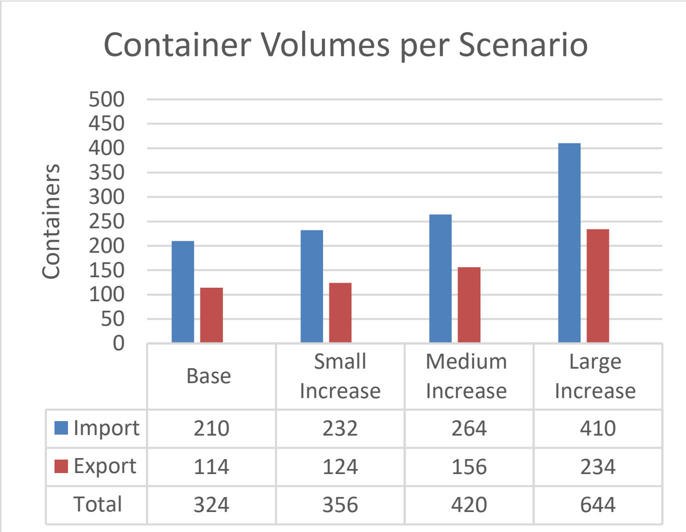


Figure2: Container volumes in each scenario

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.

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.

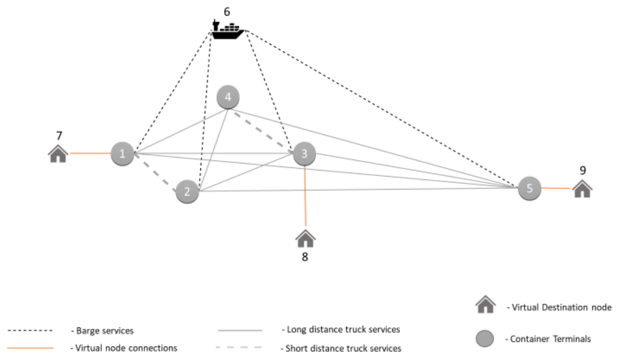


Figure 4: CTT Network with scheduled barge service (Benchmark Strategy)

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.

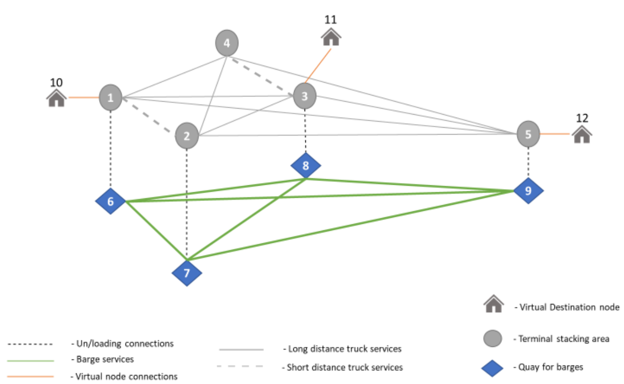


Figure 5: CTT network with flexible barge services (FBR Strategy)

4.2.3. MPC Parameters

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

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

4.2.4. Optimal 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 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.

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. The schedule is presented in Table 5 in the Appendix.

Table 2: Capacity parameters

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

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.

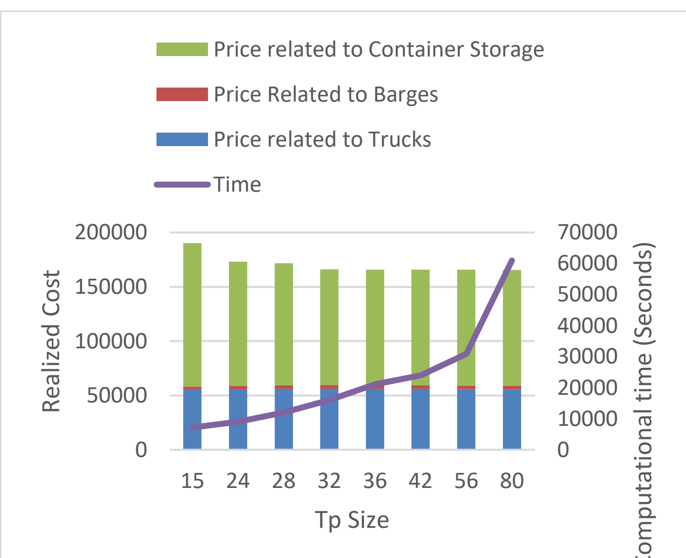


Figure 6: Comparison of realized costs and computational time in seconds.

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.

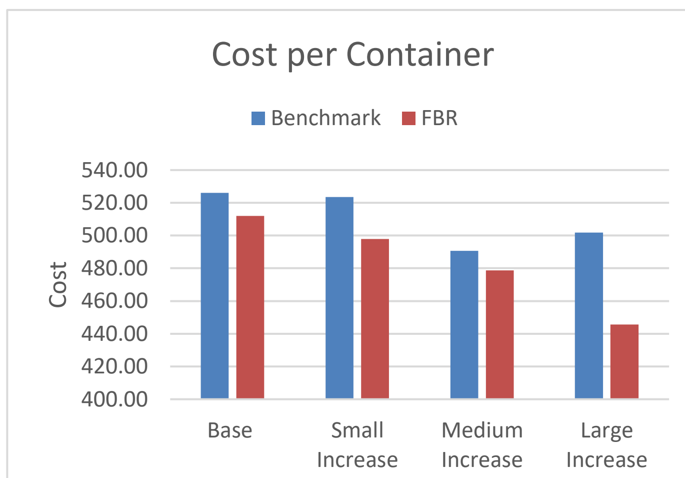


Figure 7: *Cost per container realized in experiments.*

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.

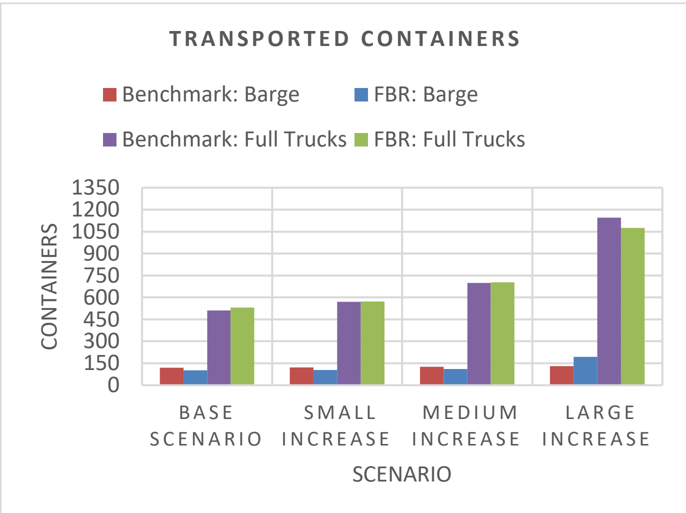


Figure 9: Number of containers transported by transport modes.

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.

5.2. 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.

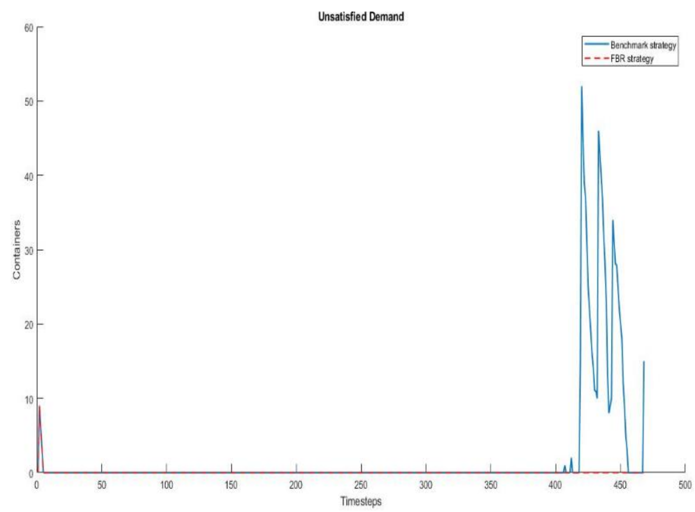


Figure 10: Unsatisfied Demand in the Large Increase Scenario

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. 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

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%

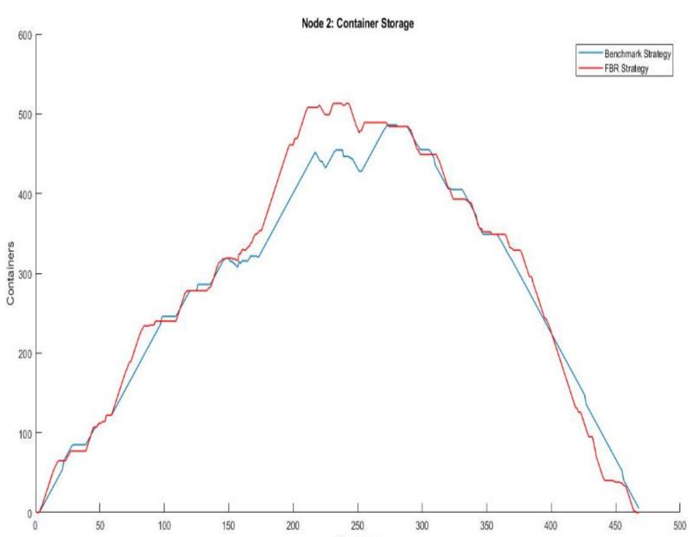


Figure 11: Node 2 Container Storage

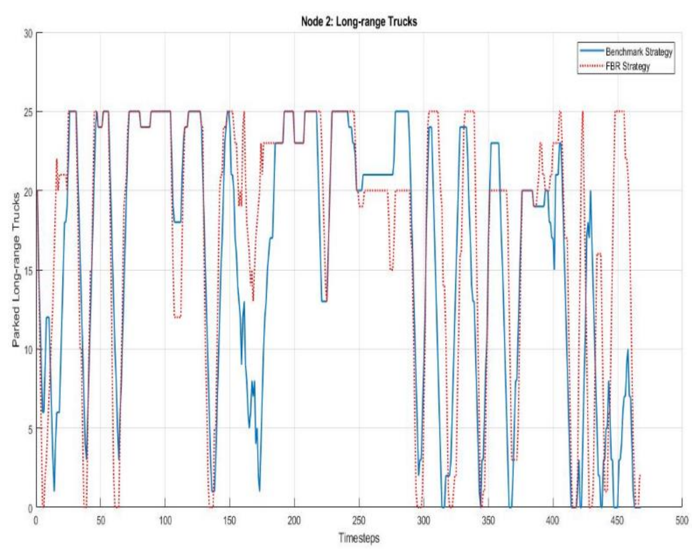


Figure 12: Long-Range Trucks parked at Node 2.

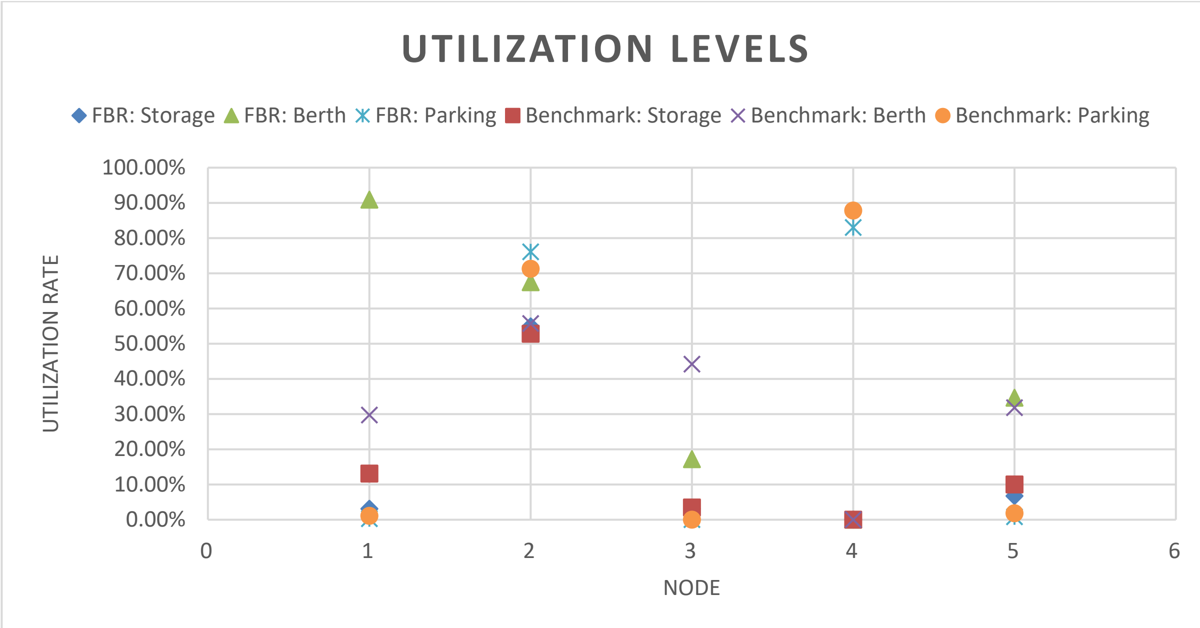


Figure 13: Utilization levels of system resources at all nodes

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.

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%.

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

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.

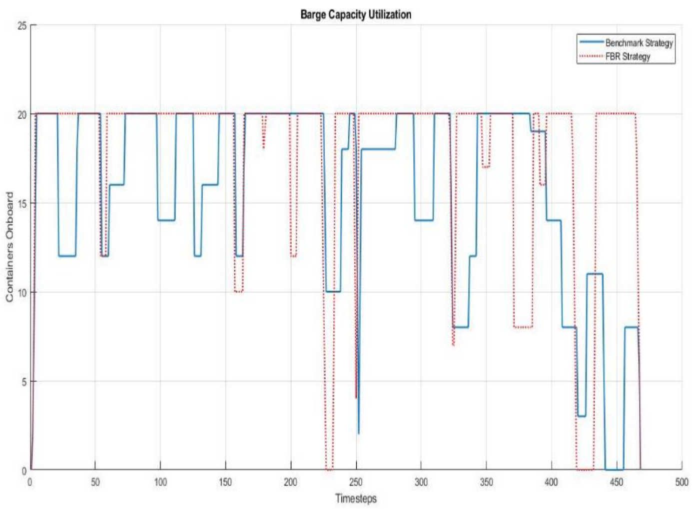


Figure 14: Comparison of Barge Capacity Utilization with both strategies

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. 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.

5.2.1. 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.

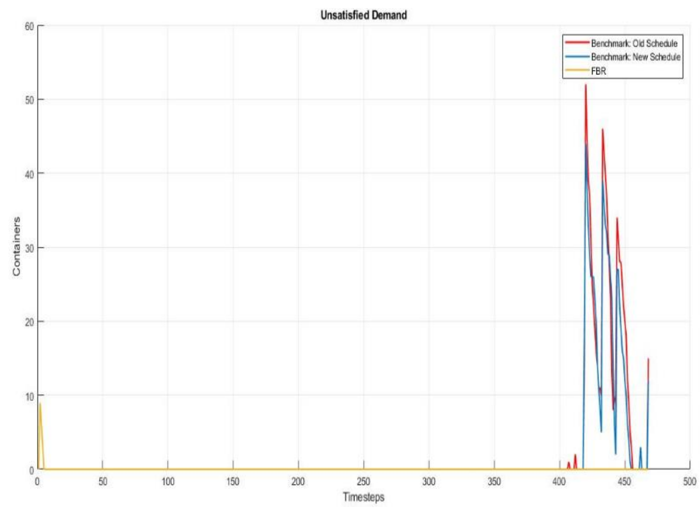


Figure 15: Unsatisfied demand of containers when the new adapted schedule is applied compared to the old schedule and the FBR strategy.

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.

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 analyzed 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
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

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}, $i \in N, j \in T_i$	Cost of a truck trip from node *i* to node *j*	*$*Travel Time ($*Timesteps)*
M_{ij}^{tb}, $i \in N, j \in B_i$	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}, $i \in N, j \in T_i$	Truck Travel time between node *i* and node *j*	*Timesteps*
φ_{imjn}, $i \in N$, $m \in Q_i$, $j \in B_i$, $n \in Q_j$	Barge Travel Time between node *i* and node *j*	*Timesteps*
ω_{im}, $i \in N, m \in Q_i$	Operational Barge Time need by a barge to leave or enter quay *m* of port *i*	*Timesteps*
$d_i \in R_{\geq 0}^{nc}$, $i \in VD$	Amount of incoming and outgoing demand which can be satisfied during at Virtual destination node *i* during timestep (*k*)	*Container Units*
$K_{max} = \{1,2, \dots k\_max\}$	Horizon length	*Timesteps*
Tp, $Tp \geq 0$	Prediction Horizon length	*Timesteps*

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*
Node States	**Description**	**Units**
$x_i^c(k) \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N$	Number of containers of each type parked at a node *i* at timestep *k*	*Container Units*
$x_i^d \in \mathrm{R}_{\geq 0}^{\mathrm{nc}}$ $i \in \mathrm{VD}$	Number of unsatisfied demands at virtual destination node *i* which is penalized	*Container Units*
$x_i^v(k) \in \mathrm{R}_{\geq 0}^{nv}$ $i \in N$	Number of trucks of each type parked at a node *i* at timestep *k*	*Trucks per type*
$x_{im}^b(k) \in \mathrm{R}_{\geq 0}^{ns}$ $i \in \mathrm{N}, \quad m \in Q_i$	Number of barges of each type berthed at quay *m* of node *i* at timestep *k*	*Barges per type*
$x_{im}^t(k) \in \mathrm{R}_{\geq 0}^{nc}$ $i \in \mathrm{N}, \quad m \in Q_\mathrm{i}$	Number of containers which are present on a barge berthed at quay *m* at node *i* at timestep *k*	*Container Units*
$\mathrm{u_i^{hv}}(k)$ $i \in N$	Number of containers approaching node *i* by trucks of all types at timestep *k*	*Container Units*
$\mathrm{u_{im}^{hs}}(k)$ $i \in N$	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**
$u_{ij}^v \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N, \quad j \in T_i, \quad v \in M$	Number of containers send from node *i* to node *j* by truck type *m*	*Container Units*
$u_{imjn}^s \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j, \quad s \in \mathrm{S}$	Number of containers send from quay *m* of node *I* to quay *n* of node *j* by a barge of type *s*	*Container Units*
$v_{ij} \in \mathrm{R}_{\geq 0}^{nv}$ $i \in \mathrm{N}, \quad \mathrm{j} \in \mathrm{T_i}$	Number of trucks of each type send from node *I* to node *j*	*Trucks per type*
$s_{imjn} \in \{0;1\}_{\geq 0}^{ns}$ $i \in N, \quad m \in Q_i$ $j \in B_i, \quad n \in Q_j$	Binary variable indicating if a barge of each type is sent from the quay *m* of node *i* to the quay *n* node *j*	
$u_{im}^l(k) \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N, \quad m \in Q_i$	Number of containers being loaded on a barge berthed at quay *m* of node *I* from the stack at node *i*	*Container Units*
$\mathrm{u_{mi}^u}(k) \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N, \quad j \in Q_i$	Number of containers being unloaded from a barge berthed at quay *m* of node *i* to the stack of node *i*	*Container Units*
$\mathrm{u_i^d} \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N, \quad d \in VD$	Containers used to satisfy the incoming demand form network node *i* to virtual destination node *d* at timestep *k*	*Container Units*
$\mathrm{u}_d^i \in \mathrm{R}_{\geq 0}^{nc}$ $i \in N, \quad d \in VD_i$	Containers used to satisfy the outgoing demand form network node i to virtual destination node d at timestep k	*Container Units*
$z_i^v \in \mathrm{R}_{\geq 0}^{nc},$ $i \in N, \quad v \in V$	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*

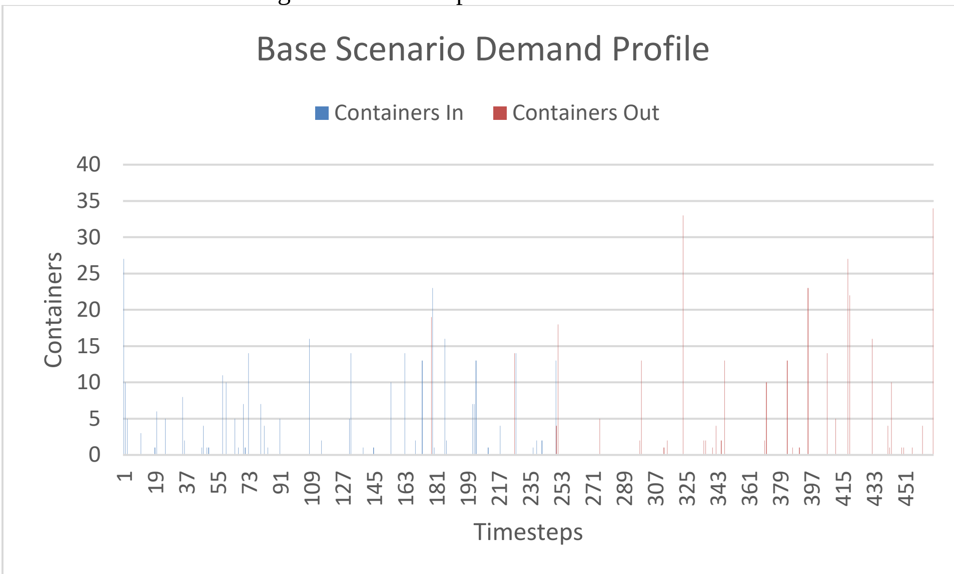
Appendix B: Terminal Characteristics

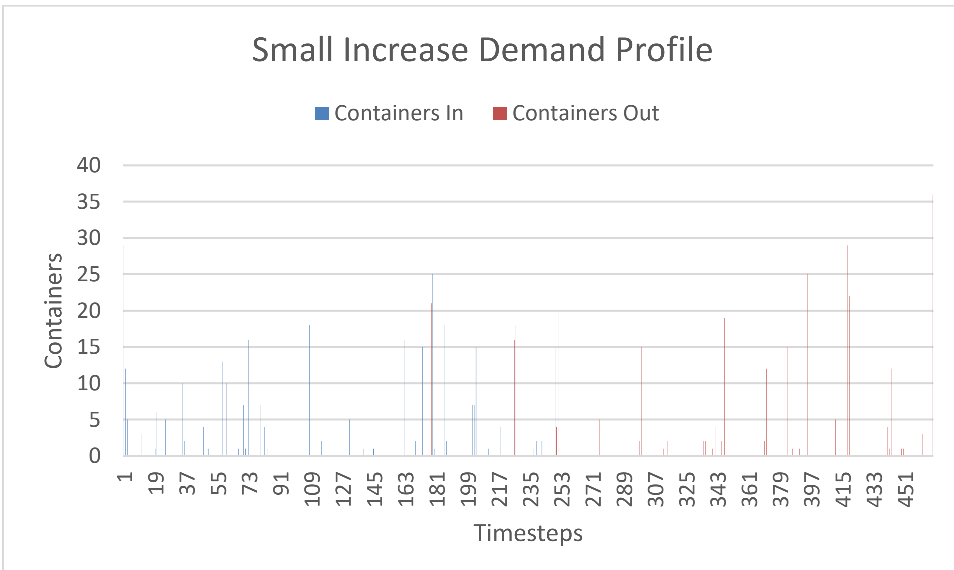
Table 2: Characteristics of container terminals at Port of Rotterdam and CTT terminal at Hengelo (*Container Port of Europe*, 2020)

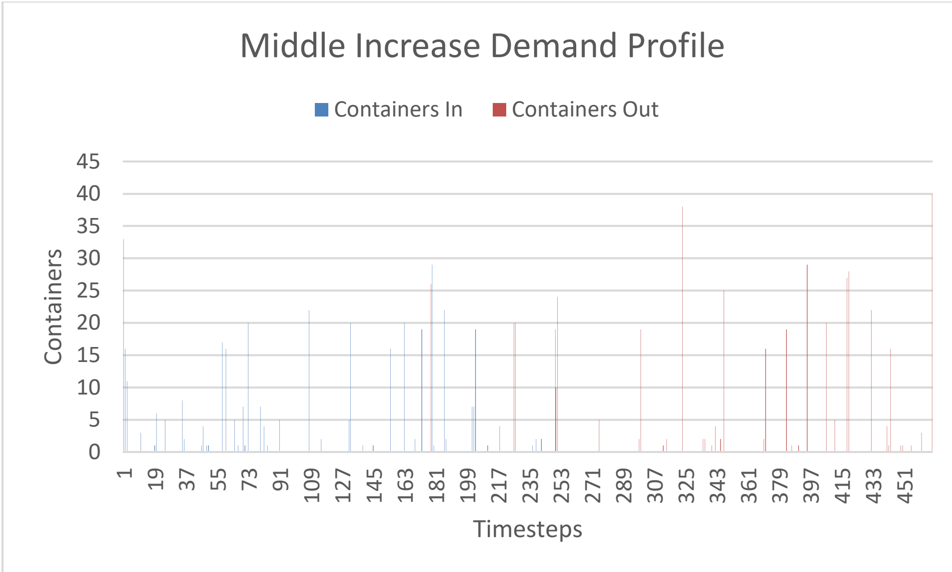
Terminals	Capacity (TEU)	Quay length (m)	Type of vessels (Ds/B)	Plot Area (ha)
Maasvlakte				
APM	3350000	1600	DS	100
APM2	2700000	1500/500	DS/B	86
Rotterdam World Gateway	2350000	1700/550	DS/B	108
ECT Euromax	*3000000*	1500	DS	84
ECT Delta	*5000000*	3600	DS	272
ECT Delta Barge	*100000*	890	B	7.5
Delta 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
Timesteps
0
5
10
15
20
25
30
35
40
45
1
19
37
55
73
91
109
127
145
163
181
199
217
235
253
271
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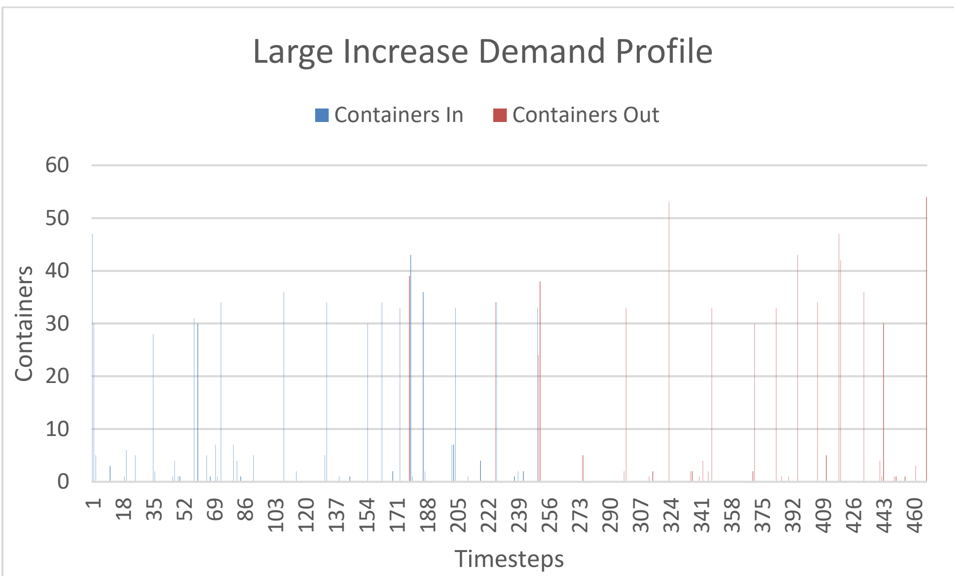
307
325
343
361
379
397
415
433
451


Large Increase Demand Profile
Containers In
Containers Out
Containers
Timesteps
0
10
20
30
40
50
60
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

Appendix D: Travel Times

Starting Node \ End Node	1	2	3	4	5
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

Starting node \ End Node	1	2	3	4	5
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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