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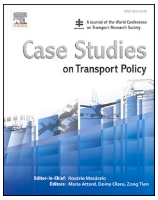

An assessment methodology for a modular terminal concept for container barging in seaports

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ABSTRACT

Container transport via inland waterways currently faces several challenges affecting its competitiveness with other modes. These challenges include the high waiting time experienced by container barges and the low priority given to container barges in deepsea ports. To mitigate these challenges, a new concept known as the Modular Mobile Terminal (MMT) is introduced to create a dedicated floating barge handling and consolidation space for containers in deepsea ports.

Based on this, the present study proposes an assessment methodology examining the feasibility of the MMT from a logistical and economic perspective. In doing this, a time optimization model was developed to determine the number of MMTs leading to the most time savings for container barges. It also helps target a market by finding the hinterland flows that can be positively linked to the MMTs. Afterward, an economic evaluation is conducted to determine the cost savings for the actors and determine under which conditions the actors would benefit from using the MMT system. The proposed methodology is then applied in a case study for the ports of Antwerp and Rotterdam to derive insights into the efficiency and profitability of the MMTs.

Results revealed that the MMTs would be most suitable for vessels transporting small cargo volumes below 60 Twenty Foot Equivalent Units (TEUs). Furthermore, the analysis suggests that two MMTs would be optimal for the port of Antwerp, and four for the port of Rotterdam, to achieve an overall net benefit for all the actors. Thus, it can be concluded that the MMTs are most suitable for handling and consolidating cargoes from container barges with small call sizes.

1. Introduction

Over the years, inland waterway transport (IWT) has significantly contributed to container seaport performance. This is due to the emergence of container transport on water, which brings about efficient accessibility to different hinterland regions. Moreso, this transport mode offers a more sustainable and cost-efficient method of accessing the hinterland and generates higher economies of scale than other transport modes. Given this, it has become more attractive to shippers as it is a better alternative to road transport, especially when a large volume of containers is involved.

Nevertheless, this transport mode still faces different challenges affecting its competitiveness, particularly the high waiting times experienced by container barges in seaports. These can be linked to two main issues: containers spread over several terminals and the low priority of barges at the terminals. Containers are often not bundled but thinly spread over several seaport terminals, thereby leading to inland vessels having to call at several terminals, at times even between six to eight, to collect a few containers at each call. Each of these calls often takes hours before the barges are handled. This is due to the low priority of container barges at each terminal. Since seagoing vessels are prioritized at terminals, inland vessels must wait for available wharf and crane facilities, with waiting time at and sailing between terminals adding up to 60 percent of the total time spent in port (Port of Rotterdam, 2019). Waiting for a slot at the large container terminals can quickly increase to one or even several days (van Hassel, et al., 2021).

This research examines how to eliminate the identified inefficiencies by reducing port sailing and waiting times for barges without expensive modifications to port infrastructures. To achieve this, a concept named Modular Mobile Terminal (MMT) is proposed, and an assessment

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methodology is developed to evaluate its potential operational efficiency. Providing a consolidation and distribution station is expected to eliminate the need for the inland container vessels to call at multiple terminals, thereby reducing the waiting times. It is also expected that consolidation will increase the attractiveness of the seaport (Fan, Behdani, Bloemhof-Ruwaard, & Zuidwijk, 2019). The consolidation and distribution station could be placed on the land. But considering the intensive land use in most ports, developing a floating terminal concept could bridge this gap. The MMT will be the interface where an Inland Waterway Vessel (IWV) can deliver and collect containers to and from the seaport terminals.

Although previous studies have explored similar ideas (Hu, Wiegmans, Corman, & Lodewijks, 2019), the present work adds to the body of knowledge by developing an assessment methodology for this innovation based on both time savings and costs while also considering the technical and operational constraints. Moreover, this particular Modular Mobile Terminal solution has not been studied before, thus this study constitutes a proof-of-concept and lays the first foundations for assessing the potential of MMTs. Because this innovation is still at an early stage, this work does not claim to provide a business model. Instead, assuming that there exists an independent operator for the MMTs that will charge its services to IWT carriers, the study provides insights into what configuration of the system needs to be investigated further to generate a positive business case based on a holistic assessment framework.

Thus, the study aims at solving the following research question: “Under which conditions are MMTs economically viable?” To answer this question, an optimization model is first conceived to determine the number of MMTs generating the most time savings and the target cargo flows. Then, an economic assessment examines the net benefits of the actors involved and the concept’s overall feasibility. Consequently, the MMT concept is evaluated based on two indicators: the ability to significantly reduce the waiting time of container vessels and enhance cargo bundling without necessarily leading to extra costs for the additional movement of cargoes.

The remainder of this article is structured as follows: a review of the related works is provided in Section 2, while Section 3 describes the MMT concept. The assessment methodology is detailed in Section 4 and applied to a case study for the ports of Antwerp and Rotterdam in Section 5. Finally, some conclusions and further research directions are proposed in Section 6.

2. Literature review

Since the early 2000 s, concerns have been raised about substantial delays for container barges in deep-sea ports. In 2004 already, barge operators experienced up to 60 h of delays in the seaports of Antwerp and Rotterdam (Vernimmen, Dullaert, & Engelen, 2007). The situation has not improved in 2021 since operators reported up to 120 h of average waiting time in the port of Rotterdam (Co, 2021). Two main issues cause these delays (Van Der Horst & De Langen, 2008): the numerous calls of small size and the lack of contractual relationships with terminal operators. Due to the small volume of containers per call, inland barges must call at multiple terminals (typically 6 to 8) to be fully (un)loaded (Ramos, et al., 2020). Moreover, terminals prioritize seagoing vessels over inland vessels (Wiegmans, 2005), which must wait for an available berth and crane facility. As a result, the waiting and sailing times of IWVs in the port exceed by far their handling time (Gumuskaya, van Jaarsveld, Dijkman, Grefen, & Veenstra, 2020).

Several models have been developed to achieve more efficient barge operations in the seaport. The barge rotation planning can either be performed by a centralized entity (Li, Negenborn, & Lodewijks, 2017) or within a distributed setting (Douma, Schutten, & Schuur, 2009). Moreover, disruptions (Tong & Nachtmann, 2017) and uncertainties (Gumuskaya, van Jaarsveld, Dijkman, Grefen, & Veenstra, 2021) are also included in the models to obtain more robust solutions.

Van Der Horst & De Langen (2008) report different cooperation mechanisms set up at the ports of Rotterdam and Antwerp and their hinterland to alleviate the existing bottlenecks. It consists of alliances of barge operators, but they also outline agreements between the barge and terminal operators about time windows allocation. Companies can also broaden their scope of services, such as the Extended Gate Model developed by terminal operators or shipping lines. Finally, new concepts, such as a feeder barge equipped with a crane to pick up and deliver containers at a regional scale, are also proposed.

Besides solutions based on information and communication technologies, the Rotterdam port authority also developed infrastructure-based strategies, such as the “container transferium” (Konings, van der Horst, Hutson, & Kruse, 2010). It serves as a consolidation point for cargo coming from the hinterland and going to the port and vice versa. It is suggested that the location of this facility should be in the direct hinterland of Rotterdam. Although its main goal is to serve trucks to decrease congestion on the port’s highways, it can also be used by inland shipping. The transport between the transferium and the sea terminals is then assured by shuttle barges. These shuttles would have dedicated quays at sea terminals. They could perform a round trip (visiting all sea terminals) or be assigned to a specific terminal (Froeling, van Schuylenburg, Groenveld, & Taneja, 2008). More recently, a Transport and Logistics floating hub not located in the hinterland but at sea was proposed within the Space@Sea project. The feasibility of the concept was assessed by simulating sea-going inland vessels calling at this offshore hub and feeder vessels linking the hub to the sea terminals. It was found that the concept was economically feasible if inland vessels directly go to the hub without stopping at the sea terminals (Assbrock, Ley, Dafnomilis, Duinkerken, & Schott, 2020).

In 2007, Konings proposed several operational solutions to reorganize container barge services in deep-sea ports to improve the attractiveness of IWT (Konings, 2007). The main idea was to reduce the number of calls for inland barges by collecting cargo at terminals with dedicated feeder vessels and redistributing it to specific locations. Three potential solutions were investigated: Containers of all terminals are grouped at a unique location; Containers of ‘small call-size’ terminals are grouped at a location, and inland barges visit ‘large call-size’ terminals themselves; Containers of ‘small call-size’ terminals are grouped at ‘large call-size’ terminals that are then visited by inland barges. The author concluded that the second solution was the most promising (even though the third option was slightly more cost-efficient) as it offers a dedicated location for inland barges. It is also underlined that board-to-board transshipment would significantly improve the efficiency of these systems.

This hub-and-spoke idea was developed further for the hinterland of the port of Rotterdam (Konings, Kreutzberger, & Maras, 2013). Three potential locations are selected at distances from the seaport ranging from 40 km to 135 km. The authors then compute the potential cost savings for inland vessels of different capacities under three distinct configurations of the feeder barges. The results show that the hub-and-spoke is more beneficial for small hinterland vessels. They also reveal that a greater distance between the hub and the seaport generates more economies of scale. The authors mention that push barges can be used to shuttle between the hub and the seaport because they can serve as floating stacks. The potential of a floating crane is also suggested but not further investigated.

A thorough technical evaluation of the so-called Floating Container Storage & Transshipment Terminal is proposed by Baird & Rother (2013). The authors state that the most promising configuration is to fit a crane on a converted container ship. They argue that this concept is technically feasible in a low-wave sheltered environment and that the investment can be covered in much less time than a conventional on-shore terminal.

Malchow (2020) takes the floating crane concept and proposes a Port Feeder Barge for inter-terminal transfers in deep-sea ports. It consists of a self-propelled container barge equipped with a mounted crane. Besides intra-port operations, the author suggests that the Port Feeder Barge can also be used as a floating terminal for inland vessels. The Port Feeder Barge would perform a round trip a day throughout the port in order to shuttle containers between the various container handling facilities. It can also meet with hinterland barges somewhere at the dolphins to exchange containers. In the course of its daily round voyage, it can collect/deliver the hinterland containers from/among the ocean terminals. Compared to additional land-based facilities, the solution offers advantages regarding implementation costs, simplicity, and environmental impacts. The author nevertheless points out that the defiance of terminal operators represents a significant obstacle as they are reluctant to delegate container handling operations to external actors.

In that sense, the proposed MMT offers a good compromise as the crane module is situated separately, thus not directly interacting with the deep-sea terminals. Containers are stacked on modules that are then conveyed to dedicated terminals that keep the crane handling operations from the modules to the yard. In addition to the evident advantages for barge operators, this concept allows terminal operators to plan their operations more effectively, as incoming cargo will already be consolidated. Furthermore, with dedicated shuttles, a fixed and regular timeslot can be agreed upon with the terminal. Based on this, the chance of missing the call is much lower than with inland vessels visiting multiple terminals. For these reasons, MMTs would lead to a win–win situation, which is essential to get the commitment of all stakeholders (Caris, Macharis, & Janssens, 2011).

Regarding methodology, the existing works have used several means to assess the efficiency of the proposed solution. Some present a cost-benefit analysis to evaluate the economic possibility of the concept (Konings, 2007; Konings, Kreutzberger, & Maras, 2013), while others make use of simulations to assess the concept's operational feasibility (Assbrock, Ley, Dafnomilis, Duinkerken, & Schott, 2020; Froeling, van Schuylenburg, Groenveld, & Taneja, 2008). The other studies mainly focus on the technical components (Baird & Rother, 2013), discuss the offered possibilities and managerial insights without numerical results (Konings, van der Horst, Hutson, & Kruse, 2010), or combine these two approaches (Malchow, 2020).

This work contributes to the body of knowledge through a unified methodology combining technical, operational, and economic aspects. Indeed, an optimization model is proposed to determine which configuration to adopt for the Modular Mobile Terminals and which market to target to generate the highest time savings under some operational constraints. The results are then used in a net benefit analysis to determine the economic feasibility of the MMT concept and financial gains for both the barge operators and the shippers.

3. Concept description

This section presents the most important aspects of the proposed Modular Mobile Terminal concept. For more detailed information, the reader is referred to the following technical reports (Ramne, et al., 2021; Thill, et al., 2022).

The MMT proposed in this study is made up of modules. The modules are configured as a dumb barge that can either be pushed or towed between the mobile terminal handling area and the sea terminals. The MMT modules will be operated in the seaport area and have no reason to move upstream and pass narrow locks. Based on the aforementioned technical reports, the dimensions of the modules are 17 m in width and 55 m in length. Moreover, a cargo capacity of 138 Twenty-Foot Equivalent Units (TEUs) per module is specified for this concept.

As depicted in Fig. 1, a Modular Mobile Terminal is composed of 4 modules coupled to a central module with a mounted crane. It is estimated that the crane will make up to 20 container moves per hour. When assembled into a Modular Mobile Terminal, all the modules will have a mooring system that will create a rigid connection between the barges. This rigid connection will increase the stability of the coupled units providing less heeling movements during cargo handling.

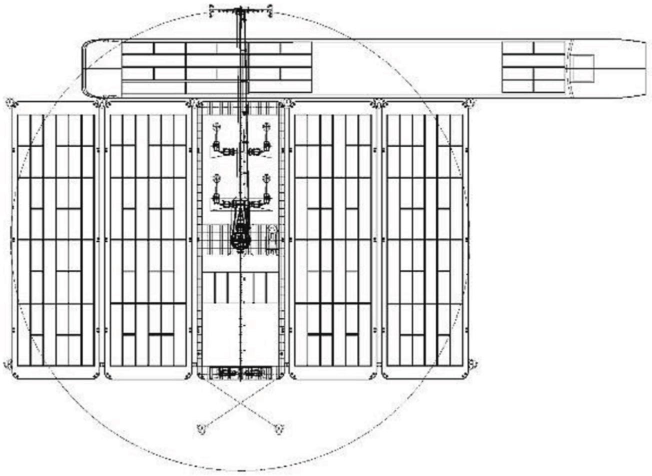

Fig. 1. Modular Mobile Terminal in action (Thill, et al., 2022).

The envisaged operation of the system is that inland waterway vessels collect containers from the inland ports. The container cargoes have different destinations, i.e., different seaport terminals. When the IWV reaches the seaport, instead of calling at different terminals to drop and pick up containers as it is currently, the IWV will instead moor at the Export MMT (see Fig. 2). The crane module will be the center point of the operation, unloading the IWV and distributing the cargo to the shuttle modules. Once the shuttle modules are sufficiently loaded, they are towed/pushed by a push boat to transport the containers to the specified seaport terminal. Each module will make a dedicated call to a single seaport terminal where the containers can finally be unloaded. The shuttle modules will also be used to transport import cargoes by transporting containers from the seaport terminal to the import MMT, where the modules are moored. At the import MMT, the crane module will transfer the cargo from the shuttle modules to an IWV for transport to the destination inland port, as shown in Fig. 2.

As mentioned earlier, the technical feasibility of a floating crane has already been demonstrated in the Port Feeder Barge project. However, the economic factors were not detailed in-depth, and this project suffered from the defiance of terminal operators (Malchow, 2020). Based on this, the concept within the Port Feeder Barge project was not further pursued (N.N., 2021; Soyka, 2020). The MMT concept proposed in the present work is similar to the Port Feeder Barge. However, to prevent similar a setback, the potential benefits for the logistics actors are carefully highlighted in this study. In particular, this work aims to dive

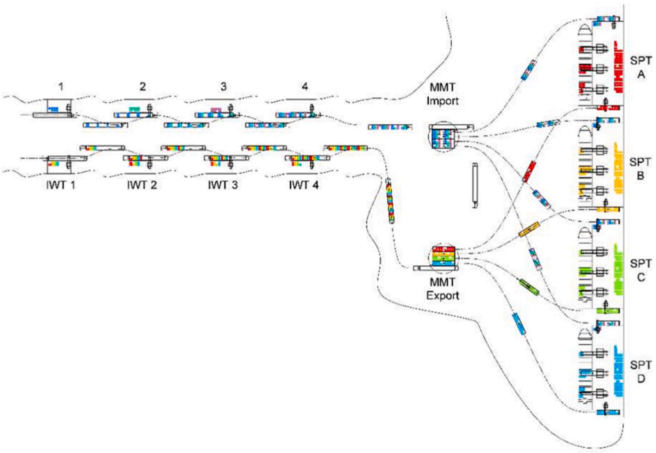

Fig. 2. Envisaged operation of the MMT concept (Ramne, et al., 2021). Although this illustration shows MMTs operating at separate locations, the import and export handling can be arranged at the same location.

further into the logistical and economic aspects of the modular terminal. The expected benefits of this innovation will be demonstrated via time optimization and cost models. The final goal is to understand better this concept's advantages for the involved actors (barge operators, terminal operators, and shippers).

Although this illustration shows MMTs operating at separate locations, the import and export handling can be arranged at the same location.

4. Assessment methodology

The proposed methodology approaches the MMT concept from the time and cost perspective. The MMTs should generate time savings for inland waterway vessels sailing between the deep-sea terminals and the hinterland to be effective. They must also be economically viable for the barge operators and the shippers. Fig. 3 shows the main steps of the assessment methodology: firstly, an optimization model computes the number of MMTs, frequency of shuttles, and linked regions that maximize the overall time savings of the vessels. These figures are then used to estimate the costs induced by the MMTs per region. Next, the time savings model also returns the utilization rate of MMTs under the optimal configuration. This rate is then used in the investment analysis to determine the handling fee the MMT operator should pay to make the investment profitable. This handling fee is used with the MMT-related costs to estimate the net benefits of using the MMTs compared to the base situation (without MMTs).

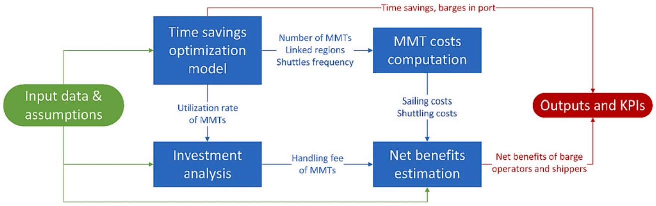

Fig. 3. Proposed assessment methodology.

The remainder of this section is as follows: first, the modeling of the MMT concept and its operations is defined. The time savings model is then presented before concluding with the economic evaluation.

4.1. Modular terminals operations

The MMT concept is applied to a seaport environment, denoted S, and its hinterland. The former is represented as a set of sea terminals I and the latter as a set of regions R. Each region has a given container transport demand via IWT to and from the seaport and some IWT services to satisfy it. Each IWV performs a roundtrip between a given region and the seaport. In the seaport area, it has to sail between multiple sea terminals to load and unload containers.

We consider that the MMTs, denoted M, are located near the seaport area and linked to some of the hinterland regions: then, all inland vessels to and from these regions are handled by the MMTs. For regions not linked to the MMTs, the operations of each IWV will not change compared to the base case. However, the vessels serving the linked regions will no longer call at the sea terminals but only at the MMTs. The MMT modules will then be shuttled by push barges between MMTs and sea terminals.[1] This concept is illustrated, together with the base case, in Fig. 4.

Based on Fig. 2, the MMTs will operate in pairs: one export MMT and

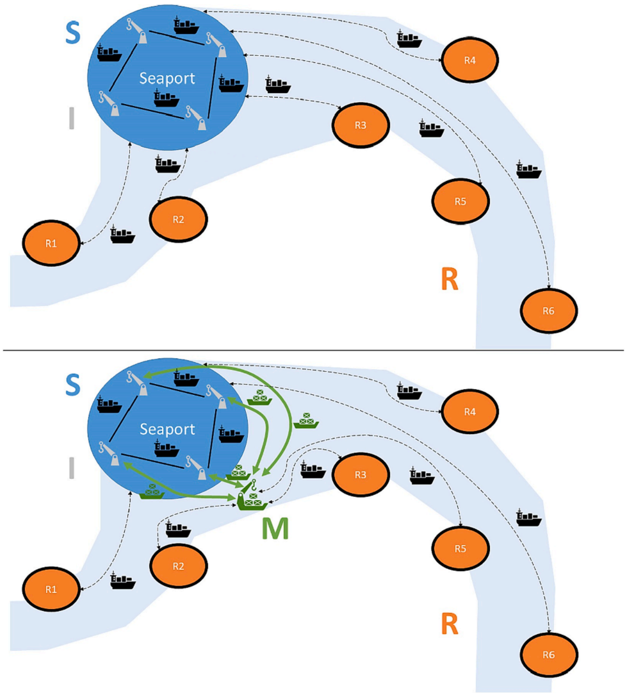

Fig. 4. Schematic representation of base case scenario (up) and situation with MMTs where regions 2,3,5 are linked (down). The inland vessels serving these regions will no longer call at sea terminals but only at MMTs. There, containers are loaded on barge modules to be shuttled to a dedicated sea terminal (green arrows).

Table 1
Time parameters and decision variables.

Notation	Unit	Description
PARAMETERS		
$\lvert I\rvert$	–	Number of deep-sea terminals in set I
t_i^{hand}	hr/ TEU	Handling time at deep-sea terminal i per container
t_S^{sail}	hr	Average sailing time between two sea terminals, incl. maneuverings
t_{ik}^{wait}	hr	Waiting time at deep-sea terminal i for an inland vessel for month k
F_{rk}	–	Number of services between seaport and region r during month k
D_{irk}	TEUs	Transport demand between sea terminal i and region r for month k
D_{rik}	TEUs	Transport demand between region r and sea terminal i for month k
t_{Sr}	hr	Sailing time between seaport area and hinterland region r
t_{rS}	hr	Sailing time between hinterland region r and seaport area
Q	TEUs	The capacity of an MMT module
t_M^{wait}	hr	Waiting time at MMT for an inland vessel
t_M^{hand}	hr/ TEU	Handling time at MMT per container
t_{MS}^{sail}	hr	Sailing time between MMT and seaport area, incl. maneuverings
t_{MM}^{man}	hr	Maneuvering time between import and export MMTs
N^{max}	–	Maximum number of MMTs allowed in the seaport area
H^{max}	hr	Maximal monthly time of operations for an MMT
VARIABLES		
$x_k^{in} \in \mathbb{N}$		Number of import MMTs operated during month k
$x_k^{ex} \in \mathbb{N}$		Number of export MMTs operated during month k
$y_{rk} \in \{0,1\}$		Whether region r is linked to MMTs for month k
$z_{ik} \in \mathbb{N}$		Total number of shuttles between MMTs and terminal i for month k

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[1] Since each module is dedicated to a single sea terminal, a fixed and regular timeslot can then be agreed with the terminal. It is thus assumed that shuttles will experience no waiting time.

one import MMT. Moreover, each module of an MMT is associated with only one specific sea terminal. The IWVs from the hinterland will first moor at the export MMT to unload their containers. When empty, they can moor to the import MMT, where containers from the seaport to the hinterland can be loaded. Finally, they will unmoor to sail back to the hinterland.

Regarding the shuttles, once a module of the export MMT is full, it is detached and shuttled to its dedicated sea terminal, where the containers are unloaded. Then containers with a destination to the hinterland are loaded, and the module is shuttled back to the import MMT, replacing an empty module. Finally, the empty module is returned and attached to the export MMT.

4.2. Time savings optimization model

The potential time savings achieved through MMTs are evaluated using a dynamic optimization model to determine which regions should be linked to the MMTs to minimize the total time of all barges in the system. The parameters and decision variables used in the model are presented in Table 1. Due to the dynamicity, the variables and some parameters are time-dependent: we thus introduce the index $k \in K = [1, 12]$ to represent the monthly variations.

The objective of the dynamic model is to minimize the total time spent by all barges during a year in the system depicted in Fig. 4. It is expressed as a sum of several components over twelve months. The first one is the sailing time of IWV between the hinterland and the seaport area:

$$T_k^R = \sum_{r\in R} F_{rk}(t_{rS} + t_{Sr}) \tag{1}$$

The three following components are related to the seaport: the service time at terminals $T_k^{S,serve}$, the time spent waiting to be served at deep-sea terminals for IWVs $T_k^{S,wait}$ and the time spent by IWVs sailing between deep-sea terminals $T_k^{S,sail}$:

$$T_k^{S,serve} = \sum_{r\in R}\sum_{i\in I} t_i^{hand}(D_{rik} + D_{irk}) \tag{2}$$

$$T_k^{S,wait} = \sum_{i\in I} t_{ik}^{wait} \sum_{r\in R}(1 - y_{rk})F_{rk} \tag{3}$$

$$T_k^{S,sail} = \sum_{r\in R} F_{rk} t_S^{sail}(1 - y_{rk})|I| \tag{4}$$

Four additional terms relate to the MMTs: the time for inland vessels being served by MMT $T_k^{M,serve}$, the waiting time at MMT for inland vessels $T_k^{M,wait}$, the sailing time of shuttles between MMT and the seaport area $T_k^{M,sail}$ and the maneuvering time between import MMT and export MMT T_k^{MM}:

$$T_k^{M,serve} = t_M^{hand} \sum_{r\in R}\sum_{i\in I} y_{rk}(D_{rik} + D_{irk}) \tag{5}$$

$$T_k^{M,wait} = 2t_M^{wait} \sum_{r\in R} y_{rk} F_{rk} \tag{6}$$

$$T_k^{M,sail} = 2t_{MS}^{sail} \sum_{i\in I} z_{ik} \tag{7}$$

$$T_k^{MM} = t_{MM}^{man}\left[\sum_{r\in R} y_{rk}F_{rk} + \sum_{i\in I} z_{ik}\right] \tag{8}$$

The objective function of the dynamic model is, therefore[2]:

$$\min\Phi = \sum_{k\in K} T_k^R + T_k^{S,serve} + T_k^{S,wait} + T_k^{S,sail} + T_k^{M,serve} + T_k^{M,wait} + T_k^{M,sail} + T_k^{MM} \tag{9}$$

Table 2
Cost parameters.

Notation	Unit	Description
$\boldsymbol{R_t}$	€	Net cash flow (inflow-outflow) in a single year *t*
$\boldsymbol{r}$	%	Discount rate
$\boldsymbol{t}$	years	Number of periods
$\boldsymbol{F_c}$	€	Cash flow
$\boldsymbol{R_L}$	€	Loan repayment
$\boldsymbol{x^*}$	€	The optimum handling price that can be charged
$\boldsymbol{O(x)}$	€	The upper-bound handling price
$\boldsymbol{x}$	€	The lower-bound handling price
$\boldsymbol{C_{\frac{tot}{teu}r,i,k}}$	[€/TEU]	Total cost per TEU between region *r* and terminal *i* for month *k*
$\boldsymbol{C_{\frac{tot}{hr}r,i,k}}$	[€/hr]	Total costs per hour between region *r* and terminal *i* for month *k*
$\boldsymbol{T_{tr,i,k}}$	[hr]	Total transport time between region *r* and terminal *i* for month *k*
$\boldsymbol{n_{TEUr,i,k}}$	TEUs	Number of TEUs transported between region *r* and terminal *i* for month *k*
$\boldsymbol{n_{TEU/trip}}$	TEUs	Number of TEUs transported per trip by the shuttle barge between the mobile terminal and the deepsea terminal.
$\boldsymbol{C_{total,mto}}$	[€/TEU]	The total cost of using the mobile terminal as transshipment
$\boldsymbol{C_{mt}}$	[€/TEU]	Cost of sailing and handling at the mobile terminal
$\boldsymbol{C_{sdt}}$	[€/TEU]	Cost of using the shuttle and sailing to a specific deep-sea terminal
$\boldsymbol{C^{mt}_{\frac{tot}{trip}}}$	[€/trip]	The total cost of sailing to and handling at the mobile terminal
$\boldsymbol{C_{\frac{fix}{trip}}}$	[€/trip]	Total fixed cost
$\boldsymbol{C_{\frac{var}{trip}}}$	[€/trip]	Total variable cost
$\boldsymbol{C_{\frac{fuel}{trip}}}$	[€/trip]	Total fuel cost
$\boldsymbol{C_{fix}}$	€	Fixed cost
$\boldsymbol{T_{port}}$	hr	Port time
$\boldsymbol{T_{idle}}$	hr	Idle time
$\boldsymbol{C_{maintenance}}$	€	Maintenance cost
$\boldsymbol{C_{\frac{fuel}{l}}}$	[€/litre]	Fuel cost per liter
$\boldsymbol{F_{sail}}$	litre	Total fuel consumed sailing
$\boldsymbol{F_{idle}}$	litre	Total fuel consumed idle
$\boldsymbol{x_k^{in.ex}}$	–	The number of import and export mobile terminals visited
$\boldsymbol{C^{sdt}_{\frac{tot}{trip}}}$	[€/trip]	The total cost of shuttle transport from the mobile terminal to the deepsea terminal
$\boldsymbol{t_{MS}^{port}}$	hr	Port time of shuttle barges between the mobile and deepsea terminals
$\boldsymbol{t_{ms}^{wait}}$	hr	Waiting time of shuttle barges at the deepsea terminals
$\boldsymbol{S_o^b}$	[€/TEU]	Cost savings of the barge operator per trip
$\boldsymbol{S_s}$	[€/TEU]	Cost savings of shippers per trip
$\boldsymbol{\overline{q}}$	[€/TEU]	Aggregated cost savings for actors per case
$\boldsymbol{\sum_{ij} x_{ij} y_{ij}}$	€	Sumproduct of cost savings per region per month weighted against the total volume transported per region per month
$\boldsymbol{\sum y_{ij}}$	TEUs	Total TEUs transported for all months and regions

The time optimization model is subject to several constraints. The first ones limit the number of hours that each import and export MMT can operate per month. This is represented as:

$$\sum_{i\in I}\sum_{r\in R} y_{rk} D_{irk} t_M^{hand} \le H^{max} x_k^{in} \qquad \forall k \in K \tag{10}$$

$$\sum_{i\in I}\sum_{r\in R} y_{rk} D_{rik} t_M^{hand} \le H^{max} x_k^{ex} \qquad \forall k \in K \tag{11}$$

The second set of constraints imposes the required frequency of shuttles to a sea terminal *i* given import and export demand, respectively, and the capacity of a module. The shuttles' frequency will then be set in the direction with the most demand:

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[2] Here, it is assumed that all those time components are equally important. But some weights could also be applied in the objective function to give more or less importance to some components.

$$\sum_{r\in R} y_{rk} D_{irk} \leq Q z_{ik} \qquad \forall i \in I, \forall k \in K \tag{12}$$

$$\sum_{r\in R} y_{rk} D_{rik} \leq Q z_{ik} \qquad \forall i \in I, \forall k \in K \tag{13}$$

The third set of constraints ensures that the number of shuttles to terminal i is null if there are no regions linked to the MMTs (note that M is a large enough positive number):

$$z_{ik} \leq M \sum_{r\in R} y_{rk} \qquad \forall i \in I, \forall k \in K \tag{14}$$

The fourth set of constraints determines how many import and export MMTs are needed to make the shuttles' frequency possible. It is assumed that only two modules per MMT per day can be shuttled to the sea terminals, whereas the other two remain at the MMT to hold the incoming/outgoing cargo. The number of MMTs should then equal the rounding up of the shuttles' frequency per day divided by two. The constraints are thus expressed as follows:

$$\frac{\sum_{i\in I} z_{ik}}{30} \bigg/ 2 \leq x_k^{in} \qquad \forall k \in K \tag{15}$$

$$\frac{\sum_{i\in I} z_{ik}}{30} \bigg/ 2 + 1 \geq x_k^{in} \qquad \forall k \in K \tag{16}$$

$$\frac{\sum_{i\in I} z_{ik}}{30} \bigg/ 2 \leq x_k^{ex} \qquad \forall k \in K \tag{17}$$

$$\frac{\sum_{i\in I} z_{ik}}{30} \bigg/ 2 + 1 \geq x_k^{ex} \qquad \forall k \in K \tag{18}$$

The final constraints prevent the total number of MMTs exceeds the maximal number allowed in the seaport area:

$$x_k^{in} + x_k^{ex} \leq N^{max} \qquad \forall k \in K \tag{19}$$

As a point of comparison, we introduce the total time of the base case scenario, where no MMTs are used. It can be expressed as:

$$\Phi^{\text{base}} = \sum_{k\in K}\sum_{r\in R}\left[F_{rk}(t_{rS} + t_{Sr}) + \sum_{i\in I} t_i^{hand}(D_{rik} + D_{irk}) + F_{rk}\left(\sum_{i\in I} t_{ik}^{wait} + t_S^{sail}|I|\right)\right] \tag{20}$$

We also define Key Performance Indicators (KPIs) to evaluate the MMT concept's efficiency further. The first one is the total number of vessels N^{port} (IWVs and shuttles) sailing in the seaport during a whole year, which is calculated with:

$$N^{port} = \sum_{k\in K}\left[\sum_{r\in R}(1 - y_{rk}^{*})F_{rk} + \sum_{i\in I} z_{ik}^{*}\right] \tag{21}$$

where z_{ik}^{*} is the optimal value of z for terminal i at month k and y_{rk}^{*} The optimal value of y for region r at month k (note that for the base case, y_{rk}^{*} and z_{ik}^{*} will be set to zero as there are no MMTs involved). This KPI reflects the level of congestion for the IWVs in the port.

The second KPI is the time savings ΔT per inland waterway vessel linked to the MMTs:

$$\Delta T = \frac{\Phi^{\text{base}} - \Phi^{*}}{\sum_{k\in K}\sum_{r\in R} y_{rk}^{*} F_{rk}} \tag{22}$$

Finally, we report the average occupation rate $\overline{\rho}$ for the MMTs over a whole year. This indicator will show if the MMTs are used efficiently and is expressed as:

$$\overline{\rho} = \frac{1}{12}\sum_{k\in K}\frac{\sum_{r\in R}\sum_{i\in I} y_{rk}^{*}(D_{rik} + D_{irk})}{(x_k^{in*} + x_k^{ex*})U^{\max}} \tag{23}$$

where x_k^{in*} and x_k^{ex*} are the optimal numbers of import and export MMTs at month k and $U^{\max}$ the maximal handling capacity of an MMT crane module during a month.

4.3. Economic evaluation

After time optimization and selecting the appropriate regions to be connected to the MMTs, the regions are further analyzed from the economic perspective to determine the economic feasibility of using the MMTs for the actors in these regions. To do this, the economic viability model is specified. This model estimates the overall net benefit of each actor and determines what conditions would generate overall cost savings from using the MMTs. Aside from the parameters specified in Table 1, further cost parameters are specified in Table 2 for the cost model.

The cost model is represented in three parts. The first part focuses on the investment analysis of the MMTs. Meanwhile, the second and third parts focus on the cost computation and net benefits of both the barge operators and shippers.

4.3.1. Investment analysis

The investment analysis is conducted by calculating the Net Present Value (NPV) of the MMTs handling and transshipment operations. This type of analysis is the generally used method to determine the viability of a project by calculating the current and future cash flow, capital investment, and terminal values generated within a given project. This is calculated as:

$$NPV = \sum_{t=0}^{n}\frac{R_t}{(1+r)^t} \tag{24}$$

$$R_t = F_c - R_L \tag{25}$$

R_t, F_c, and R_L are calculated based on specified steps. The steps are presented in Table 3 based on the specification of van Hassel (2011) and de Langhe (2019). According to the table, the first step is to derive the total operating income for the MMT. This income includes all revenues from operating the mobile terminal. Step two is to determine the total cost of operating the MMT. This consists of the maintenance, labor, and variable technological costs. Next is calculating the overhead cost, including insurance, legal fee, and marketing cost. After this, the Earnings Before Interest, Tax, Depreciation, and Amortization (EBITDA) is calculated by subtracting the operational and overhead costs from the operating revenue.

In step 5, the depreciation is calculated by dividing the capital and fixed technological investments invested over the project's life span. This result is subtracted from EBITDA to give the operational effect in step 6. Step 7 calculates the interest payable per year by multiplying the loan by the interest on the loan. The result is subtracted from the

Table 3
Investment analysis steps.

Step	Items	Calculation
1	Revenues	Operational income
2	Operational cost	Maintenance + labor + variable technological cost
3	Overhead cost	Insurance + legal fees
4	EBITDA	1 – (2 + 3)
5	Depreciation	Capital and fixed technological investments/project lifespan
6	Operational result	4 – 5
7	Interest	Loan * interest on the loan
8	EBT	6 – 7
9	Tax	If 8 <= 0, 0; otherwise 8 * tax rate
10	EAT	8 – 9
11	Cash flow (F_c)	10 + 5
12	Loan repayment (R_L)	Loan/payback period
13	Net cash flow (R_t)	11 – 12

operational result to give Earnings Before Tax in step 8 (EBT). In step 9, the payable tax is calculated. Tax can only be calculated if the EBT is greater than 0; otherwise, no tax is charged on the investment. The deductible tax is derived by multiplying the EBT by the specified company tax rate in the country. This leads to step 10, which is the Earnings After Taxes (EAT). In step 11, the investment's cash flow is calculated by adding EAT (step 10) with depreciation (step 5). The payback loan for the project is then calculated in step 12 by dividing the initial loan by the payback period of the loan. This leads to step 13, where the net cash flow is obtained. This is derived by subtracting the payback loan (step 12) from the cash flow (step 11).

Source: Own composition based on van Hassel (2011) and de Langhe (2019).

For this type of project, a 6 % discount rate is deemed appropriate, as it is considered to be a long-term investment with an average life span of 30 years (van Dorsser, 2015). The overall objective of the MMT operator in this type of investment is to generate a positive NPV which would ensure that the costs of investment are covered while also yielding a positive return. Hence, to ensure a positive NPV, an optimization technique is performed on the NPV calculation that iterates through the costs elements, the rate of return, and the potential net cash flow. This iteration generates an optimal handling price to generate a positive revenue stream that can cover the different cost levels (capital and operating costs), ensuring a positive NPV. To achieve this type of iteration, a while loop was created that iterates over the handling price, corresponding cash flows, and the discount rate and returns the corresponding NPV and price of the iteration. If the NPV remains negative, the loop continues by adding 0.1 % to the current handling price and rerunning the cashflows and the NPV until it reaches an optimum handling price that returns a positive NPV as long as the optimum price is not greater than the set upper bound price. A simple representation of this iteration loop is specified below:

$$x^* = x$$

$$\text{While } x^* < O(x):$$

$$\text{Step 1}: \; NPV = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t}$$

$$\text{Step 2}: \; if \; NPV > 0 \rightarrow break$$

$$\text{Step 3}: \; x^* = 1.001x^*$$

$$\text{Return}: \; x^* \; and \; NPV$$

where $O(x)$ is the estimated price charged at the deepsea terminal. This is specified as EUR 41.01 per TEU from the model of van Dorsser (2015). The lower bound handling price, however, is the minimum handling price of the mobile terminal without a markup margin. This price is calculated based on the capital and operating costs and the actual utilization rate estimated within the investment model. These cost elements are derived from Ramne, et al. (2021) in the cost description of the mobile terminal concept.

4.3.2. MMT costs computation

The second part of the cost representation deals with the cost estimation of transporting the containers from the selected regions to the seaports. This analysis is performed for the two cases (base case and concept case). For the base case, the analysis elaborates on the cost implication of transporting from the linked regions directly to the deepsea terminals. This analysis is represented as follows:

$$C_{\frac{tot}{teu}r,i,k} = \frac{C_{\frac{tot}{hr}r,i,k} * T_{tr,i,k}}{n_{TEUr,i,k}} \tag{31}$$

where $C_{\frac{tot}{hr}r,i,k}$ entails the fixed and variable costs, while $T_{tr,i,k}$ comprises the sailing time, port time, and idle time. Detailed specifications on these parameters are discussed in Shobayo et al., (2021a). Meanwhile, $n_{TEUr,i,k}$ is the actual number of cargoes transported. This is based on the cargo flow between the region r and the service level of the vessel.

The project case cost analysis elaborates on the cost implication of using the MMTs as a transshipment hub rather than having direct transport to the sea terminals. This calculation follows the same approach as the direct sailing analysis. However, significant changes occur in the time spent in port, thus affecting the total transport time. This is because using the MMTs means the container barges do not have to visit different sea terminals; instead, they sail to the import/export MMT pair to pick up/drop off containers. However, the cost of transporting from the MMTs to the specific sea terminal by shuttles needs to be considered (32). This is then factored in and specified as:

$$C_{total,mto} = C_{mt} + C_{sdt} \tag{32}$$

$$C_{mt} = \frac{C^{mt}_{tot/trip}}{n_{TEU/trip}} \tag{33}$$

$$C^{mt}_{tot/trip} = C_{fix/trip} + C_{var/trip} + C_{fuel/trip} \tag{34}$$

$$C_{fix/trip} = C_{fix} * (t_{rS} + T_{port} + T_{idle}) \tag{35}$$

$$C_{var/trip} = C_{maintenance} * (t_{rS} + T_{idle}) \tag{36}$$

$$C_{fuel/trip} = C_{fuel/l} * (F_{sail} + F_{idle}) \tag{37}$$

$$T_{port} = \left(t_M^{wait} * x_k^{in.ex}\right) + \left(n_{TEUr,i,k} * t_M^{hand}\right) + t_{MM}^{man} \tag{38}$$

$$T_{idle} = 0.1 * (t_{rS} + T_{port}) \tag{39}$$

$$C_{sdt} = \frac{C^{sdt}_{tot/trip}}{n_{TEU/trip}} \tag{40}$$

$$T_k^{M,sail} = 2t_{MS}^{sail} \tag{41}$$

$$t_{MS}^{port} = \left(n_{TEUr,i,k} * t_i^{hand}\right) + t_{ms}^{wait} + t_{MM}^{man} \tag{42}$$

The cost of sailing and handling at the mobile terminal is specified as the total cost per TEU of sailing and handling at the mobile terminal (33). This cost comprises the fixed cost per trip, variable cost per trip, and fuel cost per trip (34). To estimate the fixed cost per trip, a specified fixed cost is multiplied by the total transport time of the vessel (35). The transport time comprises the sailing time from the hinterland region to the seaport area (see Appendix A), the port time, and the idle time. The port time includes the waiting time at each terminal multiplied by the number of import–export mobile terminals, the handling time per TEU multiplied by the number of TEUs transported, and the maneuvering time at the mobile terminals (38). The idle time in the model is specified as the time that the vessel's engine is running without any operation on the vessel either sailing or handling (39). This time is estimated at 10 % of the port and sailing times based on van Dorsser (2015) model. The specified fixed cost is estimated at EUR 86.64 based on calculations from van Dorsser (2015) and Shobayo et al. (2021b). The variable cost per trip is specified as the cost of maintenance multiplied by the sailing time and the idle time (36). Meanwhile, the fuel cost per trip is estimated by multiplying the fuel cost per liter by the fuel consumption while sailing and idle consumption (37).

The same approach was also applied to the shuttle transport cost per trip from the mobile terminal to deep sea terminals, with significant changes to the sailing time and port time (40). In this case, the sailing time is the time the shuttle service sails back and forth to the deepsea and mobile terminals (41). In contrast, the port time (42) includes the waiting time at deepsea terminals (assumed to be 0), the maneuvering time, and the handling time of the containers at the terminal (handling time per TEU multiplied by the TEUs transported).

4.3.3. Net benefits estimation

The third part calculates the barge operator and shippers' net benefits. In doing this, the base case is compared to the project case, and the net savings are estimated for the barge operators and shippers, respectively. These are specified as follows:

$$S_o^b = C_{tot/teur,i,k} - C_{mt} - x^* \tag{43}$$

$$S_s = C_{tot/teur,i,k} - C_{total,mto} - x^* \tag{44}$$

These cost savings are aggregated per case. To do so, the net savings per month per region are weighted against the transported volumes for that month and region. The total of these then gives a net benefit of the case for the linked regions and the months within each case. The total net benefit is divided by the total volumes transported within the case to get the aggregated cost savings per TEU. Based on this, the aggregated cost savings $\overline{q}$ is specified as:

$$\overline{q} = \frac{\sum_{ij} x_{ij} y_{ij}}{\sum y_{ij}} \tag{45}$$

5. Case study

The proposed assessment methodology is applied to a case study, where the use of Modular Mobile Terminals is investigated for the ports of Rotterdam and Antwerp. For both seaports, it is assumed that each inland waterway vessel has to visit four sea terminals, where the handling capacity is 20 TEUs per hour (thus a handling time of 0.05hr/TEU). The waiting time of an IWV at each sea terminal is estimated at an average of 4 h during each terminal visit (van Hassel, et al., 2021) and sailing time between these sea terminals is set to 1 h (including maneuverings).

The data concerning hinterland container transport (using waterways) is reported in Appendix A. In particular, each seaport contains:

- the yearly import and export demand to and from each hinterland region represented at the NUTS-2 level[3];
- the distance of each region from the seaport;
- the sailing time between each region and the seaport;
- the yearly number of inland waterway transport services between each region and the seaport;
- and the average number of containers per inland waterway service.

The container volume data come from the ASTRA model (Fiorello, Fermi, & Bielanska, 2010) for 2021. This demand is assumed to be split evenly between all the visited sea terminals. The distance is estimated by (van Hassel, et al., 2019). The sailing times are issued from a cost and time model (Shobayo et al., 2021b, whereas the data concerning IWT services come from the NOVIMOVE project (Majoor, et al., 2021). Note that the number of monthly services is assumed constant and obtained by dividing the yearly services by twelve. Finally, the average number of containers per service is computed by dividing the volumes by the number of services.

Some seasonality factors are used to derive the monthly transport demand between each seaport and each region. They represent the share of the total demand in a given month and are estimated using historical data from container transport on the Rhine between 1993 and 2020 (Rhineforecast, 2021). Fig. 5 shows the factors corresponding to a typical year and the ones corresponding to the year 2018, when a major drought occurred on the Rhine, thus disrupting transport via water with capacities of IWVs decreased from a factor 4 to 5 (van Dorsser, Vinke, Hekkenberg, & van Koningsveld, 2020). For a typical year, those factors remain relatively stable, varying between 7.6 % and 9.1 %. However, the interval is much broader for 2018 (between 5 % and more than 10.5 %), with a peak in demand in March but particularly a very low demand in the last quarter of the year due to the low water levels.

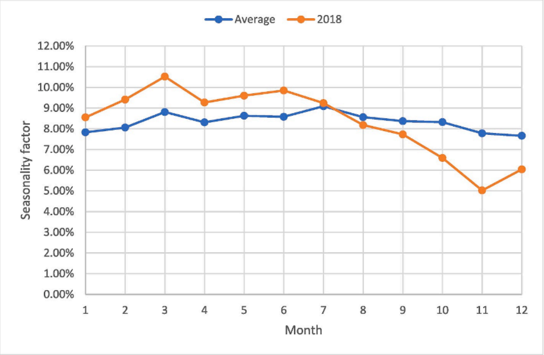

Fig. 5. Seasonality factors for an average year and year 2018, with a high seasonality pattern (Rhineforecast, 2021).

Regarding the parameters related to the MMTs, each module is a capacity equal to 138 TEUs. The handling time of the crane module is set to 0.05hr/TEU, and its maximal handling capacity during a month to 10,000 TEUs. Each inland vessel is assumed to experience a waiting time of one hour before being handled both at the import and export MMTs. Moreover, a maneuvering time of 15 min between the import and export MMTs is considered. The maximum number of MMTs allowed in the seaport is 8 for both seaports, and the sailing time of shuttles between their sea terminal and the MMTs is estimated to be 1.65 h for Rotterdam and 1.05 h for Antwerp. These last figures are based on a preceding study that evaluated some locations potentially suitable for MMTs in these seaports (Freling, Nicolet, & Atasoy, 2022).

The MMT modules and cranes have an estimated life span of 30 years, with a capital cost of EUR 1,042,000 per MMT module, EUR 30,000 for spud poles per module, and a crane cost of EUR 940,000. The MMT is estimated to have a residual value of 30 % of the initial capital investment. Other operational costs include insurance, estimated at 2 % of the capital investment, labor costs, assumed to be EUR 60,000 per year; and other overhead expenses, estimated at EUR 225,000 per year. An indexation rate of 1.4 % and a profit tax of 33 % are employed in the analysis. The costs are estimated in Ramne, et al. (2021), while the operational assumptions are based on (Shobayo et al., 2021b), and van Dorsser (2015).

Using the aforementioned inputs, the optimal configuration of MMTs will be determined for both seaports for a typical year and for a year with high seasonality to highlight the differences. In particular, for each month, the analysis determines the number of import and export terminals, the shuttles' frequency, and regions linked to the MMTs to minimize the total time spent by all vessels in the system. The KPIs corresponding to this optimal solution and the net benefits for barge operators and shippers are also reported.

Notably, the optimal number of MMTs could vary from month to month to match the demand variations. Nevertheless, from a financial point of view, investing in an asset that will be underutilized or only be used for part of the year is not desirable. Hence, further computations are performed, where the number of MMTs is fixed throughout the year. This experience is conducted for 1, 2, 3, and 4 pairs of import–export MMTs to compare the performance of each configuration and evaluate the most favorable one.

Once the most beneficial configuration is determined, it will undergo a sensitivity analysis to address the effects of cost underestimation on the profitability of MMTs. In particular, we study the impacts of a 50 % increase in the module, crane, labor and overhead costs specified above

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[3] The NUTS (Nomenclature of Territorial Units for Statistics) is the official division of the EU and the UK for regional statistics (European Commission & Eurostat, 2020).

and a 50 % decrease in the life span on the net benefits. The analysis is conducted by varying each cost component separately as well as varying them together. Finally, as it is unlikely that all costs face a 50 % underestimation at the same time, we perform a Monte Carlo simulation assuming that the variation of each component follows a uniform distribution between 0 % and 50 %. The net benefits computation is repeated 1000 times, each time drawing different error values for each component, so as to obtain confidence intervals on the potential net benefits.

In the following subsections, the optimal solution (with a variable number of MMTs through the year) in terms of time savings is first presented with the cost indicators to get insights into the impact of MMTs. Secondly, the results with a fixed number of MMTs are described. Thirdly, the outcomes of the sensitivity analysis are reported. Finally, the practical implications are discussed in more detail.

5.1. Optimal solution

The main results of the dynamic time savings optimization for the ports of Rotterdam and Antwerp are shown in Table 4. Three cases are presented: the base case where no MMTs are deployed and two cases with MMTs (one typical year and one year with high seasonality).

In almost all cases, the number of mobile terminals is set to 8 (4 import and 4 export) for each month of the year. Only the case with high seasonality for Antwerp has some variations in the number of MMTs deployed per month, which results in an average number of active import and export MMTs of 3.5 through the year. That is why the average number of shuttles per month between the MMTs and each sea terminal is only 50 in that case against around 60 for the other cases. These values represent between 14 and 15 shuttles per pair of modular terminals each month, thus a shuttle departure every two days. The average number of linked regions is noticeably higher for Antwerp than for Rotterdam. This is caused by the latter port having much greater cargo volumes per region.

For time savings, the MMTs significantly reduce the total time spent by all ships in the system: more than 7 % for Rotterdam and 5 % for Antwerp. This reduction becomes more pronounced if the time in the hinterland is not considered: Fig. 6 shows how the total time is split between sailing, serving, and waiting in the seaport and at the MMTs. It appears that a considerable reduction in the waiting time at deep-sea

Table 4
Summary of results (value of objective function, average number of MMTs, average frequency to each deep-sea terminal, average number of linked regions).

	ROTTERDAM				ANTWERP			
	Φ[hr]	$\bar{x}^{in} = \bar{x}^{ex}$	$\bar{z}$	$\bar{y}$	Φ[hr]	$\bar{x}^{in} = \bar{x}^{ex}$	$\bar{z}$	$\bar{y}$
BASE CASE	888,424	–	–	–	612,959	–	–	–
MMTs	820,163 (-7.7 %)	4	60	7.7	581,614 (-5.1 %)	4	58	13.5
MMTs 2018	819,227 (-7.8 %)	4	56	8.4	579,699 (-5.4 %)	3.5	50	12.9

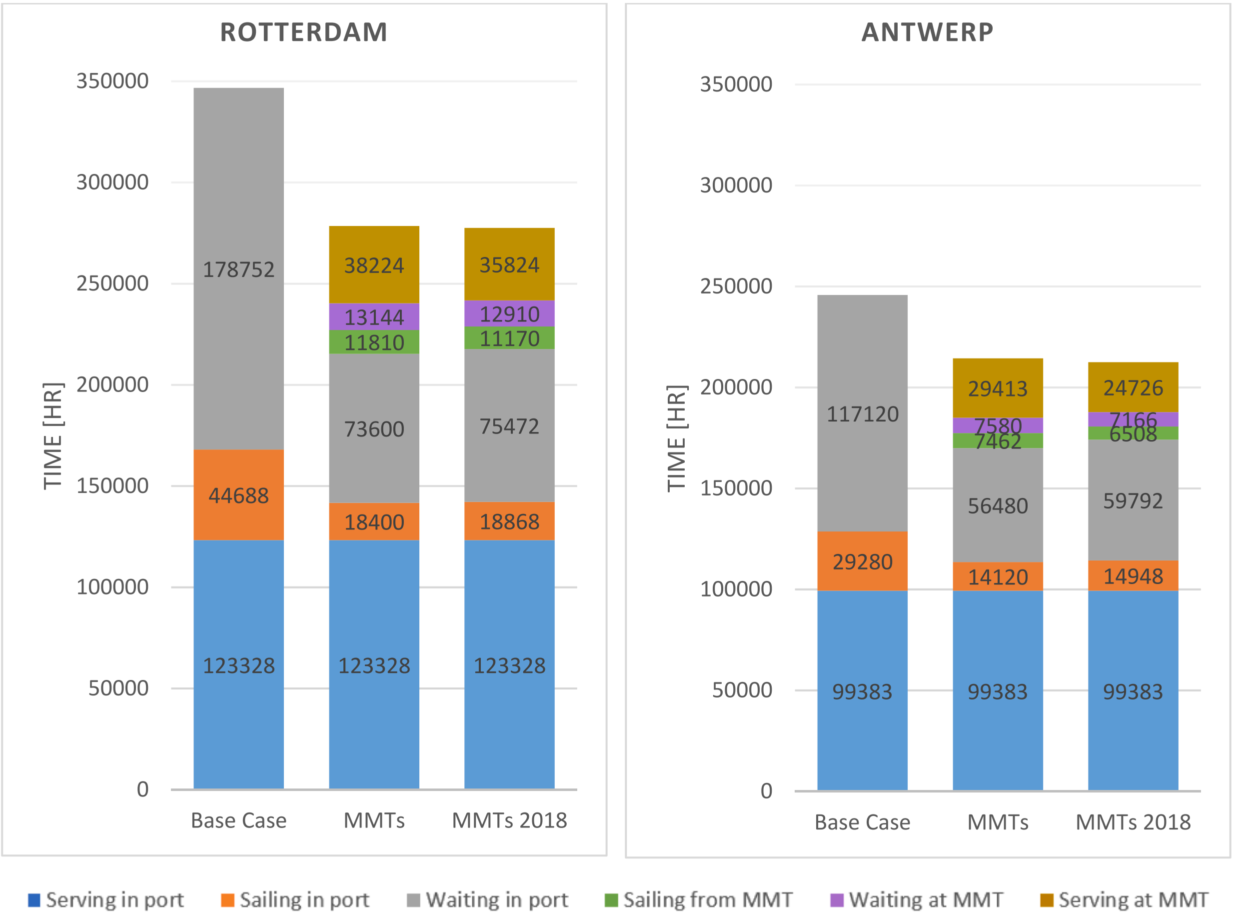

Fig. 6. Detail of time spent in the seaport and at MMTs.

Table 5
Considered regions of Rotterdam's hinterland with the average number of TEUs per vessel, the total container volume and number of services, and the number of months when the region is linked to MMTs for 2018.

Region	Average TEUs on IWVs	Yearly volume [TEUs]	Yearly numberof services	Number of months linked to MMTs
DE13	28	4,224	75	12
NL41	41	259,597	3,189	12
NL42	41	82,342	1,000	12
DE12	49	16,213	163	12
NL22	61	80,950	654	12
NL34	92	73,676	400	9
NL32	108	215,667	993	9
DEA2	123	59,523	240	4
FRF1	131	38,375	146	4
BE22	141	52,766	189	4
DE11	146	4,648	16	2
NL31	148	92,839	312	3
DE71	159	50,655	160	2
DEB1	166	19,162	58	3
BE25	172	93,117	270	1
DEA1	187	586,647	1,563	0
DEB3	197	221,315	562	0
BE23	200	320,989	800	0
CH03	243	193,827	400	0

Table 6
Values of KPIs.

	ROTTERDAM			ANTWERP		
	N^{port}	ΔT	$\overline{\rho}$	N^{port}	ΔT	$\overline{\rho}$
BASE CASE	11,172	–	–	7,320	–	–
MMTs	7,464	10.4 hr	79.6 %	6,302	8.3 hr	61.3 %
MMTs 2018	7,409	10.7 hr	74.6 %	6,125	9.3 hr	58.6 %

terminals and the sailing time between them is achieved through using MMTs. This reduction is around 50 % for Antwerp and almost 60 % for Rotterdam. This allows for considerable time savings despite the additional time required to handle vessels at the MMTs and to sail to the sea terminals.

To better understand the choice driver of linking a region to the MMTs, Table 5 reports the hinterland regions of the port of Rotterdam together with the average number of TEUs per vessel sailing between them and Rotterdam. It also shows the yearly container volume, the yearly number of services, and the number of months each region is linked to the MMTs for the year 2018. When the regions are listed in ascending order of the number of TEUs per IWV, it becomes apparent that this factor influences the decision to link a region to the modular terminals. Regions having vessels with low volumes will be linked in priority to the MMTs, whereas regions with the highest volumes will never be linked. Although Table 5 only considers the port of Rotterdam and the year 2018, the same remarks also hold for the other cases.

The values of the KPIs defined in 4.2 are reported in Table 6. The significant time reduction achieved by the MMTs translates into substantial time savings for vessels linked to these terminals. They allow saving from 8 to 11 h per vessel for each port visit. Moreover, the linked vessels will not visit the seaport anymore, resulting in fewer vessels in the ports despite the addition of shuttle barges between the MMTs and the sea terminals. There would be around 1,000 vessels less in the port of Antwerp and 3,700 in the port of Rotterdam per year, thus a diminution of 15 % and 33 %, respectively. This great reduction for Rotterdam is explained by the fact that there are a lot of services concerning the regions linked to the MMTs. For example, regions NL41 and NL42, which are always connected, represent 4,189 services: the number of IWVs in the seaport will decrease by the same amount. Finally, the average utilization rate of MMTs is around 60 % for Antwerp and 75 % for Rotterdam, but a decrease is observed for 2018 with high seasonality. This is because the demand is less stable throughout the year, and the MMTs will have less cargo to handle in the months of lower demand.

The economic implication is now examined. This is presented in Fig. 7 where the aggregate benefit of the shippers and barge operators is determined for the two ports and the two cases. The figure reveals a negative overall economic benefit of using the MMTs for the actors (shippers and barge operators) in both ports. The negative economic benefit is more severe in Antwerp than in Rotterdam. For the former, the barge operators could experience a net loss of as high as EUR 9.14 per TEU, while for the shippers it could reach more than EUR 13 per TEU. For Rotterdam, meanwhile, it performs slightly better, although still not economically favorable for shippers. In this case, the barge operators achieved a somewhat positive benefit of around EUR 1.50 per TEU, while the shippers still realized a net loss of around EUR 3.20 per TEU.

An observed reason for an aggregate net loss for the actors can be attributed to the average number of MMTs deployed (see Table 4) for each month in the year. This number does not provide an optimal solution for the actors, which means in a period of low demand, some MMTs will not be deployed. Meanwhile, costs will be accrued for these MMTs. Hence, for the investor to cover these costs, the transshipment rate has to be increased considerably, which does not provide a favorable condition for the shippers and barge operators.

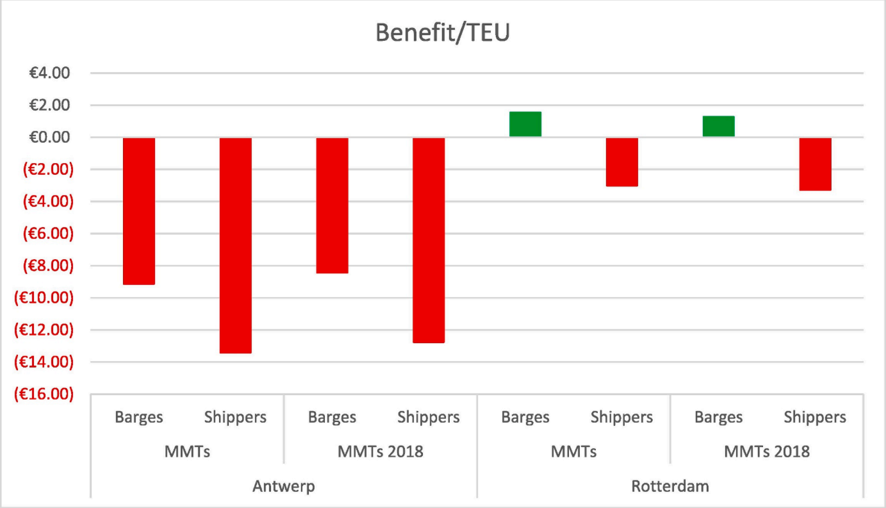

Fig. 7. Cost savings per TEU.

Table 7
Number of linked regions with a positive net benefit.

Actor	Antwerp		Rotterdam	
	MMTs	MMTs 2018	MMTs	MMTs 2018
Barges	8	8	5	4
Shippers	5	5	4	4

Table 8
Annual volume passing through MMTs and volumes on container barges.

	Antwerp		Rotterdam	
	MMTs	MMTs 2018	MMTs	MMTs 2018
Annual volume	588,190	494,481	764,453	716,496
Avg. TEUs per vessel	72	66	68	67
Threshold TEU number	48	46	62	59

Although the aggregate net benefit is negative for the actors in most cases, positive net benefits can still be achieved across the months for some individual regions. This means some regions would realize positive results even if the overall result becomes negative. This is useful to consider the specific impact of individual regions irrespective of the aggregate outcome of all regions. The practical implication is further described in section 5.4, where the redistribution mechanism of the benefit is explained. Based on this, Table 7 presents the number of regions that would yield positive net benefits for each case and port. The table reveals that both years have a similar number of positive regions linked to the MMTs for both ports. This implies that the MMTs are barely influenced by a variation in the transport demand. Hence, it can be concluded that the MMTs are suitable for dealing with container IWT transport flow disruptions. Furthermore, it can be observed that Antwerp generally has more positively linked regions than Rotterdam. This is, however, related to the fact that more regions are generally linked to Antwerp than Rotterdam due to the lower container volumes.

Table 8 where information regarding the total volume of cargo handled by the MMTs in each case and port is presented. The table also presents the average load of the vessels in these regions and the threshold of the TEUs per vessel required to achieve a positive net benefit.

Starting with the annual cargo volume being handled by the MMTs, the table reveals that Rotterdam generally has more cargo volume being handled than Antwerp. The high cargo flow from the connected regions can explain this. Nevertheless, as was earlier analyzed, handling high cargo volume does not necessarily lead to economic gains for the actors. This is due to the sub-optimal use of the MMTs versus the number of connected regions.

A second observation in the table is the average payload of the vessels using the MMTs. It can be observed that the average number of TEUs per vessel falls between 66 and 72. This suggests that the MMTs are most suitable for small barges or vessels with low occupation rates and small call sizes. Although the average payload of vessels is low, this does not guarantee a positive business case for the barge operators and shippers. Therefore, a threshold on TEUs per vessel is computed to generate a positive net benefit. This figure varies between 46 TEUs and 62 TEUs. These are the maximum payloads of the vessels to guarantee positive net benefits for the barge owners and shippers. This implies that the suitability of using the MMTs is based on small call sizes of vessels (or small vessels), hence, a niche market for the MMTs.

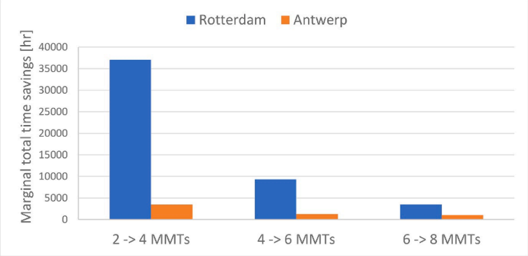

Fig. 8. Marginal time savings by adding more MMTs for both seaports.

5.2. *Fixed number of MMTs*

We now discuss the results when the number of MMTs through the year is fixed: Table 9 displays the KPIs for the ports of Rotterdam and Antwerp.

Φ is decreasing with an augmentation of the deployed MMTs. This is due to the waiting and sailing times of IWVs in the seaport diminishing as more vessels are linked to MMTs. However, it is accompanied by the increased time needed at MMTs to handle the vessels and the shuttles' frequency to the seaport. As a result, the marginal time savings become lower as the number of MMTs increases, as depicted in Fig. 8. It also highlights the differences in magnitude between the two ports, with Rotterdam experiencing much greater time savings. There are also noticeable differences between Rotterdam and Antwerp for the other KPIs: the results will be described separately in the following paragraphs.

5.2.1. *Port of Rotterdam*

Fig. 8 shows that large time savings can still be achieved by installing 4 MMTs instead of 2. The configuration with 4 Modular Terminals also generates the most time reduction per vessel that is visiting MMTs. The time savings reach 12.4 h per vessel per port visit, whereas they are below 12 h for all the other configurations. This is because the total time decreases too slowly compared to the growth in the number of vessels linked to MMTs.

Regarding the number of vessels in the seaport, the same trend as for the marginal time savings appears a great drop when passing from 2 to 4 MMTs, and then only a slight decrease. It indicates that a significant reduction of congestion in the port can be achieved with 4 MMTs instead of 2, with 2,100 vessels less in the seaport per year (about 40 per week). The configuration with 4 MMTs also allows for more efficient use of the installed capacity as the mean utilization rate rises by 7 %. However, this figure grows from a minor amount when more than 4 MMTs are installed.

Table 9
Results with fixed number of MMTs.

	ROTTERDAM				ANTWERP			
MMTs	**2**	**4**	**6**	**8**	**2**	**4**	**6**	8
Φ[hr]	870,054	833,009	823,667	820,163	587,382	583,907	582,613	581,581
ΔT[hr]	11.1	12.4	11.4	10.4	12.7	11.0	9.5	8.3
N^{port}[-]	10,231	8,131	7,620	7,464	6,032	6,066	6,163	6,312
$\bar{\rho}$[-]	70.8 %	77.8 %	78.4 %	79.6 %	69.8 %	61.0 %	59.7 %	60.8 %
NregionsBarge	3	4	4	5	8	8	8	8
NregionsShipper	2	3	4	4	7	5	5	5
Annual volume	169.978	373,369	564,437	764,453	167,428	292,801	429,613	583,986
Threshold [TEU]	54	57	60	62	51	48	47	48

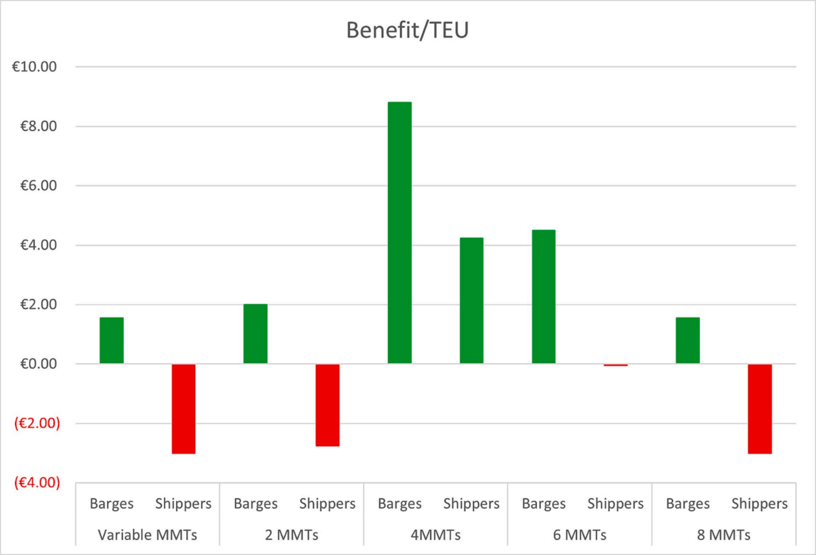

Fig. 9. Cost savings per TEU for Rotterdam.

From the economic perspective, using 4 MMTs generates the biggest cost savings for barge operators and shippers. This is demonstrated in Fig. 9, where the benefit of barge operators could be as high as EUR 9 per TEU, while that of shippers could be as high as EUR 4.5 per TEU. These MMTs would generate an annual cargo volume of 373,369 TEUs with a threshold payload of 57 TEUs for the container barges. Based on this, there will be four hinterland regions with positive net benefits from the barge operators' viewpoint. In comparison, three hinterland regions will have positive net benefits for the shippers.

Overall, the results support that installing 4 Modular Terminals (2 for import and 2 for export) would provide the biggest benefits for the Port of Rotterdam. It would provide maximal time savings for inland vessels while significantly reducing the congestion in the port. From the cost perspective, it also provides the biggest economic benefit for the barge operators and the shippers. Finally, having 4 MMTs installed would ensure that the MMTs are optimally utilized and always deployed at any time of the year.

5.2.2. *Port of Antwerp*

In the case of Antwerp, the time savings generated by installing more Modular Terminals are limited (see Fig. 8). Also, the maximal time reduction per vessel happens when 2 MMTs are installed, with 12.7 h.

For the other KPIs, the case with 2 MMTs is the most advantageous, as it has the lowest number of ships sailing in the seaport and the highest utilization rate. The former occurs because when more MMTs deployed, the number of additional vessels linked to them is lower than the number of additional shuttles needed to serve the sea terminals. Therefore, leading to increased ships in the port despite having fewer IWVs. The decreasing utilization rates are explained by the fact that volumes are less important than in the port of Rotterdam. Therefore the additional cargo passing through the added MMTs does not compensate for the increase in capacity.

Additionally, from the economic point of view, installing two mobile terminals would also lead to the only positive net benefits for actors compared to the other cases (see Fig. 10). In this case, the net benefit of barge operators will be as high as EUR 7 per TEU, while shippers will be

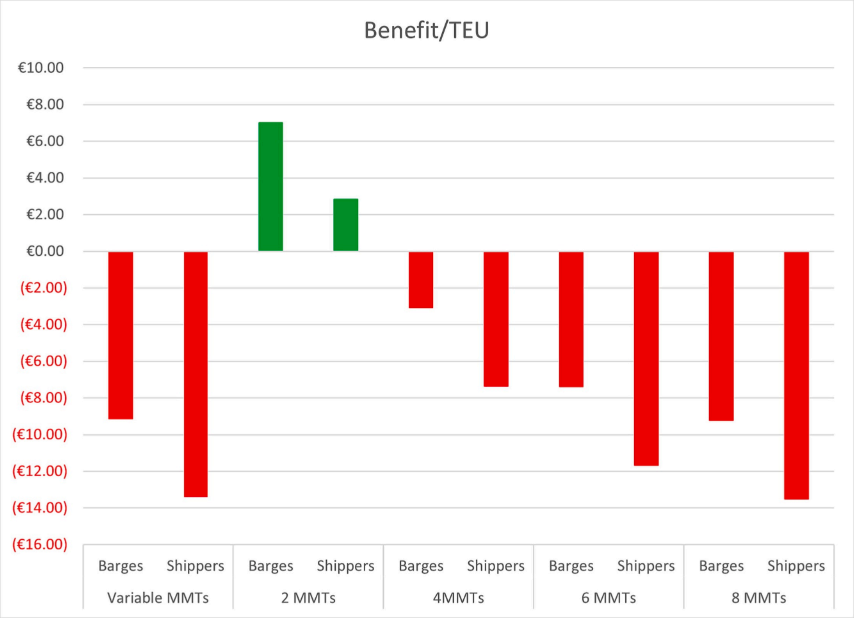

Fig. 10. Cost savings per TEU for Antwerp.

as high as EUR 3 per TEU. All other situations would lead to a net loss for the actors in the port of Antwerp, making two the optimal number of MMTs. These two MMTs will handle 167,428 TEUs annually at a utilization rate of around 70 %, the highest rate of all the configurations for the port of Antwerp. This further justifies why the MMTs are most suitable for small call sizes of inland container vessels. This analysis determined that vessels with a payload lower than 51 TEUs will be most suited to use the MMTs.

For all these reasons, the deployment of 2 Modular Terminals (1 for import and 1 for export) is sufficient for the port of Antwerp. It is indeed the most favorable case for all the considered KPIs.

5.3. *Sensitivity analysis*

The results of a 50 % increase in the module, crane, labor and overhead costs and 50 % decrease in the life span on the most beneficial configuration for Rotterdam and Antwerp (i.e. 4 and 2 MMTs respectively) are presented in Table 10. The first observation is that the increase in the labor and overhead costs has a negligible influence on the net benefits of the actors. The same remark holds for the decrease in the life span. While an increase of the crane cost has a moderate effect (the net benefits decrease by a magnitude of EUR 1), the impact of the module's cost is substantial: indeed, it induces a loss of more than EUR 5 in the net benefits. Therefore, the variation in module's cost is the main factor influencing the net benefits, also when combined with other variations.

Although the net benefits of barge operators remain positive for both Rotterdam and Antwerp, the 50 % increase in module's cost causes the net benefits of shippers to become negative. The capital cost of the modules is thus the critical component for the profitability of MMTs.

The results of the Monte Carlo simulation, where each variation is uniformly distributed between 0 % and 50 %, are displayed in Fig. 11. Among the 1000 replications, the net benefits of barge operators always remain positive for both seaports. It confirms what was already noticed above: MMTs are profitable for barge operators even in the worst case scenario. For shippers, however, it is possible that the net benefits fall below zero. Under the considered cost variations, the benefits for shippers have a 25 % chance to become negative for Rotterdam, but this exceeds 50 % for the port of Antwerp.

As highlighted in Table 10, the net benefits of shippers only become negative when the module's costs increase, whereas the impact of all other cost components is far less significant. Therefore, a special attention must be devoted to not exceeding the estimated costs for the MMT modules. Under this condition, the MMTs then represent an economically viable solution to improve container barging in seaports.

5.4. *Practical implications*

Based on the specified parameters, the developed model showed some interesting outcomes that could be implemented in practice. Firstly, it allows insights into the optimal number of MMTs to invest in for the two ports in question (2 for Antwerp and 4 for Rotterdam). This is interesting from the investment viewpoint, as strategic decisions can be made based on this. For instance, regarding the location of MMTs, it would be easier to install two MMTs in the port of Antwerp without many constraints and limitations compared to installing eight MMTs in the port area. All the more so since eight MMTs are not profitable. The same reasoning can be applied to the port of Rotterdam. In terms of the KPIs, insights from the analysis gave detailed information about the estimated utilization rate of the MMTs, the expected number of shuttle barges, and the estimated volume of container cargo to be handled annually. This information is useful for detailed daily planning of labor, time slots in deepsea terminals, and daily handling operations.

Table 10
Net benefits in EUR/TEU of the best configurations for Rotterdam and Antwerp with costs and life span variation.

Case	ROTTERDAM (4MMTs)		ANTWERP (2MMTs)	
	Barge operators	**Shippers**	**Barge operators**	**Shippers**
No change	8.96€	4.38€	7.04€	2.88€
Lifespan −50 %	8.95€	4.37€	7.04€	2.87€
Module costs + 50 %	3.71€	−0.87€	1.17€	−3.00€
Crane costs + 50 %	8.03€	3.46€	6.00€	1.83€
Labor costs + 50 %	8.96€	4.38€	7.04€	2.87€
Overhead costs + 50 %	8.95€	4.37€	7.03€	2.86€
Lifespan −50 %, Module costs + 50 %	3.70€	−0.87€	1.17€	−3.00€
Lifespan −50 %, Crane costs + 50 %	8.03€	3.46€	6.00€	1.83€
Lifespan −50 %, Labor costs + 50 %	8.95€	4.37€	7.03€	2.87€
Lifespan −50 %, Overhead costs + 50 %	8.95€	4.37€	7.03€	2.86€
Module costs + 50 %, Crane costs + 50 %	2.78€	−1.80€	0.14€	−4.03€
Module costs + 50 %, Labor costs + 50 %	3.70€	−0.88€	1.17€	−3.00€
Module costs + 50 %, Overhead costs + 50 %	3.70€	−0.88€	1.17€	−3.00€
Crane costs + 50 %, Labor costs + 50 %	8.03€	3.45€	6.00€	1.83€
Crane costs + 50 %, Overhead costs + 50 %	8.02€	3.44€	6.00€	1.83€
Labor costs + 50 %, Overhead costs + 50 %	8.95€	4.37€	7.03€	2.86€
Crane/Labor/Overhead costs + 50 %	8.02€	3.44€	6.00€	1.83€
Module/Labor/Overhead costs + 50 %	3.70€	−0.88€	1.17€	−3.00€
Module/Crane/Overhead costs + 50 %	2.78€	−1.80€	0.14€	−4.03€
Module/Crane/Labor costs + 50 %	2.78€	−1.80€	0.14€	−4.03€
Lifespan −50 %, Labor/Overhead costs + 50 %	8.95€	4.37€	7.03€	2.86€
Lifespan −50 %, Crane/Overhead costs + 50 %	8.02€	3.44€	6.00€	1.83€
Lifespan −50 %, Crane/Labor costs + 50 %	8.03€	3.45€	6.00€	1.83€
Lifespan −50 %, Module/Overhead costs + 50 %	3.69€	−0.88€	1.17€	−3.00€
Lifespan −50 %, Module/Labor costs + 50 %	3.70€	−0.88€	1.17€	−3.00€
Lifespan −50 %, Module/Crane costs + 50 %	2.78€	−1.80€	0.13€	−4.03€
Module/Crane/Labor/Overhead costs + 50 %	2.78€	−1.80€	0.14€	−4.03€
Lifespan −50 %, Crane/Labor/Overhead costs + 50 %	8.02€	3.44€	5.99€	1.83€
Lifespan −50 %, Module/Labor/Overhead costs + 50 %	3.69€	−0.88€	1.17€	−3.00€
Lifespan −50 %, Module/Crane/Overhead costs + 50 %	2.78€	−1.80€	0.13€	−4.03€
Lifespan −50 %, Module/Crane/Labor costs + 50 %	2.77€	−1.81€	0.13€	−4.03€
Lifespan −50 %, Module/Crane/Labor/Overhead costs + 50 %	2.74€	−1.84€	0.06€	−4.11€

Besides that, the economic evaluation revealed some cases where the MMTs are profitable. It does not necessarily mean that all the linked regions experience a positive net benefit but that the positive benefits exceed the negative ones. Table 11 below shows the details of the shippers' net benefits per region linked to the MMTs for the optimal case in both seaports. In the case of Antwerp, it is apparent that there are more regions with positive benefits than negative ones. Also, the positive figures are higher than the ones in the negative, which results in a positive aggregated net benefit. In the case of Rotterdam, there are more

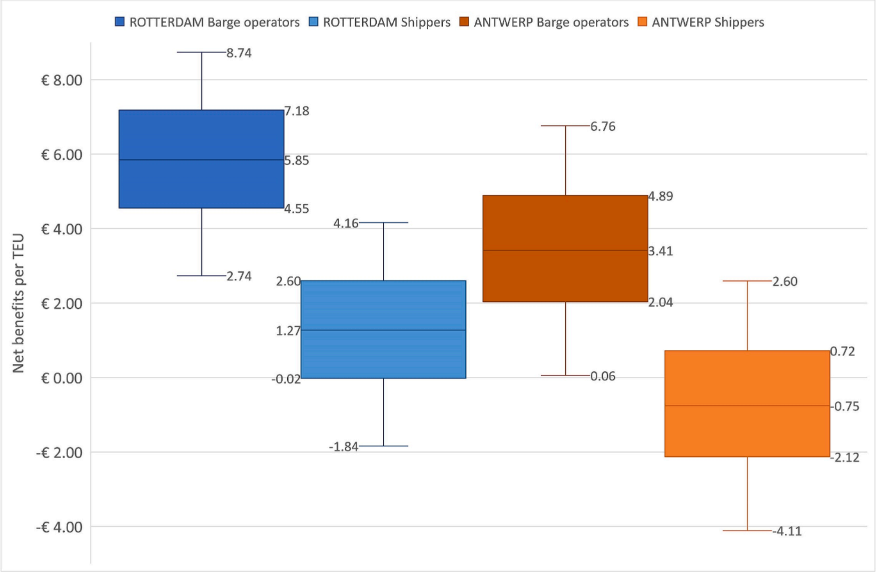

Fig. 11. Distributions of the net benefits in EUR/TEU for both ports with 1000 Monte Carlo draws for each cost component.

Table 11
Details of shippers' benefit for regions linked with MMTs for both seaports, with the number of MMTs in parentheses.

Linked region	Benefit/ TEU	Volume passing through MMTs	Number of months linked to MMTs
ROTTERDAM (4 MMTs)			
DE13	18.02€	4,224	12
NL41	5.19€	259,597	12
NL42	5.09€	74,856	11
DE12	−0.03€	13,497	10
NL22	−4.72€	13,559	2
DEA2	−13.43€	4,631	1
FRF1	−14.14€	3,005	1
ANTWERP (2 MMTs)			
NL22	17.30€	21,977	12
BE24	14.03€	17,849	12
DE11	9.58€	11,735	12
DEB2	9.28€	8,453	10
DE71	9.16€	13,781	12
DE13	2.00€	3,602	5
BE23	0.15€	36,738	12
BE22	−0.09€	25,488	12
NL31	−17.12€	27,805	12

regions with negative net benefits. But these can be compensated by the fact that region NL41 has a positive net benefit and very large container volumes, resulting in overall positive net benefits after aggregation.

Nevertheless, not all regions experience a positive net benefit: that is why a redistribution mechanism of the overall benefit should be envisioned. So that even regions with an individual negative benefit can profit from the situation and are therefore incentivized to use the MMTs. Note that if the aggregate net benefit was to be negative, even the best redistribution mechanism would not be a sufficient incentive to use the MMTs. In this case, some subsidies should be provided to support using MMTs.

In addition, the sensitivity analysis highlights the fact that module costs are a critical element of the overall MMT concept. A reduction in the capital cost of the modules will lead to a profitable business case and vice versa for the MMT implementation. Based on this, it is critical to build simple designs of MMTs, which are not expensive, can easily be maintained and, at the same time, complying with regulatory and safety standards.

Finally, this work also shows that vessels with low payloads should be targeted for a business case and that some regions are more favorable than others. In particular, the economic evaluation shows that it becomes profitable for vessels transporting less than 60 TEUs to call at MMTs. Of course, this numerical value may be case-specific: nevertheless, the overall conclusion that MMTs are more suitable for low payloads is expected to hold. In addition, MMTs could also be envisioned for vessels that could offload a part of their containers that need to go to different terminals (small call sizes) and directly call at the sea terminals with large volumes.

The aforementioned findings are also supported from the barge operators' and shippers' viewpoints, where the KPIs inform when to use the MMTs. However, a central question remains: are the additional costs induced by MMTs justified by the time savings for IWT carriers? Or, in other words, will the vessels' operators be willing to pay for this service? To answer this question, a more in-depth market analysis is required to get more information about the perspective of the involved actors.

Besides, other technical elements need to be studied further before the actual deployment of MMTs to ensure a smooth process. First and foremost, the safety must be ensured at all times. At least three dimensions can be considered here: the safety of the MMT structure itself, its operations and the safety regarding the existing port environment. The stability and resistance of the MMTs should firstly be assessed under various loading conditions and the structure must also resist to a collision and adverse weather conditions. Secondly, safety must also be guaranteed while MMTs are operating: some guidelines should be developed regarding the working conditions of personnel, the maneuvers, the area of liability and the interactions with other users of the port infrastructure. And thirdly, the integration of the MMTs into the port system has to be done correctly. A breakdown of information with, for example, a yard management system can lead to delays or errors in container handling thus threatening the overall operations of the port system. In addition, the infrastructural limitations of seaports, such as the dimensions of navigable ways, may hinder the manoeuvrability of the MMT modules or the inland vessels mooring along them. Therefore, the potential location of MMTs in the seaport has to be carefully evaluated (Freling, Nicolet, & Atasoy, 2022).

Next to safety, the existing communication technologies allow for the automation of operations of both the crane and the modules, at least partially. The former could be controlled from the shore or even by the barge operators themselves. The latter can be designed as self-propelling modules with a specific level of automation (e.g., remote control system or fully autonomous). In any case, the power supply of the crane and modules should be sustainable. Further research in these areas should be

Table A1
Data of hinterland container transport via waterways.

ROTTERDAM						
Region	**Import volume [TEUs]**	**Export volume [TEUs]**	**Distance [km]**	**Time [hr]**	**Services**	**TEUs/ vessel**
BE22	48,662	4104	233	19	189	140
BE23	288,188	32,802	175	14	800	201
BE25	87,598	5519	223	15	270	172
CH03	177,029	16,798	860	18	400	242
DE11	0	4648	736	23	16	145
DE12	13,192	3021	673	69	163	50
DE13	2088	2136	858	54	75	28
DE71	22,307	28,348	529	69	160	158
DEA1	402,797	183,850	258	43	1563	188
DEA2	37,054	22,469	331	21	240	124
DEB1	9795	9367	434	27	58	165
DEB3	172,465	48,850	586	35	562	197
FRF1	17,910	20,464	923	47	146	131
NL22	54,805	26,145	145	74	654	62
NL31	35,208	57,630	101	12	312	149
NL32	84,436	131,231	144	8	993	109
NL34	33,494	40,181	172	12	400	92
NL41	115,328	144,269	110	14	3189	41
NL42	43,977	38,364	259	9	1000	41
ANTWERP						
Region	**Import volume [TEUs]**	**Export volume [TEUs]**	**Distance [km]**	**Time [hr]**	**Services**	**TEUs/ vessel**
BE22	6850	18,638	91	7	275	46
BE23	12,385	24,353	87	7	400	46
BE24	3401	14,448	42	3	300	30
BE25	163,011	102,007	128	10	600	221
BE33	12,685	46,247	138	11	250	118
CH03	27,875	25,808	885	71	180	149
DE11	4345	7390	761	61	175	34
DE12	15,654	34,258	698	56	141	177
DE13	1491	7483	883	71	101	44
DE71	6038	7743	554	45	203	34
DEA1	56,223	163,721	283	23	870	126
DEA2	12,103	30,901	356	29	241	89
DEB1	9689	44,069	459	37	184	146
DEB2	657	9639	559	45	150	34
DEB3	69,422	97,953	611	49	618	135
FRF1	22,994	79,406	948	76	252	203
NL22	9579	12,398	170	14	400	27
NL31	27,573	232	182	15	98	142
NL32	278,516	205,043	225	18	993	243
NL41	83,951	121,367	122	5	444	231
NL42	32,576	77,476	164	10	450	122

conducted to come up with the most suitable design.

6. Conclusions

This study has demonstrated the economic potential of using the Modular Mobile Terminal as a floating consolidation and a dedicated handling space for container barges. An assessment methodology has been proposed for this purpose, where time savings optimization and cost estimation models were developed. In doing this, the proposed methodology combines logistical and economic aspects in a unified framework. The obtained results lay the groundwork for a business case with important insights that helps to narrow down the research scope for follow-up studies. These insights are related to:

- the suitable number of MMTs to operate;
- the cargo flows that are relevant to target;
- the elements of MMTs that are critical for the success of the project.

The proposed assessment methodology is applied to two ports (Rotterdam and Antwerp) and two cases (moderate seasonality and high seasonality scenarios). The overall conclusion of the analysis suggests that the MMTs are most suitable for regions and vessels with small cargo volumes and can deal with the effects of a high seasonality pattern (caused, for example, by a disruption). Regarding the specific ports, the study indicates that four MMTs would be optimal for the port of Rotterdam, while two MMTs would optimally be installed in Antwerp. Thus from the assumptions and available data, the concept can be seen as a viable solution from an economic viewpoint for consolidating and handling low container volumes.

The assumptions in the study have been reasonably used to represent practical situations. However, more detailed research should be conducted based on more data to generate a more accurate result for practical implementation. In particular, in this work, regional flows are used. Still, a study at the vessel level could provide more information, as the MMT operations could be simulated with a higher level of detail. For example, a queueing model could be introduced to accurately infer the vessels' waiting times at the MMTs and sea terminals. The shuttles and sea terminals could also be explicitly modeled; thus, every shuttle could be assigned to a specific sea terminal. Another consideration to be examined is the party investing and operating the MMTs. This factor needs to be examined in detail as this would have a significant impact on the level of relationship between the MMTs and the deepsea terminals. This would decide the practical operations of the shuttle barges to the deepsea terminals and whether they get fixed slots and no waiting time at the deepsea terminals.

Regarding the demand, an uneven split of containers between the sea terminals should be considered as it would be more realistic, and the different inland waterway vessel types could also be represented. This would help to get a more detailed idea of the market to target. Nevertheless, the present study is essential as it provides primary answers and makes the first step toward more detailed models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1

References

Assbrock, G., Ley, J., Dafnomilis, I., Duinkerken, M.B., Schott, D.L., 2020. Waterborne hinterland transports for floating port terminals. In: International Conference on Computational Logistics. Springer, Twente, The Netherlands, pp. 101–118.
Baird, A.J., Rother, D., 2013. Technical and economic evaluation of the floating container storage and transhipment terminal (FCSTT). Transportation Research Part c: Emerging Technologies 30, 178–192.
Caris, A., Macharis, C., Janssens, G.K., 2011. Network analysis of container barge transport in the port of Antwerp by means of simulation. J. Transp. Geogr. 19 (1), 125–133.
Contargo GmbH & Co. KG. (2021, September 28). UPDATE: congestion in Antwerp and Rotterdam - 28 Sep 2021. Retrieved December 1, 2021, from CONTARGO: https://www.contargo.net/en/news/2021-09-28_congestion_update/.
De Langhe, K., 2019. What role for rail in urban freight distribution? Universitas, Antwerp, Antwerp.
Douma, A., Schutten, M., Schuur, P., 2009. Waiting profiles: an efficient protocol for enabling distributed planning of container barge rotations along terminals in the port of Rotterdam. Transportation Research Part c: Emerging Technologies 17 (2), 133–148.
European Commission, E., Eurostat., 2020. Statistical regions in the European Union and partner countries : NUTS and statistical regions 2021. Publications Office of the European Union.

Fan, Y., Behdani, B., Bloemhof-Ruwaard, J., Zuidwijk, R., 2019. Flow consolidation in hinterland container transport: an analysis for perishable and dry cargo. Transportation Research Part e: Logistics and Transportation Review 130, 128–160.

Fiorello, D., Fermi, F., Bielanska, D., 2010. The ASTRA model for strategic assessment of transport policies. Syst. Dyn. Rev. 26 (3), 283–290.

Freling, P., Nicolet, A., Atasoy, B., 2022. An analysis of the potential locations for Modular Mobile Terminals. Delft University of Technology, Delft, The Netherlands.

Froeling, D., van Schuylenburg, M., Groenveld, R., Taneja, P., 2008. Container Transferium Rotterdam. In: First International Conference on Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA). IEEE, Rotterdam, The Netherlands, pp. 1–6.

Gumuskaya, V., van Jaarsveld, W., Dijkman, R., Grefen, P., Veenstra, A., 2020. Dynamic barge planning with stochastic container arrivals. Transportation Research Part e: Logistics and Transportation Review 144, 102161.

Gumuskaya, V., van Jaarsveld, W., Dijkman, R., Grefen, P., Veenstra, A., 2021. Integrating stochastic programs and decision trees in capacitated barge planning with uncertain container arrivals. Transportation Research Part c: Emerging Technologies 132, 103383.

Hu, Q.u., Wiegmans, B., Corman, F., Lodewijks, G., 2019. Critical literature review into planning of inter-terminal transport: in port areas and the Hinterland. Journal of Advanced 2019, 1–15.

Konings, R., 2007. Opportunities to improve container barge handling in the port of Rotterdam from a transport network perspective. J. Transp. Geogr. 15 (6), 443–454.

Konings, R., van der Horst, M., Hutson, N., Kruse, J., 2010. Comparative strategies for developing hinterland transport by container barge: analysis for rotterdam and US ports. Transp. Res. Rec. 2166 (1), 82–89.

Konings, R., Kreutzberger, E., Maras, V., 2013. Major considerations in developing a hub-and-spoke network to improve the cost performance of container barge transport in the hinterland: the case of the port of Rotterdam. J. Transp. Geogr. 29, 63–73.

Li, S., Negenborn, R.R., Lodewijks, G., 2017. Closed-loop coordination of inland vessels operations in large seaports using hybrid logic-based benders decomposition. Transportation Research Part e: Logistics and Transportation Review 97, 1–21.

Majoor, I., Ramos, C., Burgess, A., Van der Geest, W., Hendriks, I., van Hassel, E., & Hofman, P. (2021). D2.2: NOVIMOVE transport model architecture and data collection.

Malchow, U., 2020. Port Feeder Barges as a Means to Improve Intra-Port Container Logistics in Multi-Terminal Ports. In: Böse, I.J.W. (Ed.), Handbook of Terminal Planning. Springer, pp. 465–480.

N.N. (2021). Port Feeder Barge Hamburg: Konzept. Retrieved from http://www.portfeederbarge.de.

Port of Rotterdam, 2019. Barge Performance Monitor. Retrieved from. https://www.portofrotterdam.com/de/geschaeftsmoeglichkeiten/logistik/verbindungen/barge-performance-monitor.

Ramne, B., Martens, S., Pot, H., Friedhoff, B., Ley, J., Thill, C. (2021). D.4.2: Concepts and selection of innovative NOVIMOVE concepts.

Ramos, C., Burgees, A., van der Geest, W., Hendriks, I., van Hassel, E., Shobayo, P., Alias, C., 2020. D.2.1: Detailed requirements of the NOVIMOVE transport model. NOVIMOVE Technical Report.

Rhineforecast, W., 2021. Real Time Rhine Water Level Forecasts. Retrieved from Rhineforecast: https://www.rhineforecast.com/form.

Shobayo, P., Nicolet, A., van Hassel, E., Atasoy, B., Vanelslander, T. (2021). Conceptual development of the logistics chain flow of container transport within the Rhine-Alpine corridor. European Transport Conference (ETC), 13-15 September, 2021, (pp. 1-17).

Shobayo, P., van Hassel, E., Vanelslander, T., 2021b. Socio-economic evaluation of palletized shuttle barges (PSBs) for urban freight delivery. International Journal of Transport Economics 48 (3–4), 525–550.

Soyka, M., 2020. December). Wirtschaftsbehörde verweigert Mitwirkungserklärung für Förderwettbewerb des Bundes. Stadt Land Hafen, Port Feeder Barge ausgebremst, pp. 14–15.

Thill, C., Jacobi, G., Pot, H., Martens, S.-E., Ley, J., Friedhoff, B., Ramne, B. (2022). D4.3 Technical verification results.

Tong, J., Nachtmann, H., 2017. Cargo prioritization and terminal allocation problem for inland waterway disruptions. Maritime Economics & Logistics 19 (3), 403–427.

Van Der Horst, M.R., De Langen, P.W., 2008. Coordination in hinterland transport chains: a major challenge for the seaport community. Maritime Economics & Logistics 10 (1), 108–129.

van Dorsser, C., Vinke, F., Hekkenberg, R., van Koningsveld, M., 2020. The effect of low water on loading capacity of inland ships. Eur. J. Transp. Infrastruct. Res. 20 (3), 47–70.

van Dorsser, C. (2015). Very long-term development of the Dutch inland waterway transport system.

van Hassel, E., 2011. Developing a small barge convoy system to reactivate the use of the small inland waterway network. University of Antwerp, Antwerp.

van Hassel, E., Colling, A., Hekkenberg, R., Boukani, L.N., Moschouli, E., Verberght, E., Moshseni, S.A. (2019). D2.4 Benchmark the VT concept against the baseline.

van Hassel, E., Alias, C., Gründer, D., zum Felde, J., Pedersen, J.T., Samuel, L., Nicolet, A. (2021). D2.4 Development of the NOVIMOVE logistics innovations.

Vernimmen, B., Dullaert, W., Engelen, S., 2007. Schedule unreliability in liner shipping: origins and consequences for the hinterland supply chain. Maritime Economics & Logistics 9 (3), 193–213.

Wiegmans, B., 2005. Evaluation of potentially successful barge innovations. Transp. Rev. 25 (5), 573–589.