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Waterborne Hinterland Transports for Floating Port Terminals

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Abstract. Port terminals on floating modular platforms are a conceivable solution for the problem of limited space and water depths restrictions of ports in estuary regions. A design of a dedicated Transport&Logistic hub has been developed in the scope of the Horizon 2020 project Space@Sea. This paper addresses dedicated options of waterborne hinterland transports and discusses opportunities for bypassing onshore terminals by means of river-sea or sea-going inland vessels. A tailored simulation method for ship operations utilises a specific cost model and is applied to derived demand scenarios. Cargo flow statistics of an onshore port have been projected onto the hub to identify relevant waterborne transports to the hinterland. Three different vessel types are implemented, whereas inland vessels are considered with two different sizes. A comparison of round trip durations and transport costs per transported container between a floating terminal and a relevant hinterland port pointed out, that a non-stop connection with sea-going inland vessels is the economically favourable solution. A feeder vessel is the faster solution in coastal waters but it can not compensate the time saved by omitted terminal visits on a direct hinterland connection.

Keywords: port terminal at sea · waterborne hinterland transport · strategic simulation model

1 Introduction

Over the last decade global trade has increased noticeably in all dimensions like tonnage, number of containers, size and number of vessels and port size. However, the expansion of handling capacity is a major issue for many sea ports because of limited space and water depths restrictions in adjacent rivers or channels. Innovative solutions are required to overcome these problems. Kim and Morrison [1] as well as Baird and Rother [2] provide an overview of different floating concepts and their technical feasibility in a low-wave sheltered environment. A modular floating logistic hub, namely a Transport&Logistic (T&L) hub that has been developed in the Space@Sea project [3], constitutes one possible solution for this problem. It is assumed to be located in the North-Sea in front of the River Scheldt's estuary. Van den Berg and Langen [4] already discussed the added value in port development considering hinterland connections during expansion planning. A logistic concept including a terminal design [5] and hinterland connections bypassing ashore terminals was elaborated and optimised on a strategic level. Konings et al. [6] also proposed a container hub but along inland waterways to equalise the congestion in sea ports. Waiting times and congestion of inland vessels in sea ports is also discussed and modelled by Shobayo and van Hassel [7]. Most approaches focus on the assessment of waterborne inter terminal transport in sea ports as discussed by Li et al. [8]. Here, relevant connections to the hinterland are investigated including the combination of short-sea shipping and inland waterway shipping with two vessel types or a direct connection by river-sea shipping. Vantorre et al. [9] emphasised that inland vessels can establish a technically feasible hinterland connection as long as they are capable of navigating estuaries and coastal waters. These vessel types are considered in this publication.

Floating terminals near shore are meant to meet demands of vessels growing in size and capacity driven by an increasing cargo flow. Integrating those in an existing inter terminal transport is crucial for economic port expansion. It is expected that direct connections to the hinterland with vessels operating on coastal as well as on inland waterways can optimise the integration of a near shore terminal. Different types of vessel services are compared to identify the economically most favourable solution. The objective is to analyse the potential of direct hinterland connections from the offshore T&L hub with a strategic simulation method calculating round trip durations and transport costs.

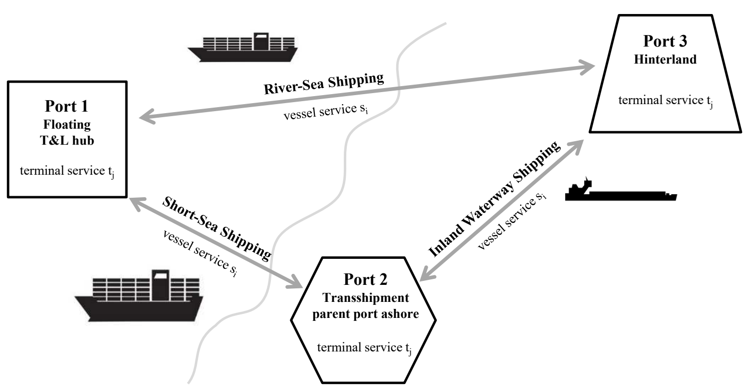

Fig. 1. Overview of modelled solutions. A combination of short-sea and inland waterway shipping or the utilisation of vessels being capable of river-sea shipping to serve a cargo request.

The strategic simulation bases on demand scenarios. This way, hinterland connections can be evaluated for their performance in a variety of boundary conditions and demands. The methodology applied considers four steps: It begins with an analysis of an origin-destination matrix to identify relevant cargo requests on hinterland connections for a proposed floating terminal location. The definition of a cost model that includes capital and operational costs for different types of vessels and transsshipment at terminals follows. Including both a simulation method is developed. The assessment of transport paths by costs and number of vessels that service a given scenario of cargo requests concludes the analyses.

Relevant hinterland connections in the populated area of Central and North Europe are considered. Major container cargo flows are derived from statistics for the Port of Antwerp together with its cargo sources and drains in the hinterland, e. g. in the adjacent Benelux countries and federal states of Germany along the river Rhine. Under the premise of optimising the remote terminal integration traditional ways of shipping are combined to serve the hinterland connection. Figure 1 illustrates two different solutions connecting the hub to the hinterland. Focussing on inter terminal transport with an existing port ashore, one hinterland connection is realised with two types of vessels and an additional handling. The other proposed solution relies only on one vessel type being capable of navigating both waters, coastal and inland waterways.

2 Hinterland Transport Scenarios

Cargo throughputs are required as input for the strategic simulation. From trade statistics and prognoses for upcoming demands of transport throughput, scenarios and an origin-destination matrix are derived. The latter yields relevant connections between the T&L hub and the hinterland that are applied to the simulation method.

2.1 Assumptions

A scenario provides the required boundary conditions for the model. For the strategic simulation it sets the amount of TEU that are handled on T&L hub within a specific time scale, the cargo throughput respectively. Knowing the demand from the prognosis for a sea port in North-Central Europe in 2030, [10] the throughput at the T&L hub can be a portion of the total handled TEU at that port. It is assumed, that a T&L hub will relieve the Port of Antwerp by a throughput of 6 million TEU. Due to an additional demand for specific infrastructure for the storage and handling of reefer containers, a split of 6 % is not handled at the hub. With a ratio of FEU and TEU of 1.5 (60 % FEU and 40 % TEU containers respectively) it leaves 3.525 million containers to be handled at the floating terminal each year. The simulation takes a daily throughput of 18193 TEU as input which is based on a one day dwell time and 310 days of operation.

2.2 Container Split on Hinterland Connections

A T&L hub is proposed to act as an additional terminal of a nearby onshore port on the one hand and as an independent hub on the other hand. As a hub other sea ports are served by short-sea connections and on direct hinterland transports. To identify and prioritise relevant hinterland destinations for the T&L hub, the major container cargo flows to and from Belgium were identified first. The Netherlands and Germany were found to be major trading partners for Belgium. Since Antwerp is Belgium's major container port, these cargo flows were expected to be representative of the considered use case. It was decided to focus on possible hinterland cargo drains and sources between Port of Antwerp and Germany and to project the results onto the T&L hub. The statistics from 2016 contain the distribution of containers for each federal state of Germany which is trading with the Port of Antwerp, being either the shipping or the receiving instance [11]. The three most important states are North Rhine Westphalia (NRW), Rhineland Palatinate (RP) and Baden-Wuerttemberg (BW). As expected, destinations far downstream the river Rhine (Rhine-kilometre > 500) take the greatest share of all containers. The cargo source or drain NRW is represented by the conglomeration of inland ports of Duisburg, Düsseldorf and Cologne. With 45 %, it takes the largest split of the total container transport between Port of Antwerp and Germany. The total waterway distance between the T&L hub and the conglomeration of terminals in NRW is about 398 km and includes about 102 km to be covered by inter terminal transport between the T&L hub and the sea port onshore.

Based on the chosen scenario of cargo throughput at the T&L hub, see section 2.1, this hinterland connection provides the portion of containers that has to be covered by a vessel service. The modal split at the Port of Antwerp for hinterland connections reveals 38 % of waterborne container transport [12] in 2017, whereas 62 %, represent the inter terminal transport. This split is also projected onto the T&L hub.

3 Simulation Model

General assumptions build the fundament of the strategic simulation method. With respect to time scales the operational downtime of a terminal influences the yearly throughput of cargo. The annual productivity of any service is subject to the assumption of 310 days of operation per year and 20 hours of operation per day. Uneven distributions between shipping and receiving shares are averaged unweighted, since the import–export factor is assumed with 0.5.

3.1 Vessel Types

For the service of above discussed hinterland connections different types of vessels are considered. Two major characteristics are distinguished, since different operational areas need to be navigated. For the connection of the T&L hub to the hinterland, a short-sea segment and inland segments have to be completed. A vessel servicing the short-sea segment requires a classification of its structural strength to withstand wave loads and a dedicated crew for navigation in coastal waters. The critical parameters for transport on inland waterways are the maximum clearance under bridges and the draught to water depth ratio.

When the hub is operated as an additional terminal to an existing port ashore, a container feeder vessel is proposed to establish the waterborne inter terminal transport. This vessel type is denoted a feeder in the following. Direct hinterland connections can either be serviced with a transshipment in the parent onshore port or by a vessel type that can complete the river-sea connection non-stop. sea-going inland vessels can realise a direct connection and integrate the T&L hub in a network of hinterland terminals. To compare this solution to the established way with additional handling at an onshore port also inland vessels are introduced, which are less expensive than sea-going inland vessels. This type of vessel is entrenched with different sizes and corresponding container capacities, whereas two are considered for the analysis in combination with the feeder. The combination of vessel type and terminal has an influence on the processing time in port, since the number of cranes processing a vessel is limited by the vessel's length. The vessels given in Table 1 with examples for reference, are found to be suitable for the terminal integration.

The velocities over ground of each vessel are set constant for the conducted simulations and depend on the operational area. The approach of velocity estimation for the short-sea services is described in section 3.2. Average velocities of the feeder and sea-going inland vessel in the operational area of coastal waters are linked to a sea state common for southern North Sea territories. The influence by current or by runoff in m^3/s, which is entrenched navigating on rivers, is only considered for services on inland waterways. Half the velocity over ground is assumed, when the vessel sails upstream. The velocity corresponds to a moderate usage of engine power and fuel consumption. Hence, higher velocities may be possible for round trips being time-sensitive. Although, it is recommended to assume moderate velocities, since the ratio of draught to water depth has a strong impact on maximum velocities over ground and is not considered throughout this analysis. For very deep hinterland penetrations, e. g. upstream the Rhine (Rhine-kilometre < 550), the river gets more shallow and an additional operational area allowing only smaller drafts and velocities needs to be modelled.

3.2 Ship Velocity at Sea

Round trip durations and transport costs depend on the achievable ship's speed. As connections between the T&L hub at sea and the hinterland are considered, the hydrodynamic behaviour of a ship is affected by two principle environments, namely by the sea and inland waterway. Wave loads are dominating the ship's speed at sea; currents and limited water depths significantly affect the achievable ship's speed on inland waterways. The applied approach of the velocity estimation for the waterborne transport service at sea is described next.

Table 1. Container capacity, main dimensions, ship speeds and assigned cranes per type or the Conférence Européenne des Ministres de Transport (CEMT) water way class

Vessel type	Feeder vessel	sea-going inland vessel	inland class Va	"Jowi" class
Capacity [TEU]	734	380	240	510
Length L [m]	140.0	110.0	110.0	134.9
Breadth B [m]	21.5	17.0	11.45	16.9
Draught T [m]	7.0	4.0	3.0	3.0
Velocity short-sea segment [km/h]	22.0	8.0	-	-
Velocity up-/downstream [km/h]	- / -	8.0 / 16.0	8.0 / 16.0	8.0 / 16.0
No. of cranes at terminal to un-/load	3	2	2	3
TEU / FEU per move	4 / 2	4 / 2	2 / 1	2 / 1

It is obvious, that different vessel types come along with various seakeeping abilities leading to different ship speeds and operational days per year. For instance, small sea-going inland vessels are more sensitive to wave loads and equipped with less propulsion power than feeders. Thus, it is necessary to distinguish these ship types and to quantify their speed losses in waves.

For the ship speed estimation, wave loads are separated into two load components, namely first and second order loads. First order wave loads (wave amplitudes) rather cause ship motions and affect the seakeeping ability in terms of the required minimum bow height and freeboard. Second order wave loads increase the required propulsion power of the vessel or cause a speed loss for a given propulsion power. In case of head waves, the resulting forces are denoted as added resistance. The approach to estimate the speed loss in relevant sea state conditions is based on the following steps:

1. Ship type selection (hull dimensions and geometry)
2. Estimation of the calm water resistance R_T
3. Calculation of the Response-Amplitude Operators (RAO) for the second order wave forces for different wave frequencies.[3]
4. Calculation of the mean added resistance for irregular sea states by multiplying the RAOs with the spectral energy density function $S(\omega)$ for given sea states and integration over the relevant wave frequency range.
5. Calculation of the speed loss.

The fundamental assumption is that the effective propulsion and the provided power by the main engine stay unaffected during the operation at sea. For the moderate sea states considered, it is a reasonable assumption. For extreme and steep seas, the propulsion efficiency will change and more power is required. Hence, an additional speed loss induced by a lack of power may be the consequence.

Calm water resistance prognoses for ships can be carried out on the basis of the empirical approach proposed in [17]. If required, even more sophisticated

[3] For the sake of simplification, head sea conditions are considered.

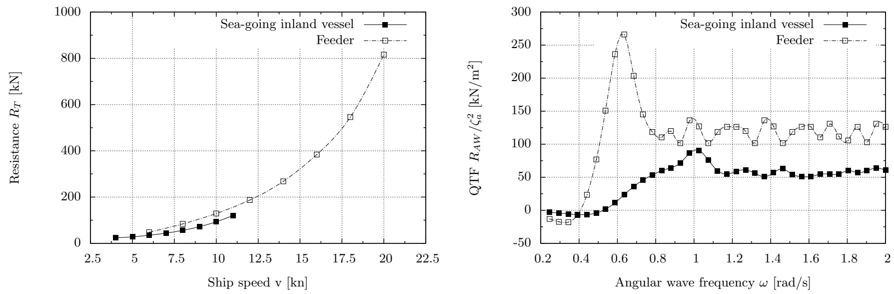

Fig. 2. Estimated calm water resistance R_T [kN] (left) and Response Amplitude Operators for the added resistance [kN/m^2] of the Feeder at 12 knots and the sea-going inland vessel at 8 knots (right)

numerical methods based on the solution of Reynolds-Averaged Navier-Stokes Equations (RANSE) or model tests can be used as well as done in [18].

Exemplary results are shown here for the feeder and the sea-going inland vessel, see Figure 2 (left). The resistance prognosis for the feeder bases on the approach by Holtrop&Mennen [17]; the prognosis for the sea-going inland vessel was based on model test results of a comparable vessel with similar ship dimensions. A Boundary Element Method (BEM) based on potential theory was applied to perform hydrodynamic diffraction calculations in waves. Potential theory is known to be suitable for proper prediction of ship motions in waves. In addition, the method can be used to estimate the second order drift forces. The vessel's responses were calculated in regular waves for a relevant range of wave frequencies and fixed speeds. Forces acting on the vessels in longitudinal direction were extracted from the diffraction calculation. The Quadratic Transfer Function (QTF) is plotted against the angular wave frequencies ω of the incident wave and presented for both vessel types in Figure 2 (right). The maximum added resistance for the feeder is found at $\omega \approx 0.635$ rad/s; for the sea-going inland vessel at $\omega \approx 1.05$ rad/s. Irregular sea states are described by statistical properties such as the spectral energy density distribution S. In analogy to the added resistance, the exciting forces are expressed at different angular wave frequencies ω. A suitable semi-empirical expression for the North Sea was published in [19] and represents the well known JONSWAP spectrum. It reads

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \cdot \exp\left[-\frac{5}{4} \cdot \left(\frac{\omega_p}{\omega}\right)^4\right] \cdot \gamma^{\exp\left(-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right)} \text{ with } \sigma = \begin{cases} 0.07 : \omega \leq \omega_p \\ 0.09 : \omega > \omega_p \end{cases} \quad (1)$$

and covers the peak frequency ω_p, α controlling the overall energy of the spectrum, peak enhancement factor γ, and σ modifying shape and width of the spectrum.The significant wave weight H_S can be obtained by means of the zeroth order spectral moment m_0

$$H_S = 4\sqrt{m_0} \qquad \text{and} \qquad m_0 = \int_0^\infty \omega^0 S(\omega) d\omega \quad (2)$$

The multiplication of both, the quadratic transfer function R_{AW}/ζ_a^2 and the exiting wave spectrum $S(\omega)$, yields the response acting on the vessel per frequency. Integrating over the given frequency range, the mean added resistance $\overline{R}_{AW}$ in the considered sea state can be estimated. The consecutive speed loss in percent, denoted by v_{loss}, is the ratio between mean added resistance and the corresponding calm water resistance.

$$\overline{R}_{AW} = 2\int_0^\infty \frac{R_{AW}}{\zeta_a^2} S(\omega)d\omega \qquad \text{and} \qquad v_{loss} = \frac{\overline{R}_{AW}}{R_T} \tag{3}$$

As a result, the different sailing speeds can be derived for the relevant sea states at the T&L hub's site. Assuming a mean sea state with a significant wave height $H_S = 1.5$ m and peak period $T_p = 6.5$ s, the velocity of the feeder reduces about 18 %, while the sea-going inland vessel looses speed by about 38 %.

3.3 Cost Model

The concept in focus evaluates the beneficial effect of a direct hinterland connection with established vessels for river-sea shipping. The non-stop solution is compared with the connection including one transshipment at a parent onshore port. With the developed model also short-sea shipping can be addressed. A comparison of solutions for relevant connections is done calculating the duration of round trips between the hub and a hinterland destination. With a dedicated cost model that includes capital, maintenance, personnel and fuel costs for each vessel type the most efficient solution is calculated. The applied cost model makes use of the following assumption:

The capital costs consist of a vessel's lightweight approximation that defines the costs for the hull and fixed rate for machinery and equipment, which is specific for the type of vessel and installed power. For the investment a fixed lending term of 20 years and a rate of interest of 1.5 % are assumed. With 2 and 5 % per year of the total investment, costs for maintenance and insurance are covered. The total capital costs per day for the considered vessels are summarised in Table 2.

The personnel costs depend on the crew size and assumed salaries for personnel being skilled for either navigation on inland waterways or seaways. Since the operational hours throughout the analyses of terminal design and hinterland logistics are set to 20 hours, the personnel works in two shifts. An associated employer outlay is already included in the personnel cost in Table 2. Capital costs and personnel costs are calculated for every operational hour. On a round trip, two different operational modes are distinguished and costs scale only with the corresponding mode. One mode is the processing at a terminal, that includes hours of vessel coordination in the port, and the loading and unloading at the terminal. In the second mode the vessel is under way in operation on a short-sea segment or on an inland segment considering sailing up- or downstream.

Fuel costs are only applied for the operational mode under way. Depending on the vessel's heading on an inland waterway, the necessary shaft power is related

Table 2. Costs per time unit and vessel in EUR

Vessel type / waterway class	feeder vessel	sea-going inland vessel	Va class	"Jowi" class
Capital costs - per day	10548	1964	1133	1699
Personnel costs - per day	2310	858	762	762
Fuel costs - per hour	500	93	47	86

to the assumed velocity it sails up- or downstream (see Table 1). A margin of 15 % is assumed and applied on the total costs per vessel on a round trip. More sophisticated cost models including a case study and aspects of pollution are provided by Al Enezy et al. [13] or Wiegmans and Konings [14].

The major contributions to transport costs are those for handling. Terminal brochures provide the handling costs to analyse the connections. The transhipment on the T&L hub is charged with 23.71 EUR/TEU [5]. A research on costs for handlings at existing terminals at sea and inland ports is documented below. For example, the handling of one container FEU or TEU between a vessel and the terminal is charged with approximately 75.00 EUR [15]. At a representative inland terminal in NRW the handling of one container is charged with 10.00 EUR on average [16]. In case the solution with stopover is calculated, costs for handling in the Port of Antwerp are charged for each move unloading from the feeder and loading on the inland vessel. Since vessel capacities for the short-sea segment and inland waterway segment do not match, it is assumed that also partially utilised vessels are available. For these vessels the full capital and personnel costs are applied, whereas fuel costs are only considered relatively. Since all analyses assume only a one-day dwell time, solutions with storage of containers at stopover ports are not considered. Hence, it is secured that the calculation of needed vessels per day is sufficient. The following paragraph sums up all assumptions and boundary condition assigned to the mode of operation.

- Duration for **Processing at Terminal** in port
  - at the floating T&L hub in coastal waters at least 1 hour
  - at hinterland or sea port for transshipment at least 2 hours

  A minimum duration for processing at terminals is set, since delays in ports commonly occur due to vessel coordination and the general risk of congestion. Thus, it considers the time the port needs to assign a vessel to its terminal after the vessel arrived. For the T&L hub this duration is assumed to be half of the time needed in established ports, since modern vessel and crane scheduling techniques will be applied. The actual time for loading or unloading scales with the number of cranes, their productivity in moves per hour, the spreader size setting, the TEU per move and the utilisation of the vessel for the cargo request. An example of concatenated durations is shown in Figure 3.
- Cranes operate with a productivity of 20 moves per hour regardless of the terminal or port. This is a reasonable assumption following Baird and Rother [2]. The spreader and number of cranes that can be used to process one vessel

depend on the vessel type. The number of cranes depends on the vessel's length. In case a vessel is equipped with cell guides a double spreader can be used. It is assumed that only the feeder and the sea-going inland vessel can be processed with a double spreader.

- At this stage of model development, it is assumed that only one vessel can be processed per terminal. Although, round trip durations are given per vessel service.
- At the terminal of stopover no ship to ship handling is assumed, which results in slightly higher durations and costs for the transhipment to the connecting vessel. It is a reasonable assumption, since no time for storage and transfer within a terminal are considered. It is further assumed, that the calculated minimum processing duration of 2 hours per vessel before unloading, compensates it.
- Costs are calculated per handled container, whereas prices for TEU or FEU depend on the terminal. Costs for the vessel are calculated on an hourly basis but only capital and personnel costs are considered.
- The **Vessel under way in Operation** sails at a dedicated velocity in coastal waters assuming common moderate sea state conditions or rather up- or downstream on inland waterways.
- The necessary power is coupled to the sailing velocity and influences the fuel costs, whereas fuel costs depend on the vessel's utilisation.

3.4 Mathematical Model Formulation

The formulated approach calculates the transport costs $Z_{r,p}$ on a feasible path p as a concatenation of shipping s and handling services t for a cargo requests r. An assumed scenario sets the boundary conditions for the relevant hinterland connections being analysed. The model is implemented in Visual Basic for Applications (VBA) and is structured by the following indices, variables and parameters. Considered types of services are distinguished by the following indices in given intervals. The index $i \in [1, ..., 4]$ distinguishes vessel services $s_i \in S^{Vessels}$, whereas $j \in [1, 2, 3]$ differentiates terminal services $t_j \in T^{Cranes}$. The integer $r \in \mathbb{N}$ enables contrasting costs of different cargo requests. To differentiate partial costs e. g. for fuel or crane moves, s and t are used as indexes for parameters discussed below. Scaling of the objective quantities round trip duration τ and costs Z needs the following dimensionless variables: $n_i \in \mathbb{N}$, the number of vessel services of type s_i, $u_i \in [0, 1]$, the utilisation of vessel service of type and $m_j \in \mathbb{N}$, the number of terminal services of type t_j. Parameters specify the cargo request and the considered types of services. Each cargo request r is the product of a given scenario with its container throughput CT and a suitable hinterland connection with its cargo portion. It is characterised by the origin and destination of a round trip and CT_r denoting the container throughput on request r [TEU].

Each vessel service $s_i \in S^{Vessels}$ is characterised by its operational area OA_S namely an inland waterway up-/ downstream or an estuary or coastal waters. Moreover, the service is defined by $d_S(OA_S)$ denoting the spatial distance the service can cover depending on the operational area given in [km], the nominal capacity UN_S in [TEU] and $v_S(OA_S)$ the average velocity as a function of the waterway, the operational area and the average conditions along each area e. g. v_{loss} equation (3). Furthermore, there are CF_S denoting the fuel costs in [EUR/hour], the personnel costs CP_S in [EUR/day], CC_S for the capital costs in [EUR/day], NC_S as the dimensionless nominal number of cranes to un-/load the vessel and NM_S the spreader type that is suitable for un-/loading in [TEU/move]. Each terminal service $t_j \in T^{Cranes}$ is characterised by its operational area OA_T namely a remote terminal, an onshore terminal or an inland terminal. Moreover, it needs PM_T describing the performance of cranes in [moves/hour], $CH_T(OA_T)$ denoting the handling costs in [EUR/TEU] and the minimum duration τ_0 for processing a vessel at the terminal due to expected congestion in [hours].

The objective function minimises the total costs per container [EUR/TEU] for a request r as a result of the concatenated path p of services s_i and t_j. Let $x_{r,p} \in \{0, 1\}$ be a binary variable equal to 1 if shipping s_i and terminal services t_j are compatible with respect to operational areas $OA_{S \vee T}$ and concatenate to a feasible path p for request r, 0 otherwise. The transport costs $Z_{r,p}$ are obtained following equation (4).

$$Z_{r,p} = \sum_{i,j} n_i x_{r,p} \left(u_{S,i} \left(\tau_i \cdot CF_{S,i} + UN_{S,i} \cdot CH_{T,j} \right) + \tau \cdot \left(CP_{S,i} + CC_{S,i} \right) \right) \quad (4)$$

A path $p = [s_i, ..., t_j, ...]$ is feasible to service a request r, if it satisfies the compatibility of operational areas OA_S, e.g. a vessel service with the OA_S coastal and estuary waters is necessary to reach a service t_j with OA_T remote terminal.

Following equation (5), the total duration τ to service a request r on path p with service combinations s_i and t_j is the sum of time elapsed at terminals and under way, it reads

$$\tau_{r,p} = \sum_{i,j} \left(\tau_i + \tau_j \right) . \quad (5)$$

Here τ_i is the time each service s_i needs to cover the spatial distance of a request r and the velocity $v_S(OA_S)$. The time sailing and the time a vessel needs to be processed at a terminal τ_j, read

$$\tau_i = v_{S,i}(OA_{S,i}) \cdot d_{S,i} \quad \text{and} \quad \tau_j = \tau_{0,j} + \frac{UN_{S,i} \cdot u_{S,i}}{NC_{S,i} \cdot PM_T \cdot NM_{S,i}} \quad (6)$$

and are subject to

$$CT_r = \sum_{i} \left(n_i \cdot UN_{S,\,i} \cdot u_{S,\,i} \right) . \quad (7)$$

The constrain given by equation (7) ensures that the container throughput of request r for a given scenario on a given hinterland connection is met by the assigned services. The most economic path p of all feasible paths is found, when $Z_{r,p}$ and $\tau_{r,p}$ reach a minimum. Minima are approached varying the type and number n_i, m_j as well as the utilisation u_i of assigned services which build a feasible path.

Table 3. Round trip durations per vessel for the hinterland connection T&L hub to NRW with stopover at Port of Antwerp a) and with non stop solution b).

Segment	Vessel type	No. Vessels (avg. utilisation)	Under way $[h]$	Processing at terminal $[h]$	Days in total
a)					
short-sea	Feeder vessel	2 (97.5 %)	9.17	15.23	1.22
inland	"Jowi" class	3 (93.5 %)	55.56	21.00	3.83
	Days in total		3.24	1.81	**5.05**
b)					
short-sea	Sea-going inland	4 (94.2 %)	25.47	5.75	1.56
inland			55.56	11.50	3.35
	Days in total		4.05	0.86	**4.91**

4 Simulation Results

A scenario demanding 18193 TEU per one day dwell time was analysed. For a comparison always two feasible paths are calculated, one with transhipment and a non-stop connection. The cargo request between a T&L hub in the estuary of the River Scheldt and NRW breaks down to 1002 containers (573 TEU and 429 FEU) per day. The duration for a round trip fulfilling the request is compared for services in the two operational areas by Table 3 a). The path combines feeder vessels and the largest inland vessels ("Jowi" class) available with a capacity of 510 TEU. The round trip of one feeder takes 1.22 days (102 km one way) and the inland vessel needs 3.83 days for 296 km each way including loading and unloading at the port of destination and stopover. These durations depend on the vessels velocity in the respective operational area and its capacity that defines the time needed for processing in the port (see Table 1).

In Table 3 b) the path with a sea-going inland vessel is summarised. This non-stop solution requires more time, since the sea-going inland vessel is assumed to sail only with approximately one third of the feeder's velocity, but compensates time at the terminals. Although the sea-going inland vessel's capacity is about half of the feeder's, only two more vessels per type are necessary to fulfil this cargo request with 1002 containers each day. In total it is one vessel less than for the solution with stopover at the T&L hub's parent port onshore.

A detailed split of durations is shown in Figure 3. Here port 1 abbreviates the T&L hub, port 2 the parent port ashore of stopover and port 3 the conglomeration of terminals in the hinterland. An illustration of the hinterland connection is provided by Figure 1. All durations related to port 2, where the handling from sea-going to inland vessel takes place, are obsolete in case of the non-stop solution. This time saving amounts to about 3 % of the path with stopover. The favourable solution is found to be the fastest and most beneficial one. Raising only the fastest path as the promising one for an economical integration of the T&L hub takes into account that fewer vessels are needed, since round trip durations reach a minimum even if the capacity of the deployed vessel is smaller.

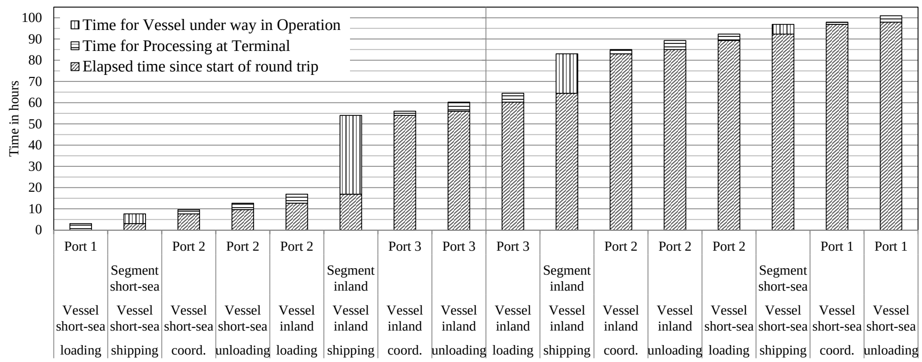

Fig. 3. Split of durations for individual operations (hatched horizontally in port and vertically under way) along a round trip between the T&L hub and NRW with a feeder and large inland vessel (Jowi). The cumulative sum shows the elapsed time (hatched diagonal) until the current operation (from left to right). Vessels are heading upstream/inbound first, left of the vertical line that indicates half way, and downstream on the way back.

As the non-stop solution reveals time savings, it is even worth to look at costs and their evolution. For the hinterland connection between the T&L hub and NRW a breakdown of costs per vessel service and by the two operational modes is given by Table 4 a) and b). These two tables deal with the costs per vessel, whereas Table 4 c) and d) present the costs per TEU. Comparing both paths by the total costs per TEU on a round trip the non-stop connection with the sea-going inland vessel is about 35 % less expensive than the path including additional handlings at the parent onshore port between the large inland and the feeder vessel. As observed for the round trip durations, the sea-going inland vessel is slower and also more expensive. Costs per vessel are about 7 % higher than for the combination of sea-going and inland vessel on the analysed hinterland connection. Looking at costs per TEU, the benefit is even more on the solution with two vessel types, since the capacity of the sea-going inland vessel is only 380 TEU. Thus, the sea-going inland vessel is 38 % more expensive considering the costs during transit.

Another aspect can be observed at the partial costs in the two operational areas of short-sea and inland waterway shipping separately. Analysing costs per vessel service and operational area on the path with stopover, the feeder is much more expensive than the inland vessel, even though it completes only about a third of the distance on inland waterways. This is due to the high handling costs at the stopover. If the costs are normalised by the vessel capacity, the feeder vessel is slightly less expansive than the inland vessel on the inland waterway segment. Evaluating this split for the path with one vessel type, the short-sea segment is always less expensive, since the costs are almost equally distributed over both modes of operation (50.6 % under way to 49.4 % processing at the terminal).

Table 4. Breakdown of costs per deployed vessel type and mode of operation in EUR on a round trip between T&L hub and NRW with stopover at Port of Antwerp a) and non-stop solution b) as well as a breakdown of costs per TEU for the solution with stopover at Port of Antwerp c) and with no stopover d).

Segment	Vessel type	No. Vessels (avg. utilisation)	Under way [EUR]	Processing at terminal [EUR]	Total costs [EUR]
a)					
short-sea	Feeder vessel	2 (97.5 %)	4582	33806	38388
inland	"Jowi" class	3 (93.5 %)	7956	20501	28457
	Total costs in EUR		12538	54307	**66845**
b)					
short-sea	Sea-going inland	4 (94.2 %)	4774	7118	11892
inland			8680	5990	14670
	Total costs in EUR		13453	13109	**26561**
c)					
short-sea	Feeder vessel	2 (97.5 %)	6	46	52
inland	"Jowi" class	3 (93.5 %)	16	40	56
	Total costs in	EUR/TEU	22	86	**108**
d)					
short-sea	Sea-going inland	4 (94.2 %)	13	19	32
inland			23	16	39
	Total costs in	EUR/TEU	35	35	**70**

5 Conclusions

Regional cargo demands were analysed to assess the potential of different waterborne transport between hinterland ports and a floating T&L hub in coastal waters. A strategic simulation method was developed and applied to scenarios evaluating different paths of hinterland transport. Navigational and operational profiles for types of sea-going and inland vessels build the method's core in combination with a dedicated cost model. Round trip durations as well as transport costs for containers on relevant waterborne transports were calculated. Connections between the hub and the hinterland base on a cargo flow prognosis that focuses on established connections of the Port of Antwerp. If another waterborne transport is of interest, e. g. by short-sea shipping to other sea ports, a more extensive cargo flow analysis is required, which can be included in the developed model as a larger data base. The hinterland connection between the federal German state NRW and the T&L hub with a given cargo request was found to be representative for a relevant waterborne transport. Two feasible paths to fulfil the request with combinations of vessel services were compared, one with additional transhipment at the hubs parent port ashore and another one with a non-stop solution.

Servicing this cargo request on a path concatenated of two vessel services results in longer round trip durations and higher transport costs of about 35 % per TEU than with the non-stop solution. The combination of short-sea and inland waterway shipping needs one more handling at a port ashore, here the

Port of Antwerp. On the path with non additional stop, the transport costs of 70 EUR per TEU were estimated, while the path with an additional terminal service yielded about 108 EUR per TEU. The duration of a round trip along the non-stop path with the sea going inland vessel lasts up to 4.91 days which is about three hours faster than the path of two vessel services with stopover.

Moreover, it turned out that, as long as the demand scenario provides enough throughput of containers, the feeder vessel should be deployed in combination with the largest available inland vessel. Although, the sea going inland vessel is assumed sailing slower in coastal waterways, the non-stop solution is economically favourable as long as the depth of hinterland penetration permits it. Further research has to show if this may change when deep hinterland connections are serviced by inland waterway shipping, thus that an additional handling at the onshore port from the feeder to the inland vessel is negligible in terms of costs and time. An underestimated contribution to round trip durations is the vessel scheduling in ports, which can change the processing times at terminals significantly.

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Nomenclature

Symbol	**Description**	**Dimension**
Latin Symbols		
B	Vessel Breadth	m
CC_S	Capital costs per hour	EUR/h
CF_S	Fuel costs per day	EUR/d
$CH_T(OH_T)$	Handling costs per TEU	EUR/TEU
CP_S	Personnel costs per day	EUR/d
CT_r	Container throughput on request r per day	TEU/d
$d_S(OA_S)$	Spatial distance covered by service s_i	km
g	Acceleration due to gravity	m/s^2
H_S	Significant wave height	m
L	Vessel length	m
m_j	Number of terminal services of type t_j	-
m_0	Zeroth spectral moment of $S(\omega)$	m^2
NC_S	Nominal number of cranes to un-/load the vessel	-
NM_S	Spreader capacity of service s_i per move	TEU
n_i	Number of vessel services of type s_i	-
OA	Operational area of service s_i or t_j	-
PM_T	Crane moves per hour	1/h

r	Cargo request per day	TEU/d
R_{AW}	Added resistance	N
R_T	Calm water resistance	N
s	Vessel service	-
$S(\omega)$	Energy density spectrum	m^2 s
t	Terminal service	-
T	Vessel draught	m
T_P	Peak period	s
u_i	Utilisation of vessel services of type s_i	-
UN_S	Nominal transport capacity of service s_i	TEU
v	Velocity	m/s or kn
v_{loss}	Velocity loss	-
$v_S(OA_S)$	Average velocity of vessel service s_i	m/s
$x_{r,p}$	Feasibility of path p with $x_{r,p} \in [0, 1]$	-
$Z_{r,p}$	Transport costs on path p for cargo request r	EUR
Greek Symbols		
α	Constant scaling the spectrum $S(\omega)$	-
γ	Peak enhancement factor	-
σ	Factor modifying the shape of spectrum $S(\omega)$	-
$\tau_{r,p}$	Total duration to service request r on path p	h
τ_0	Minimum duration of processing a vessel in port	h
τ_i	Duration of service s_i under way in operation	h
τ_j	Duration of service t_j un-/loading a vessel	h
ω	Angular wave frequency	rad/s
ω_p	Angular peak frequency	rad/s
ζ_a	Wave amplitude	m
Indizes		
i	Type of vessel service s_i with $i \in [1, ..., 4]$	-
j	Type of terminal service t_j with $j \in [1, 2, 3]$	-

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