SHALLOW-DRAUGHT VESSELS FOR THE VESSEL TRAIN

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Abstract. The Vessel Train is a novel semi-autonomous waterborne transport concept that implies a convoy of digitally connected vessels. Only the first vessel in the Vessel Train (the so-called "lead vessel") is fully manned, while the remaining vessels (the so-called "following vessels") are remotely controlled from the lead vessel and thus may sail either with a reduced crew or with the crew off-duty. The Vessel Train was the subject of the research project NOVIMAR (NOVel Iwt and MARitime transport concepts), funded by the European Commission within the framework of the Horizon 2020 program. One of the tasks of the project concerned the design of novel vessels for the Vessel Train. The Vessel Train ships were designed in compliance with a specific requirement: to utilize the horizontal (Ro-Ro) container handling. Additionally, two inland vessels had to fulfil another condition: to have as low design draught as possible, so as to provide for uninterrupted navigation even during the low-water periods which tend to be extended and more extreme on all major European inland waterways. Both the Ro-Ro handling of containers and the shallow draught considerably affect the ship general arrangement, cargo stowage and handling, structural strength, intact and damage stability, etc. Thus, this paper discusses the challenges encountered in design of large inland container Ro-Ro vessels with extremely shallow draughts, intended for the use in the Vessel Train.

Keywords: Vessel Train, Inland vessels, Container Ro-Ro vessels, Shallow draught, Unconventional vessels.

1. Introduction

Although the advantages of the waterborne transport over other transportation modes are well-known, its potential is yet to be fully unlocked. This seems to be particularly valid for inland waterway transport. To adequately respond to the contemporary socio-economic challenges, climate change effects, and shipping decarbonization requirements, both the design and operation of inland cargo vessels should be enhanced. The Vessel Train (VT) concept aims to tackle some of these challenges primarily by creating a novel mode of operation which is based on "partially unmanned" or "periodically unmanned" shipping. Namely, the Vessel Train concept implies a convoy of digitally connected vessels whereby only the first vessel in the convoy (the "lead vessel") is fully manned, while the remaining vessels sail with the crew off-duty (in a periodically unmanned regime) or with a reduced crew (in a partially unmanned regime), see Figure 1. To enable this, the following vessels are controlled from the lead vessel via a control system.

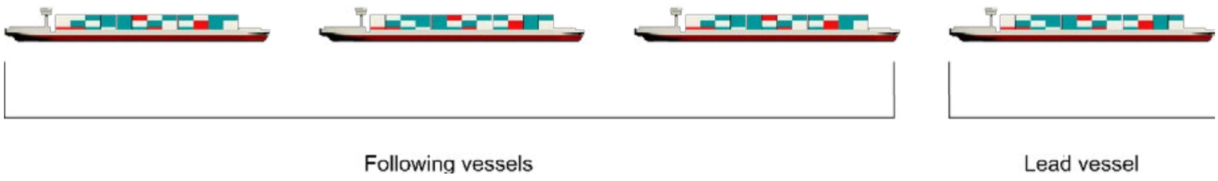

Figure 1. The Vessel Train concept. The Figure does not present the distance between the vessels in scale.

Several effects could be achieved with the Vessel Train. The vessels which joined the VT as the following vessels could sail continuously, in a 24-hour sailing regime, without changing the crew, which otherwise would not be possible as the inland vessels in Europe are subject to regulations which limit the operational time. Furthermore, an increase of cargo capacity and decrease of operational costs attained by forming of VT could lead

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to a specific economy of scale effect. It is also expected that the VT would extend the waterborne transport further down the supply chain.

The VT, however, has to be adequately supported by design measures. The Vessel Train concept is principally applicable to the existing ships. However, to be able to join the VT, the existing ships would have to undergo some modifications, the extent of which could significantly vary, depending on the features of the vessel and its intended role in VT (lead vessel or a following vessel). Thus, the vessels specifically designed for the VT would facilitate its deployment and increase the efficiency of the concept.

The Vessel Train is intended for transport of unitized cargo in short sea shipping, sea-river shipping, and inland navigation. Therefore, a suite of novel ship designs suitable for diverse waterborne transport segments has been developed within the project NOVIMAR. The overview of NOVIMAR ship design solutions was presented in [1]. In this paper, however, the focus is on the large inland vessels with shallow design draughts. The paper presents innovative, unconventional concepts which introduce several non-standard features and notably differ from the present, standard European cargo ships of the same or a similar purpose and size. Thus, the design process cannot extensively rely on the existing designs; it is inevitably iterative and as such may be only outlined herein.

2. Design objectives, challenges, and approach

The vessels presented in this study were designed aiming at several objectives, whereby it may be distinguished between the specific NOVIMAR design objectives, the objectives of the shallow-draught vessels design, and the general design objectives typical for containerships. The NOVIMAR design objectives include:

- A reduction of costs, time, and risk associated with the cargo unit shift between transportation modes.
- A design which would enable the vessels to alternate their roles within VT and operate both as the lead vessels and as the following vessels.
- A design which would enable the vessels to be efficient as standalone cargo ships when no VT is formed.

The main objective of the shallow-draught design is to provide as far as possible an uninterrupted service throughout the year, that is, even during the low water periods, thus increasing the reliability of the inland waterway transport. Finally, the objectives of the containership design address the cargo capacity in terms of maximizing of both the number of containers carried and the mass of deadweight.

To shorten the time required for cargo loading/unloading and for cargo transfer between the transportation modes (and thus reduce the associated costs), to lower the likelihood of damage of cargo units (and thus diminish the insurance claims), the cargo handling should be simplified, and the number of operations should be reduced. In principle, this may be achieved with the horizontal (Ro-Ro) handling of containers. Using a vehicle, the containers may be loaded onto the vessel in the port of origin, stowed in a proper position, and unloaded in the port of destination. This would enable a faster transshipment and/or transloading of cargo units. Waiting time at terminals could be reduced, and a number of roundtrips per year could be increased. In addition, this would allow the operators to frequent the ports which lack the (vertical) container handling equipment and infrastructure. Consequently, the vessels for the Vessel Train could be designed as the container Ro-Ro ships. An additional benefit of such a design is the possibility to load other sorts of rolling cargo, such as trucks/truck trailers.

However, the vehicles employed in the existing horizontal container handling techniques are not capable of performing the said operations without auxiliary devices, such as the terminal trailers or the cassettes, which are stowed onboard together with the containers. The ship payload is thus reduced, which diminishes the attractiveness of the concept. This is particularly valid for inland container vessels whose payload may be already limited by the available fairway depth.

To keep the advantages of the Ro-Ro handling of containers, but to eliminate the need for an intermediary device, the NOVIMAR project partner ScandiNAOS has developed a special cargo handling vehicle (CHV), Figure 2. CHV is capable of loading, carrying, and unloading a stack of two containers. CHV can lift the containers directly from the pier or the deck of a ship, and conversely, drop them onto the pier or the deck, without auxiliary and intermediary devices. Furthermore, CHV can be carried onboard and used in other ports. More details on the NOVIMAR CHV may be found in [2]. It is going to be demonstrated that the choice of the cargo handling technique and the specific features of CHV have a far-reaching impact on the design of the vessels.

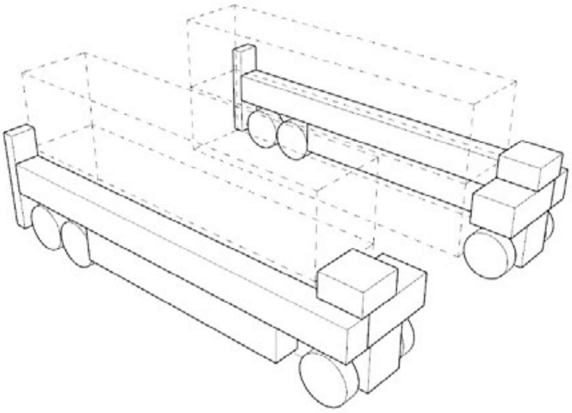

Figure 2. Cargo handling vehicle (CHV) developed within the project NOVIMAR

In general, the vessels may either lead the Vessel Train or may join as the following vessels. However, the research on safety and the human skills required for VT operation, conducted within the NOVIMAR project, has shown that the lead vessels would be subject to the specific technical requirements.

The Vessel Train may be formed on a regular basis or ad hoc, when an opportunity arises, which depends on the adopted business model. (The business models which were investigated in the project NOVIMAR are described in [3]). Whatever the case, it is reasonable to assume that the vessels would not be permanently employed in the Vessel Train. Thus, it would be prudent to design the vessels which could efficiently operate as standalone cargo ships too.

In line with the design objectives, and findings of the project NOVIMAR which concern multiple aspects of the Vessel Train operations, such as the safety, the required human skills, and economy of the Vessel Train, two designs were conceptualized. To fully utilize the advantages of the Ro-Ro technology, a ferry-inspired design which would allow an unobstructed cargo flow from bow to stern and vice versa ("the double-end access") was proposed (Figure 3). The concept foresees a flat weather deck (flush deck); the cargo would be loaded and unloaded by means of two ramps fitted at the bow and the stern. A large, centrally positioned wheelhouse would provide 360 degrees view from the bridge and comfortable working conditions for the Vessel Train operators; both features would facilitate navigation in the convoy. On the other hand, the possibility to lower the wheelhouse, which is a standard feature on European inland cargo ships, would be very limited. A greater lowering of the wheelhouse could be possible only if the containers would not be stowed beneath it, which would result in a considerable loss of payload.

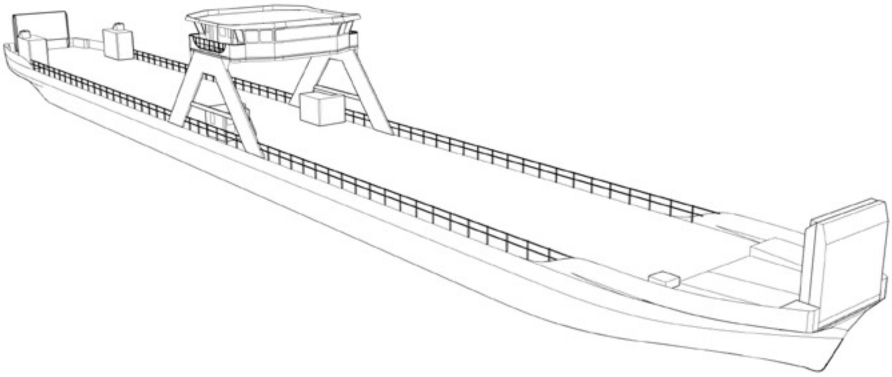

Figure 3. Sketch of the double-end access large inland container Ro-Ro vessel

From the safety point of view, however, the possibility to lower the wheelhouse is very important. It facilitates sailing under the bridges and reduces the likelihood of the ship-bridge allisions, which are regarded as one of the most dangerous hazards in inland navigation. It is obvious that the loss of wheelhouse would imply the interruption of the Vessel Train operations and a possible onset of a range of hazards. Therefore, another concept ("the stern access") was proposed (Figure 4). The cargo would be loaded onto and unloaded from the flush deck using a ramp fitted at the stern. Unlike the typical arrangements on inland cargo vessels in Europe, the accommodation spaces and the wheelhouse would be positioned forward instead of aft. The benefits of such an arrangement include improved working conditions for the crew (less vibration and noise in the accommodation and working areas) and, possibly, a better and timely estimation of the available clearance when passing below the bridges. It is to be noted that this arrangement has gained some popularity in novel inland container vessel designs such as the novel battery-electric design of inland container vessel for Sweden [4], Zulu vessels and concepts† and new COSCO battery-electric propulsion container vessels for the Yangtze River [5].

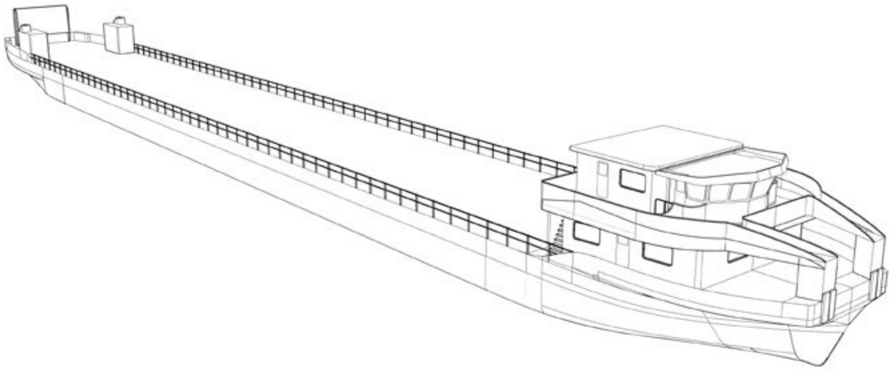

Figure 4. Sketch of the stern access large inland container Ro-Ro vessel concept

Another design objective concerns the increase of operability and reliability of inland cargo vessels in Europe. During the low water periods, the vessels sail at lower draughts which results in reduced payload and, in turn, causes the increase of freight rates. In extreme cases, the navigation has to be suspended. The cargo owners are thus reluctant to ship cargo via inland waterways and instead tend to rely on other modes of transportation (such as the rail and road transport) which do not depend on environmental phenomena, and hence offer a dependable service. These problems are emphasized in the shallow-water sectors such as e.g. the Lower Danube. However, in recent years, several major inland waterways all over the world have experienced the extreme (and extended) low water periods. A shallow design draught would enable the extended operability of the vessels without compromising the hydrodynamic performance. Obviously, the payload would be decreased in comparison to the standard inland container vessels with a deeper design draught. However, the reliability of the service would be improved while the lost cargo capacity could be compensated (and possibly increased to reach the economy of scale effects) by forming the Vessel Train.

3. Selection of main particulars

In the step following the first conceptualization, the choice of the principal dimensions should be addressed. The ship main dimensions in inland navigation may be subject to a range of constraints depending on the waterway features and parameters. The ship length and beam may be restricted by the dimensions of lock chambers, while the ship air draught depends on the (statistically defined) available clearance below the bridges. The design draught of inland ships is arguably the most critical and thus, the most difficult parameter to be decided upon.

From an economic point of view, it is expected that the large vessels would benefit the most from the Vessel Train concept [6]. Thus, the vessels should have the length corresponding to the length of the European CEMT class Va vessels [7] at least. In general, the greater the length, the more gains from the hydrodynamics point of view could be expected. However, the requirement for a shallow design draught could lead to a relatively low vessel depth and the longitudinal strength issues associated with large L/D ratios, which could offset the hydrodynamic benefits gained by extending the vessel length. In line with the outcomes of the previous studies on design of shallow-draught vessels (see [8] and [9]) it was decided to limit the length of the vessels to $L = 104$ m.

Regarding the vessel beam, two opposing design objectives were considered within the project NOVIMAR: to maximize the number of pallet-wide containers carried abreast, but to keep the beam within the dimensions which

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† see https://www.zulu-associates.com/

would enable the vessel to enter the 12 m wide lock chambers. Namely, the standard beam of CEMT class Va container vessels is B = 11.4 m, which results in 0.3 m clearance (on each side of the vessel) between the vessel side and the lock chamber wall. On the other hand, considering that the required width of the double sides is 0.65 m according to the rules [10], the available cargo hold width allows loading of four rows of ISO containers. ISO containers, being 2.438 m wide, do not allow loading of two pallets abreast inside the container; two pallets abreast could be loaded in the so-called continental, pallet-wide container (PWC) which is 2.5 m wide. To load four rows of PWC in the cargo hold of a CEMT Class Va ship, however, would require the beam to be increased to B = 11.55 m at least. Nevertheless, it seems that the vessels with B > 11.45 m are not admitted to the locks with 12 m wide chambers.

Such considerations, however, do not apply to the concepts analyzed in this paper. The proposed container Ro-Ro vessels would not have a cargo hold; a flat deck would facilitate the horizontal loading of containerized cargo, so an 11.45 m wide vessel would seemingly allow for loading of four rows of PWC on the deck, without constraints. Considering the 0.05 m distance between the container rows, the clear width of the side deck would be 0.65 m which is greater than the minimum (0.6 m) required by the ES-TRIN regulations. Thus, B = 11.45 m is tentatively adopted as the vessels' beam. It is, however, going to be demonstrated that the stowage of container units in the proposed concepts is not without its specific challenges, precisely because of the adopted container handling technique.

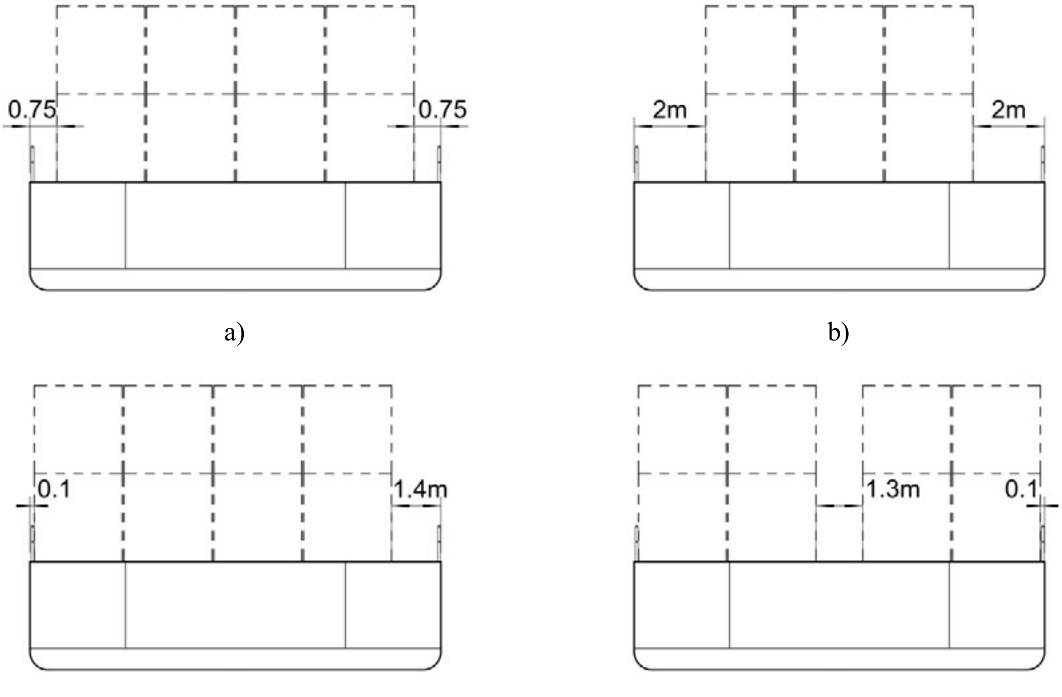
The design draught of the vessels is adopted as d = 2 m, in line with the previous research on design on shallow-draught inland cargo ships see [8], [9], [11]. This is far below the typical draughts of the standard European inland cargo vessels of the same class which may exceed 3.5 m. The navigation conditions on the Danube were extensively examined in [8]. It may be added that, according to the data of the Danube Commission, during 2020 it was possible to attain 2.5 m draught only occasionally in February and March, whereas throughout the rest of the year the available draught varied between 1.85 m and 2.4 m [12]. A comprehensive overview of the water depths on different sections of the Rhine in 2018, when the historically low water levels were recorded, was elaborated in another H2020 research project NOVIMOVE, see [13]. The water levels on the Rhine should not fall below the reference water level GlW for more than 20 ice-free days in a 10-year average. It was shown, however, that in 2018, the water levels on the different sections of the Rhine were below GlW between 90 and 140 days.

The depth of the vessels depends on the general arrangement of the vessel, the available air draught on the examined routes, the structural design, as well as on the (intact and damage) stability assessment. Considering a very low design draught, to attain a sufficient (standing) height in the machinery space, the depth of the vessels has to be increased. The flush deck requirement, however, does not allow to raise the depth locally, in way of poop deck; instead, the depth has to be increased over the complete length of the vessel. On the other hand, an increase of the depth leads to an increase of the air draught, which is limited by the height of the bridges along the waterway. In this respect, the available "design space" may be very restricted: the variations of air draught of an order of magnitude of 0.1 m may substantially extend or shorten the vessel's operational range on major European inland waterways. Considering the abovementioned, the depth of D = 3 m was tentatively adopted for both concepts.

The feasibility of the proposed length, beam, draught, and depth were verified by cargo handling and stowage considerations, structural design, and stability calculations, and other ship design aspects which are presented in the following sections of the paper.

4. Cargo handling and stowage

The horizontal cargo handling approach adopted within the project NOVIMAR enables the loading of two tiers of containers on the weather (Ro-Ro) deck using CHV. Considering the length and the beam of the vessels, a total of approximately 100 TEU containers could be loaded. However, due to the adopted container handling approach the containers could not be loaded in the "traditional" arrangement, i.e. four container rows next to each other, symmetrically positioned with respect to the vessel centerline (Figure 5a). In such an arrangement, CHV would be able to load three container rows only; the fourth row could not be loaded due to a lack of space necessary for the CHV movement (Figure 5b). As an alternative, the containers could be positioned asymmetrically with respect to the centerline, leaving sufficient space for CHV movements on one side of the vessel (Figure 5c). This may, however, cause a significant heel during the loading/unloading and slow down the cargo handling. The solution is found in a non-standard container arrangement which implies that two container rows are loaded to the port side, and two container rows are loaded to the starboard side with a 1.3 m wide walkway in between (Figure 5d).



a) b)

c) d)

Figure 5. The possibilities for loading of four rows of containers in the proposed concepts

A uniform cargo loading and a minimum heel during loading/unloading operations could be achieved by alternate loading of units on the port side and the starboard side, using the “left-hand” and the “right-hand” cargo handling vehicles, see Figure 6.

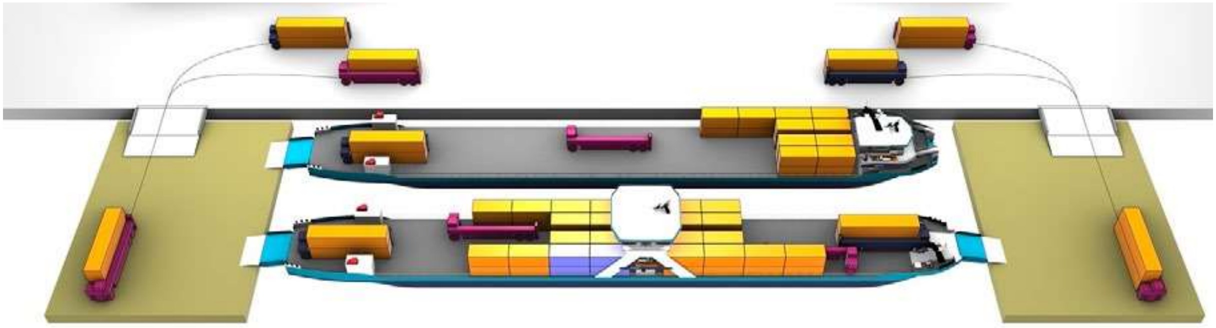


Figure 6. Loading procedure aimed at minimizing the heel during loading operations

The number of units carried by the designs analyzed in this paper is considerably smaller than in the standard European inland container vessels of the same class which may load up to 208 TEU. The cargo-carrying capacity of the vessels could be expanded to approximately 150 TEU with the third tier of containers. The third tier, however, would have to be loaded vertically, using cranes, which diminishes the appeal of the Ro-Ro concept. Thus, two-tier loading would be preferred if handling speed is the priority, while three-tier loading would be preferred if space utilization is the priority. On the other hand, when sailing outside of the Vessel Train, the stern access vessel may expand her cargo-carrying capacity by forming a pushed convoy with a barge.

5. Structural design

The vessels’ scantlings have been determined using Bureau Veritas (BV) Rules for the Classification of Inland Navigation Vessels [14]. However, besides the standard structure calculations, several features influencing the structural response were additionally considered, namely:

- high length to depth ratio (*L/D* = 34.67);
- loading/unloading in one run;
- deck strengthened to withstand the concentrated loads from the special cargo handling vehicle (CHV);
- closed cross section.

Higher *L/D* ratio is directly related to longitudinal strength issues as it provides higher longitudinal stresses, especially in deck and bottom structures. Therefore, most of the classification societies state that their rules are not fully applicable to vessels having *L/D* > 35 and remark that such vessels should be considered as "unusual" or "unconventional" and as such should be assessed on a "case by case basis". In practice, this means that the additional strength calculations are necessary to prove the vessel strength. They primarily include direct longitudinal strength calculation (rather than rule-based estimation of bending moment) and more comprehensive buckling checks. Moreover, the rules may require a finite element analysis of a part of the hull structure which was previously evaluated to exhibit a critical structural response. In case of the vessels presented in this paper, since the *L/D* ratio is close to the rule limit, additional longitudinal strength and buckling checks have been performed. Moreover, the vessels are designed to be loaded or unloaded in one run which delivers more uneven weight distribution and furthermore, increases bending moments.

However, deck strength is already increased to facilitate the concentrated loads from container corners and CHV wheels. Normally, two tiers of containers would deliver their weight in four symmetrically positioned corners. In this case, however, CHV has three wheels which are dividing the maximum force (the weight of two 40 feet containers and the vehicle itself) into three asymmetrically positioned points on deck. This significantly amplifies the concentrated loadings and increases the thickness of the deck structure compared to the one which would be designed without the vehicle being considered. Moreover, as the vessels have the closed cross section (due to the presence of flush deck) the section modulus is higher as compared to the standard open deck container vessels, and the corresponding longitudinal response is reduced.

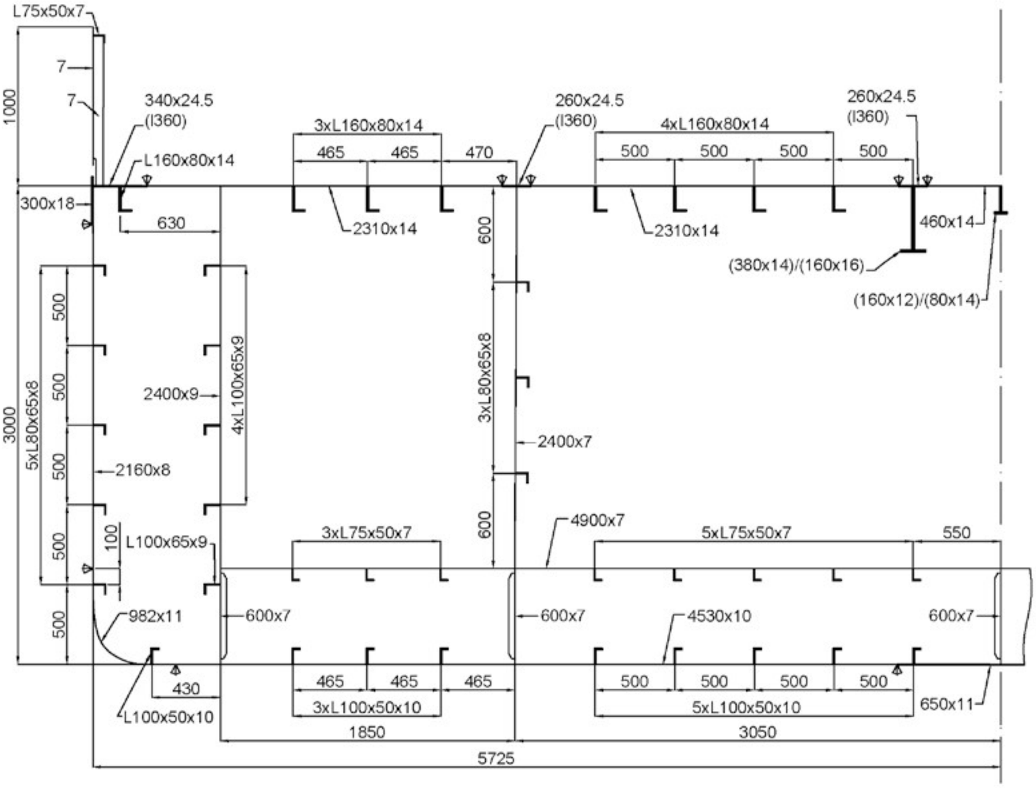


Figure 7. Normal frame of the proposed concepts

Consequently, direct longitudinal strength calculations are carried out followed by buckling checks (based on the stresses obtained by the longitudinal strength calculations) to prove the vessels strength. Although the high *L/D* and one run loading/unloading sequence could deliver structural issues, the additionally strengthened deck due to CHV operations and the closed cross section significantly reduce the bending moments making the vessels structurally safe. The final structures of both vessels are almost identical and include longitudinally framed hull with girders and stiffeners positioned below the container corners. The mid-section frame is shown in Figure 7. Its specifics include:

- spacing between the longitudinals: 465-600 mm, 500 mm for most of the spacings;
- main frame spacing: 1530 mm;
- double bottom height: 600 mm in the mid ship and 500 mm in the engine room;
- double side width: 800 mm.

6. Safety and stability assessment

In general, ship safety is achieved by two distinct, but complementary aspects: safety by design (comprising the technical measures required by the relevant regulations and industry standards) and safety in operation (comprising the activities of a trained, skillful, and experienced crew) [15]. It was, however, demonstrated that safety in operation plays a significant role in safety of inland vessels, considering that the technical requirements are often low [16]. As the Vessel Train concept implies a reduced human involvement in ship operation, it is necessary to increase the safety by design requirements for the vessels participating in the Train as compared to the standard European inland cargo ships.

Specific technical requirements for the following vessels are intended to enable early detection of hazards and automatic or remote execution of safety functions. Therefore, the following vessels should be equipped with:

- means for cargo shift monitoring and water ingress detection;
- fire detection and fire extinction systems;
- tools for stability management and cargo loss prevention;
- automatic draining systems;
- means for remote / automatic anchoring;
- secondary means of steering.

Technical requirements for lead vessels include:

- redundancy of propulsive system comprising secondary means of propulsion and secondary means of steering;
- fire alarm systems (fire detectors, fire indicators, control panel with at least two electric power sources) and fire extinction systems (permanent firefighting systems);
- an emergency power supply of VT control system;
- tools for stability management and cargo loss prevention.

In addition, the space intended for placement of VT control system onboard lead vessels should be designed so as to take ergonomics and habitability appropriately into account because the operation of the Vessel Train implies at least one additional human operator. Finally, both the lead vessels and the following vessels should comply with the damage stability requirements for dry cargo vessels carrying dangerous cargo.

Considering the container arrangement, the proposed concepts feature a single communication path (passageway) along the centerline of the vessels instead of two independent walkways from bow to stern, on the port side and the starboard side, which exist on the standard inland cargo vessels. The lifeboat is positioned in the vicinity of the accommodation and wheelhouse, see Figure 8. Thus, on the double-end access vessel there would be two escape routes inside the protected area[‡] leading in opposite directions and one lifeboat, while on the stern access vessel, there would be one escape route inside the protected area and one lifeboat at the opposite end. Therefore, it may be considered that both vessels comply with appropriate ADN regulations on means of evacuation, see [17].

[‡] *"Protected area" is a virtual space which includes cargo holds (and adjacent spaces above the deck) on dry cargo inland vessels intended for carrying dangerous cargo. For the precise definition of "protected area" see ADN regulations [17].*

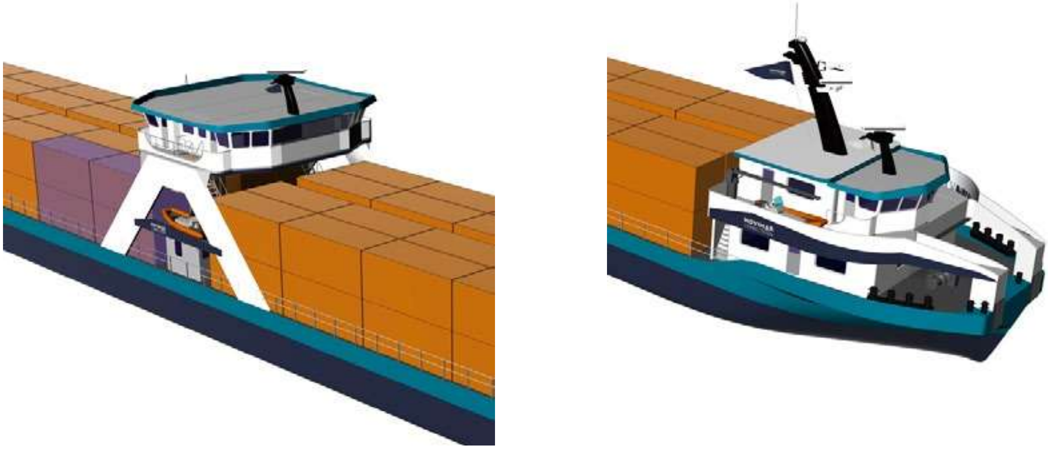


Figure 8. Placement of lifeboats in the proposed concepts

A reliable stability assessment requires a reliable estimation of the (major) weight groups and their vertical centers of gravity. Such an estimation could not have been performed with sufficient accuracy before the structural design was completed, which enabled the calculation of the steel weight (a major part of the lightship). The average mass of containers which could be carried by the proposed concepts is given in Table 1.

Table 1. Average mass of containers carried by the proposed concepts

Vessel	Number of tiers	Number of TEU	m_{TEU} [t]
Double-end access	2	100	11.8
	3	146	8.4
Stern access	2	104	11.3
	3	152	7.8

The intact and damage stability of the vessels should comply with the stability regulations enforced on the European inland waterways. The applicable regulations are found in Chapter 27 (Special provisions applicable to vessels carrying containers) of ES-TRIN (European Standard laying down technical requirements for Inland Navigation vessels) [10] and in Chapter 9.1 (Rules for construction of dry cargo vessels) of ADN (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways) [17]. The calculations are performed for vessels carrying unsecured containers.

6.1. Intact stability assessment

In brief, the rules [10] stipulate that the minimal metacentric height of the vessel carrying unsecured containers should be 1 m, while the static angle of heel of the vessel due to simultaneous action of beam wind and turning, taking into account the effect of free surfaces, should not be greater than 5 degrees or the angle at which the deck becomes submerged (whichever is less).

The outcome of intact stability calculations is expressed in form of the maximum allowable vertical center of gravity of the vessel at design draught, $VCG_{\max}$. In Table 2, the actual values of VCG attained when the vessels are fully loaded with two and three tiers of containers are compared to $VCG_{\max}$. The stability is verified in two hypothetical scenarios. In the first scenario, VCG values of the vessels correspond to the loading cases in which the weight of all the containers would be the same. It may be observed that even in such cases, the attained vertical center of gravity is far below the allowable maximum. The goal of the second scenario is to find a vertical cargo distribution with realistic container weights which results in the limiting value of the vertical center of gravity, $VCG_{lim} \leq VCG_{\max}$. With two container tiers loaded, VCG_{lim} would be far below $VCG_{\max}$ even if the containers in the first tier would be empty. $VCG_{\max}$ could be reached only in the (unlikely) loading cases in which heavy containers would be placed atop of the empty ones, and only if three container tiers would be loaded. It may be concluded that, as far as intact stability is concerned, there are no practical limitations in the container stowage (with respect to the vertical arrangement) at design draught.

Table 2. Verification of compliance with the intact stability requirements: (a) maximum allowable vertical center of gravity according to the rules [10]; (b) uniform vertical cargo distribution; (c) vertical cargo distribution which results in the limiting value of the vertical center of gravity.

	(a)	(b)			(c)		
	$VCG_{\max}$ [m]	Tier	m_{TEU} [t]	VCG [m]	Tier	m_{TEU} [t]	VCG_{lim} [m]
Double-end access	5.637	I II	11.8 11.8	3.975	I II	2 21.6	4.548
Double-end access	5.517	I II III	8.4 8.4 8.4	4.563	I II III	2 5 20.8	5.513
Stern access	5.637	I II	11.3 11.3	3.845	I II	2 20.7	4.45
Stern access	5.51	I II III	7.8 7.8 7.8	4.507	I II III	2 3.1 19.1	5.509

6.2. Damage stability assessment

The regulations [17] prescribe the extents of the side and the bottom damage and require the verification of compliance with the damage stability standards in case of flooding of two (or more) adjacent compartments. In the final stage of flooding the angle of static equilibrium should not be greater than 5 degrees, the openings which cannot be closed watertight should not be submerged, and the area under the *GZ*-curve of the damaged vessel should attain a prescribed quantity.

The outcome of damage stability calculations is expressed in form of the maximum allowable vertical center of gravity of the vessel at design draught, $VCG_{\max}$. The actual values of VCG attained when the vessels are fully loaded with two and three tiers of containers are compared to $VCG_{\max}$ in Table 3. The vessels cannot meet the damage stability standards if the containers of equal weight are loaded in three tiers. In addition, the double-end access vessel would only marginally fulfil the damage stability criteria in case of the uniform distribution of weight in two container tiers; thus, this is also the limiting vertical cargo distribution case for this vessel when two tiers are loaded. The limiting three-tier vertical cargo distribution case for the double-end access vessel implies that the containers in the third tier should be empty and that care should be taken when loading the first two tiers. The stern access vessel has a greater stability margin and therefore, there would be more flexibility with respect to the vertical cargo distribution.

Table 3. Verification of compliance with the damage stability requirements: (a) maximum allowable vertical center of gravity according to the rules [17]; (b) uniform vertical cargo distribution; (c) vertical cargo distribution which results in the limiting value of the vertical center of gravity.

	(a)	(b)			(c)		
	$VCG_{\max}$ [m]	Tier	m_{TEU} [t]	VCG [m]	Tier	m_{TEU} [t]	VCG_{lim} [m]
Double-end access	3.98	I II	11.8 11.8	3.975	I II	11.8 11.8	3.975
		I II III	8.4 8.4 8.4	4.563	I II III	13.3 8.7 2	3.98
Stern access	4.355	I II	11.3 11.3	3.845	I II	3.6 19.1	4.35
		I II III	7.8 7.8 7.8	4.507	I II III	9.1 8.1 6	4.353

There are different ways to improve the damage stability performance including variation of main dimensions, relocation of weathertight and/or unsecured openings, repositioning of weight groups, modification of subdivision, or any combination thereof. Nevertheless, the possibilities in this respect may be limited unless extensive design changes are made. To improve the damage stability of the proposed concepts, a moderate modification of subdivision was considered: the addition of two watertight bulkheads in the double bottom and the double sides of the vessels, see Figure 9 and Figure 10. The verification of compliance with the damage stability standards following the modification of the subdivision is presented in Table 4. The vessels still cannot meet the damage stability requirements in case of uniform vertical distribution of cargo in three tiers. Nevertheless, in such cases, it is much easier to attain the required value of *VCG* with a realistic distribution of cargo. Furthermore, the stability margin of the double-end access vessel with two container tiers is much greater now.

Table 4. Verification of compliance with the damage stability requirements after the modification of the subdivision: (a) maximum allowable vertical center of gravity according to the rules [17]; (b) uniform vertical cargo distribution; (c) vertical cargo distribution which results in the limiting value of the vertical center of gravity.

	(a)	(b)			(c)		
	$VCG_{\max}$ [m]	Tier	m_{TEU} [t]	VCG [m]	Tier	m_{TEU} [t]	VCG_{lim} [m]
Double-end access	4.383	I	11.8	3.975	I	4.9	4.378
		II	11.8		II	18.7	
		I	8.4	4.563	I	10	4.378
		II	8.4		II	8.5	
		III	8.4		III	6.4	
Stern access	4.382	I	11.3	3.845	I	3.1	4.380
		II	11.3		II	19.6	
		I	7.8	4.507	I	8.9	4.380
		II	7.8		II	8	
		III	7.8		III	6.3	

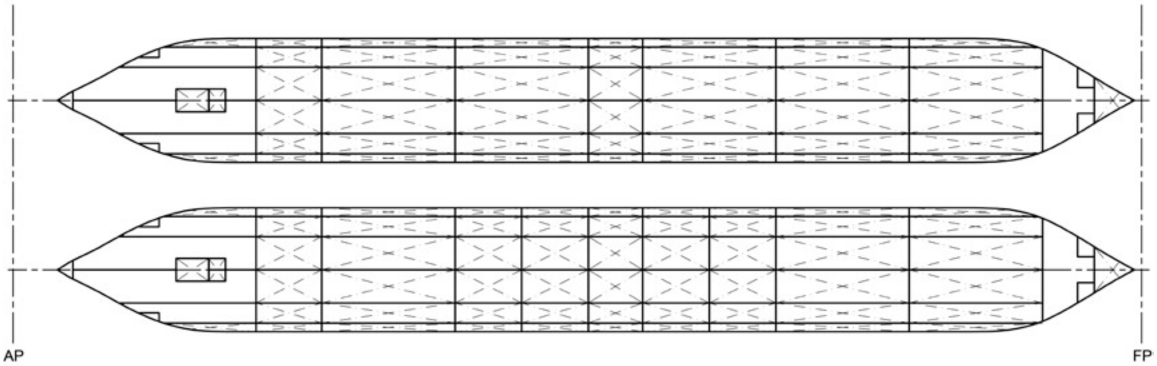


Figure 9. Original (upper image) and modified (lower image) subdivision of the double-end access concept

Figure 10. Original (upper image) and modified (lower image) subdivision of the stern access concept

7. Propulsion, maneuvering, and mooring

With a conventional propulsive complex consisted of two diesel engines (2x750 HP@1600 rpm) and twin, ducted propellers (whereby the propeller diameter is $D_p = 1.55$ m) the vessels would sail at the speed of $v = 18$ km/h. To ensure the redundancy of the propulsive system, in line with the safety requirements presented in Section 6, the engine room would be divided by the longitudinal watertight and fireproof (A category) bulkhead in two parts.

The vessels would be equipped with two rudders at the stern and a 4-channel Veth Jet bow thruster which enables 360° of steering. Furthermore, this type of Veth Jet bow thruster could be used for auxiliary or emergency propulsion which would fulfil the requirements for the secondary means of steering of the vessels sailing in the Vessel Train. It is powered by an electric motor and a separate generator set (to secure redundant power for the bow thruster) placed in the fore engine room. A hybrid propulsive complex in which the Veth Jet would be powered by the Li-ion batteries could be configured as well.

Considering the reduced presence of human operators foreseen by the Vessel Train concept, the mooring systems should be arranged for minimum manning requirements and with an option to be remotely or fully automatically operated. This can be attained with the spud pole mooring. In addition, conventional electric mooring winches would be provided to be used whenever the spud pole could not be used (if, for instance, there is a risk of a damage to river bed, cables, etc.).

8. Design appraisal

The main dimensions and the most important features of the proposed concepts are summarized in Table 5. The concepts are visually presented in Figure 12 (double-end access) and Figure 13 (stern access vessel).

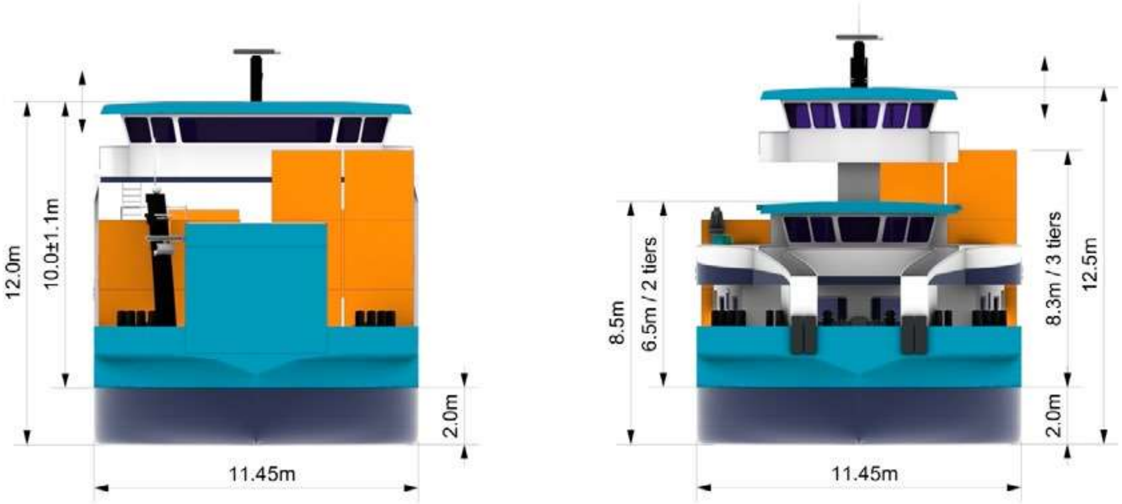
Even though the vessels carry around one half of the maximum cargo-carrying capacity (both in terms of the container units carried and in terms of mass of deadweight) of the standard European inland container vessels of the same class, they are well-balanced according to [11] considering that the average TEU container mass is close to 12 t.

Table 5. Main particulars of the shallow-draught container Ro-Ro vessels for the Vessel Train

			Double-end access	Stern access
L		[m]	104	104
B		[m]	11.45	11.45
d		[m]	2	2
D		[m]	3	3
d_A	two tiers	[m]	8.9	6.5
	three tiers	[m]	8.9	8.3
v		[km/h]	18	18
Δ		[t]	2097	2097
m_{LIG}		[t]	799	780
TEU	two tiers	[–]	100	104
	three tiers	[–]	146	152
m_{TEU}	two tiers	[t]	11.8	11.3
	three tiers	[t]	8.4	7.8
trailers		[–]	24	26

Both vessels feature retractable, hydraulically driven wheelhouses. Air draught of the double-end access concept corresponds to the lowest position of the wheelhouse ($d_A = 8.9$ m) and it should enable unrestricted navigation on the Rhine downstream of Strasbourg. Air draught of the stern access vessel with two container tiers is determined by the lowest position of the wheelhouse ($d_A = 6.5$ m) and it should enable unrestricted navigation downstream of Basel. If three container tiers are loaded ($d_A = 8.3$ m), the stern access vessel should be able to sail downstream of Strasbourg without restrictions. If the vessels would be deployed on the Danube, the double-end access vessel could sail from the Black Sea upstream to Vienna (1932 km of the Danube waterway), while the stern access vessel with two container tiers could sail from the Black Sea upstream to Passau (2225 km of the

Danube waterway). With three container tiers, the stern access vessel would be able to sail from the Black Sea upstream to Linz (2135 km of the Danube waterway).



a) b)

Figure 11. Main vertical dimensions of the concepts: a) double-end access, b) stern access

Figure 12. Concept of the double-end access container Ro-Ro vessel for the Vessel Train

Figure 13. Concept of the stern access container Ro-Ro vessel for the Vessel Train

9. Conclusions

This study presents two innovative designs of the large inland container Ro-Ro vessels with shallow design draughts. The designs were developed within the framework of the R&I project NOVIMAR which analyzed the possibilities for deployment of the Vessel Train (VT), a novel semi-autonomous waterborne transport concept, in inland, coastal, and sea-river navigation. Therefore, the concepts were designed primarily for VT operations on the European inland waterways. Nevertheless, they may be successfully used as standalone cargo vessels when no VT is formed.

The study demonstrated the far-reaching impact of two features on design of the vessels: the use of the specific cargo handling technique and the choice of the design draught. Both aspects simultaneously offer opportunities and impose limitations. The horizontal handling of the containers is carried out by the cargo-handling vehicle (CHV) specially designed within the NOVIMAR project. CHV is capable of lifting, carrying, and unloading a stack of two containers without an additional, intermediary device. This simplifies the container handling and increases the speed of cargo transloading. However, it also governs the cargo stowage and limits the number of units carried. It was demonstrated that the third tier could be loaded but only by means of vertical container handling which diminishes the advantages of the concept. To add two tiers of containers which would be handled by CHV, it would be necessary to add an additional deck; this would lead to a more complex arrangement and structure, additional steel weight, and reduction of stability margin. Thus, the overall result would be an increase of both capital and operational costs.

Design draught is perhaps the most important single aspect in design of inland cargo ships, considering that the payload lost due to a decrease of the draught cannot be easily compensated because the length, beam, and air draught of the vessel are restricted. The proposed concepts, due to a very shallow design draught in comparison to the standard European inland container vessels, have a much lower payload. On the other hand, since the number of units carried is also limited (by the container handling technique capabilities), the vessels are well-balanced as the average mass of the containers is close to 12 t.

The design of inland vessels has long followed the concept of maximizing the cargo carrying capacity, typical of design of seagoing ships. Nevertheless, the varying water levels, an aspect of inland navigation which has been exacerbated with the climate change, prevented such a concept to be fully realized in inland waterway transport. The vessels presented in this study embody a different approach, which follows the principle of maximizing the reliability of the service provided (attained by the shallow draught) and flexibility (attained by the horizontal cargo handling technique). The Authors believe that this could be one of the paths towards increasing the resilience and future-proofing of inland navigation in Europe.

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