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New Design Options for Container Barges with Improved Navigability on the Danube

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Abstract: One of the measures required by the European Green Deal to decarbonise the freight transport sector is the promotion of inland waterway transport (IWT), in particular intermodal transport in Europe. To facilitate intermodal transport on the Danube, we developed six new barge designs for the transport of 45' pallet-wide high-cube containers using a four-step approach. Our approach consisted of detailed desk research, followed by design and further analysis of the identified barge types, taking into account, for example, sight lines or stability. The container carrying capacity reaches up to 90 containers in three layers, which is double the capacity of existing standard barges on the Danube. Nevertheless, three-layer transport is hardly feasible in several cases, due to restrictions regarding sight lines and stability. We conclude that each loading condition must be evaluated separately to determine the best barge design option for each case. The study is limited by its geographical scope and the type of container used to develop the new barge designs. This could be a possible direction for further research on this topic: using other container types and/or extending the geographical scope.

Keywords: barge design; navigability; low water level; container transport; naval architecture; CAD; Danube

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1. Introduction

The European Green Deal has set ambitious targets: climate neutrality by 2050 & reducing transport related greenhouse gas emissions by 90% by 2050. The Sustainable and Smart Mobility Strategy lays the foundation for how the EU transport system can achieve its green and digital transformation. One measure which has been identified to reduce transport emissions is a shift to inland waterway transport (IWT). IWT can reduce negative impacts from road transport, such as emissions, noise, and congestion costs [1,2]. Over several years, the European Commission has been promoting shifts from road freight transport to more sustainable modes. Nonetheless, these alternative modes currently account for only a limited portion of transport activities across most European regions [3]. IWT has a limited network density and is dependent on multimodal transport, with pre-carriage and on-carriage often carried out by road due to the high road network density for collection and delivery [4,5]. As containers are mostly standardized and usually used as an equipment for multimodal transports, it is essential to enable and facilitate their transport on inland waterways. While the transport of containers is already common on rivers, such as the Rhine, there are hardly any container transports carried out on the Danube [6]. Thus, enabling container transports on the Danube could on the one hand promote multimodality and on the other hand increase the usage of the Danube significantly by attracting new customers [7].

To enable efficient multimodal transport a continuous and resilient infrastructure for the involved transport modes is required [8,9]. For IWT this means that there are minimum fairway parameters, such a minimum fairway depth and width, which are needed, to ensure an economic viable transport and a resilient infrastructure [10]. The IWT infrastructure faces two main challenges,

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which hamper the deployment of this minimum fairway parameters. Firstly, as a natural resource, inland waterways have uneven riverbeds, which means that the fairway depth of the river can vary throughout the course of the river and throughout a year. This could be a cause for the development of bottlenecks for inland navigation [11]. To maintain a water depth of 2,5m throughout the year maintenance works, such as continuous dredging works, to remove surplus sediment on the rivers are essential. Secondly, there have been increasingly frequent periods of low water in recent years. Low water means that a river does not carry enough water due to metrological conditions, e.g. droughts. Periods of low water often last for several months and massively hinder inland navigation, as the resulting shallower fairway depth means that ships can bear less cargo. This leads to delayed, unreliable and uneconomical transports [10].

One possibility to improve the navigability on inland rivers in low water periods is to adapt the current available ship designs to the increasingly frequent low water conditions. Few studies have addressed this issue.

The study from Obidike [12] investigates the possibility for improvement of cargo transport within the European inland water ways by exploring the design and optimization of a pushed barge capable of coping with the events of shallow water while also maintaining a plausible solution in normal water conditions. The proposed vessel is optimized with the aim of minimizing the overall light ship weight through structural weight reduction by a careful assessment of the vessel's main dimensions and hull structure while conforming to structural, economic and production constraints [12]. Sha et al. [13] present a new design for a 3000 tonnes dead weight barge. Alternate stern shapes are examined using CFD software SHIPFLOW. The hull form is modal tested. The propeller geometry is optimized for the given engine and a suitable gear box. The proposed design is then investigated for its manoeuvring ability in shallow waters. The hydrodynamic sway forces yaw moments and nominal wake distribution for port and starboard propellers during manoeuvring motion are estimated by CFD software SHIPFLOW. The barge's directional stability performance is investigated for twin-propeller twin –rudder configuration [13]. Radojčić et al. [14] addresses key aspects for the design of contemporary, shallow draught IW vessels for the transport of dry cargo (containers and bulk cargo). Most of the logic that is presented is applicable to the design of river vessels for any river, but the material that is presented is focused on vessels for the Danube and its tributaries. And Backalov et. al [15] investigates the possibilities for improvement of container transport on the Danube by means of an innovative and unconventional container vessel design. The proposed design differs from standard European inland ships of the same capacity by shallow draught and increased breadth.

Our paper follows the aim of identifying new barge options for an improved navigability in fluctuating water conditions. To focus on fluctuating water levels rather than on low water levels was a decision based on the fact that vessels, which are built specifically for low water, are in most cases less cost-effective at sufficient fairway depth. Therefore, we agreed on designing barge designs for fluctuating water levels. The research questions, which guide this paper are the following:

(RQ1): Which design options effectively enhance navigability for container barges on the Danube River?

(RQ2) How do these improvements compare in terms of stability and sightlines assessment?

This paper is structured as follows. Section 2 focuses on the methodology. Section 3, which presents the new barge designs in detail, followed by an in-depth analysis of the barge designs, including the analysis of the sightlines and a stability analysis. In Section 4, the results are discussed, and further research needs are identified.

2. Materials and Methods

Our approach to developing and evaluating new barge design options for the fluctuating water conditions on the Rhine-Main-Danube corridor involved a systematic four-step process.

First, we embarked on a comprehensive data collection phase, meticulously gathering information on the infrastructure along the corridor. This included detailed data on locks, bridges and ports, which was essential to understand the operational constraints and navigational challenges faced by barges. Through extensive desktop research and literature review, we synthesised this data to gain insight into the specific requirements and constraints of the waterway.

We then engaged in detailed discussions to establish the precise parameters of the barge's intended operation. This crucial step involved defining the specific waterways the barge would navigate and identifying the types of goods it would carry. With a view to seamlessly integrate inland water transport into existing logistics chains it is essential for the barges to be able to carry 45′ pallet-wide high-cube units (dimensions: 13,716mx2,55mx2,896m), as these are the predominant types for road and rail transport in mainland Europe. By aligning our design objectives with the unique requirements of the waterway and cargo, we ensured that the resulting barge designs would be optimally suited to their intended purpose.

With a clear understanding of the operational context and design objectives, we proceeded to analyse the existing barge options for container transport on the Danube. This comparative analysis provided valuable insights into the strengths and limitations of current designs and laid the groundwork for the development of innovative solutions. Based on this analysis, we conceptualised and designed a series of new barge prototypes equipped to navigate safely and economically through fluctuating water levels. To the determination of the lightship weight all barge types have been modelled with the structural 3D CAD software SOLIDWORKS according to the dimensions derived from the longitudinal strength assessment. As building material conventional grade A shipbuilding steel has been assumed, with the following material properties [16]: Relative density: 7,8 t/m^3; Yield strength: 235 N/mm^2 All hydrostatic calculations (floating position under different loading conditions, stability, bending moments) have been performed with the naval architecture software Delftship [17].

To achieve acceptably comparable results, the preliminary dimensioning for all barge versions has been carried out using the software GLRulesND (Version 2.950, Edition 2014). Based on the preliminary results for the thickness of bottom, bilge, and side plating as well as dimensions of bottom and side girders the main sections for all barge versions have been drawn up. The structural design has been further refined by assessing the individual moments of inertia and section moduli of the cross sections of the different barge versions against the bending moments resulting from a standardised load distribution at a draught of 2,70 m. The structural design has been carried out for all barge version for grade A shipbuilding steel. With a view to as far as possible achieve directly comparable results for lightship weights and draughts at different loading conditions of the various barge versions we endeavoured to keep the safety factor between the maximum permissible bending moment and the actually given bending moment in a range between 2,15 and 2,3.

In the final stage of our approach, we carried out an in-depth assessment of the identified design options, examining their stability, line of sight requirements and suitability of construction materials. We also carefully evaluated key nautical factors such as draught and air draft to ensure compatibility with the dynamic water conditions of the Danube. This rigorous evaluation process enabled us to refine and prioritise the design options based on their feasibility, performance and potential to improve navigational efficiency and safety.

By rigorously following this systematic approach, we not only developed a diverse range of innovative barge designs, but also laid the foundation for informed decision-making regarding their implementation and deployment in real-world scenarios. It has to be noted that the barge designs have not been optimized from a hydrodynamic perspective as the focus was placed on the optimization of the cargo capacity.

3. Results and Discussion

Generally, there is minimal room for enhancing or refining barge dimensions to efficiently utilize current infrastructure on the Danube. Regrettably, the existing infrastructure lacks a coherent size framework. For instance, locks that are 24 meters wide can accommodate two vessels that are 11.75

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meters wide each, whereas to accommodate three barges in the larger 34-meter-wide locks on the Danube, the maximum width of such barges would be capped at 11.16 meters. Therefore, for all further considerations on barge design therefore the following limits have been applied as these dimensions are considered to be an acceptable compromise between lock utilization and sufficient flexibility with a view to the accommodation of 45′ high-cube containers.

Maximum length 97,50 m

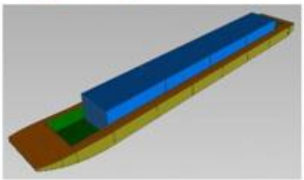
Maximum breadth 11,45 m

The chapters below describe the new barge designs one by one, addressing various characteristics, such as sight lines, stability, and capacity of each barge.

3.1. Design Design Options

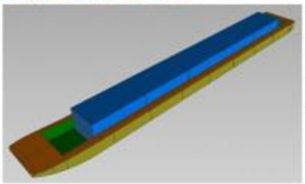
Based on the Europe 2b (001 Europa 2b) and Europe 3a (002 Europa 3a) barges, six new barge designs were developed. The Europa 2b barge can be regarded as a prototypical example of a utilitarian vessel within the realm of European inland navigation. For the analysis of design options for new barges within the IW-NET project it serves as a benchmark for comparison purposes. Many barges of this type or with slightly varied main dimensions can be found in operation on the European inland waterways for a wide range of different cargoes (bulk, containers, high and heavy etc.). The Europa 3a a larger version of the Europa 2b barge and also serves as a benchmark for comparison purposes for the new barge designs. **Error! Reference source not found.** shows the CAD models and details of the Europa 2a and Europa 2b barge designs, which are used as a basis for the new barge designs created.

Barge Europa 2b



Project ID		001	
length	[m]	76.5	
breadth	[m]	11.5	
lightship displacement	[t]	368.1	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		24	36

Barge Europa 3a

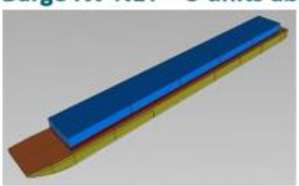


Project ID		002	
length	[m]	90.0	
breadth	[m]	11.5	
lightship displacement	[t]	433.4	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		30	45

Figure 1. CAD models and details about Europa 2b and Europa 3a barges.

The general idea behind the design of the "*IW-NET – 3 units abreast*" barge is to tightly fit the principal geometry of the Europa 2b and Europa 3a barges around a container stack of 3 by 5 by 2 45′ high-cube containers; i.e. in particular to reduce the width of the barge to the width necessary for the cargo hold and two side decks in accordance with the applicable statutory technical requirements and to fit a bow and a stern section similar to the Europa barges to the cargo hold lengthwise. **Error! Reference source not found.** shows the IW-NET – 3 units abreast barge design.

Barge IW-NET – 3 units abreast

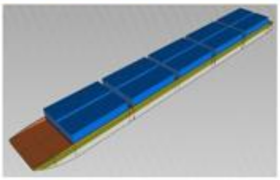


Project ID		003	
length	[m]	81.0	
breadth	[m]	9.5	
lightship displacement	[t]	334.4	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		30	45

Figure 2. CAD model and details about "IW-NET - 3 units abreast" barge design.

The general idea of *004 IW-NET NEWS Evolution* barge design, which is presented in **Error! Reference source not found.**, is to optimise existing barge designs (namely Europa 2b and Europa 3a) for container transport by replacing the two side decks with a center walkway and to create container bays in order to fit four rows of (ISO-) containers abreast. The need to accommodate in particular 45′ high-cube pallet-wide containers in order to facilitate integration of inland navigation into logistics chains in mainland Europe (i.e. in particular pre- and post-run by road or rail instead of seagoing vessel) is also taken account.

Barge IW-NET – NEWS Evolution v2

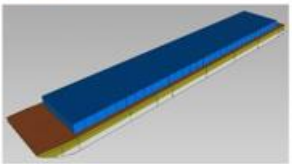


Project ID		007	
length	[m]	97.3	
breadth	[m]	11.5	
lightship displacement	[t]	501.4	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		48	72

Figure 3. CAD model and details about 004 IW-NET NEWS Evolution barge design.

The *005 IW-NET containers transverse* design (see **Error! Reference source not found.**) is the result of an attempt at "thinking out of the box". Instead of the usual lengthwise placement of the containers in this design option for the containers are arranged transverse to the longitudinal center plane. Naturally, this results in a much broader barge, which does not fit into the usual convoy patterns etc. However, it was nevertheless considered worthwhile to include this option in the analysis. With a view to the breadth of the barge it would not be possible to pass the locks on the upper Danube (upstream of Regensburg) an on the Main-Danube-Canal. Considering the low grade of compatibility of this barge for convoy formations the basic design might be converted into a self-propelled motor cargo vessel.

Barge IW-NET – Containers transverse v2

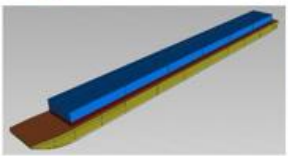


Project ID		005_v2	
length	[m]	89.8	
breadth	[m]	16.3	
lightship displacement	[t]	611.9	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		60	90

Figure 4. CAD model and details about 005 IW-NET containers transverse bnarge design.

This version, i.e., *006 IW-NET 3 units abreast long,* which is shown in ***Error! Reference source not found.*** is a variation of the IW-NET 3 units abreast barge, lengthened to accommodate an additional stack of containers.

Barge IW-NET – 3 units abreast long



Project ID		006	
length	[m]	94.8	
breadth	[m]	9.5	
lightship displacement	[t]	389.6	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		36	54

Figure 5. CAD model and details about 006 IW-NET 3 units abreast long barge design.

The variation called *007 IW-Net NEWS Evolution long* of the IW-NET NEWS Evolution barge has been designed with six instead of ten container bays, however, the individual container bays can accommodate two lengths of 45′ high cube containers instead of just one. This variation therefore provides higher flexibility for other container types, for example being capable of receiving three lengths of 30′ containers or four lengths of 20′ containers in the container bays. The CAD model with details is presented in **Error! Reference source not found.**

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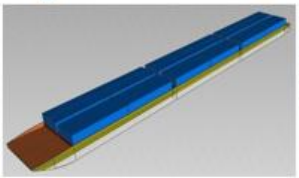
Barge IW-NET – NEWS Evolution long

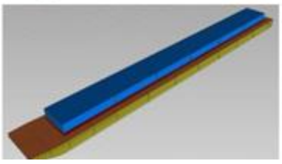


Project ID		004_v2	
length	[m]	85.9	
breadth	[m]	11.5	
lightship displacement	[t]	465.6	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		40	60

Figure 6. CAD model and details about 007 IW-Net NEWS Evolution long barge design.

008 IW-NET 3 units abreast long-shallow (see **Error! Reference source not found.**) is a further variation of the IW-NET 3 units abreast barge, which keeps the container hold of the "long" variation while at the same time increasing the breadth to 11,45 m (instead of 9,50 m). The changes provide additional buoyancy, thus improving the shallow water capabilities, and more favourable stability characteristics than the other two variations.

Barge IW-NET – 3 units abreast long/shallow



Project ID		008	
length	[m]	94.8	
breadth	[m]	11.5	
lightship displacement	[t]	448.7	
No. of Containers (45" pallet-wide)		2 layers	3 layers
		36	54

Figure 7. CAD model and details about 008 IW-NET 3 units abreast long-shallow barge design.

In the following sub-sections, the modeled barge design will be further evaluated and assessed regarding their stability and the given sightlines.

3.2. Analysis of Sightlines

A sufficiently unobstructed view from the wheelhouse / the helmsman's positions is essential for safety of navigation on inland waterways. For non-motorized barges the provisions of the European Standard for Technical Requirements for Inland Waterway Vessels (ES-TRIN) are not applicable as they are not equipped with a wheelhouse, however, operational limits as defined in the navigational police regulations have to be taken into account. Most navigational police regulations for the European inland waterway network are at least based on the European Code for Inland Waterways (CEVNI) of the UNECE Inland Water Transport Committee [18] there-fore this set of rules has been used as a benchmark for the assessment of sightlines. Article 1.07 of the CEVNI requires that the "load […] of the vessel shall not restrict the direct view at a distance of more than 350 m in front of the vessel." This means that a direct sightline from the helmsman's position to a point not farther than 350 m in front of the bow of the vessel or convoy on the surface of the water must be present.

To cover a realistic range of possible pusher vessels two different types which are typical for Danube navigation have been taken into consideration for the assessment of sightlines – the main difference between the two versions is that type 1 has a fixed wheelhouse while type 2 is equipped with an elevating wheelhouse which can be lifted to provide more favourable visibility for high cargoes.

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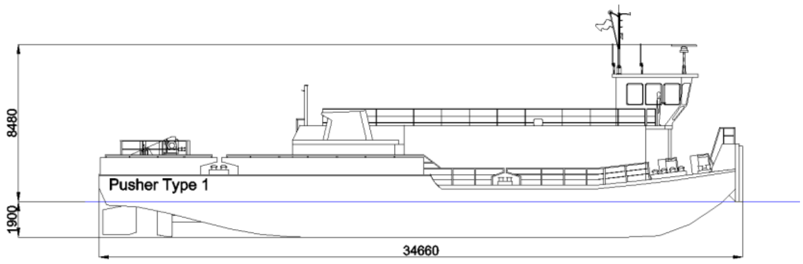

Figure 8. Pusher type 1 – fixed wheelhouse.

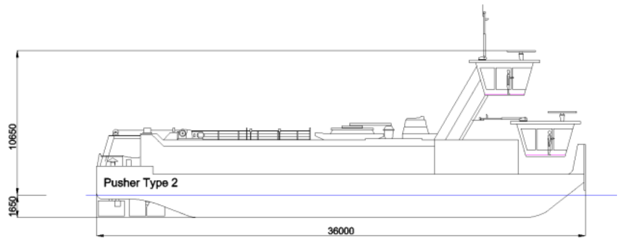

Figure 9. Pusher type 2 – elevating wheelhouse.

The analysis has been carried out under the assumption that for all considered loading conditions the barges are floating on level trim and for convoy formations with only one barge length. In line with the initial thoughts on barge design it has furthermore been assumed that the load consists of 45′ high-cube containers, which certainly have a considerable impact on the sightlines.

For all combinations of pushers and barges three different loading conditions for the containers have been considered: (1) all containers empty, (2) all containers loaded to 70% of the permissible maximum load and (3) all containers loaded to the maximum permissible load. The sightlines have been assessed geometrically, assuming a height of eye of 1,65 m above the wheelhouse floor at the steering position [19]. The assessment shows that pushers with a fixed wheelhouse will mostly not be suitable to be used for the transport of 45′ high-cube containers. In general, sightlines in compliance with the applicable rules can only be demonstrated for one layer of containers. For two layers of containers compliance with the applicable rules can mainly be demonstrated for maximum load only. The detailed analysis is presented in **Error! Reference source not found.**.

Pusher Type 1 (fixed wheelhouse)						pushed convoy one barge length – loading condition						
						2 layers				3 layers		
Vessel type	Project ID	length	breadth	side height		empty	70 % full	100 % full		empty	70 % full	100 % full
Europa 2b	001	76,50	11,45	3,20								
Europa 3a	002	90,00	11,45	3,25								
IW-NET 3 units abreast	003	81,00	9,50	3,20								
IW-NET NEWS Evolution v2	004_v2	85,92	11,45	4,10								
IW-NET Containers transverse v2 (Solidworks)	005_v2	89,80	16,28	4,00								
IW-NET 3 units abreast long	006	94,77	9,50	3,20								
IW-NET NEWS Evolution long	007	97,32	11,45	4,10								
IW-NET 3 units abreast long/shallow	008	94,77	11,45	3,20								

Figure 10. Analysis of sightlines for pusher type 1 (fixed wheelhouse).

As **Error! Reference source not found.** reveals, the situation is much more favorable for pushers with elevating wheelhouses as two layers of containers can be carried within the applicable legal framework in all standard loading conditions assessed in this study. For a three layers transport in most pusher/barge combinations compliance can be demonstrated for containers with 70 % of the maximum load.

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Figure 11. Analysis of sightlines for pusher type 2 (elevating wheelhouse).

3.3. Stability Analysis

Both, technical requirements (ES-TRIN) and navigational police regulations (CEVNI) address the issue of stability of inland navigation vessels carrying containers. The provisions of Article 1.07 No. 5 of CEVNI focus on the individual operational situation and require a stability check prior to loading and unloading as well as prior to departure. The responsibility for such stability checks lies with the boat master. Exemptions from per-forming stability checks apply to certain loading configurations which are always deemed inherently stable. Regarding the technical characteristics of an inland navigation vessel the ES-TRIN sets out a range of provisions in Chapter 27 concerning limit conditions and methods of calculation for the transport of non-secured and secured containers, taking into account the hydrostatic characteristics of the hull (mainly depending on the shape of the hull and the weight distribution), the loading situation and the heeling moments to be considered. For the purpose of this study, it was decided to assess the stability of the different barge designs under the conditions set out in Article 27.02 of ES-TRIN (non-secured containers) and for six standard loading conditions:

(1) 2 layers of 45′ high-cube containers empty.

(2) 2 layers of 45′ high-cube containers 70 % full

(3) 2 layers of 45′ high-cube containers 100 % full

(4) 3 layers of 45′ high-cube containers empty.

(5) 3 layers of 45′ high-cube containers 70 % full

(6) 3 layers of 45′ high-cube containers 100 % full

For each loading condition the calculation delivers a maximum allowable vertical center of gravity (VCG) that must be met to ensure compliance with the requirements of Article 27.02 of ES-TRIN. The actual VCG of each loading condition is assessed against the maximum allowable VCG.It can be shown that most of the loading conditions comply with the statutory requirements, the only exceptions being the 9,50 m wide barge versions in the short and long variants for three layers of loaded containers (70 % and 100 %) and the long version of the NEWS Evolution barge for three layers of fully loaded containers.

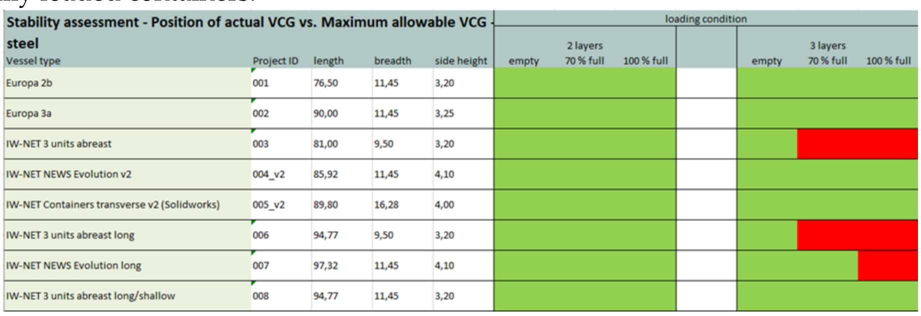

Figure 12. Stability assessment of different barge designs in six loading conditions.

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When comparing loading scenarios, it's important to note that the results discussed are based on standardised conditions. Optimising the loading situation for individual cases may give better results, especially when considering the transport of three layers of containers. Only high-cube containers were considered for the standardised loading conditions. However, by using standard height containers, the total load height for three layers could be reduced by approximately 1.20 metres, which would improve visibility and the vertical centre of gravity of the load, thereby increasing stability. In addition, the use of a pusher with a longer operating range for the lifting wheelhouse could further improve sightlines compared to the pusher type analysed in this study.

Looking at the overall assessment of the different design options, it's clear that there is no single optimal solution. Barge design must always be tailored to the specific application and the operator's requirements, considering the available infrastructure in the intended navigation area.

Nevertheless, there's considerable room for improvement compared to the current barge types (001 Europa 2b and 002 Europa 3a), especially when it comes to accommodating the 45' high-cube pallet-wide containers commonly used in European road and rail transport. It's estimated that a minimum of 30 45' containers per barge is required to achieve competitive freight rates on the Danube corridor. While standard Europe 2b barges fall short of this capacity, Europe 3a barges barely meet it. Conversely, all new design options meet or exceed this threshold.

With low water resistance as the primary consideration, the 005 IW-NET Containers transverse version appears to be the most favourable design. However, this design has operational drawbacks that need to be carefully considered. Considering other factors such as stability, traffic safety and unobstructed views from the wheelhouse, the best design choice can only be made on an individual basis, taking into account specific transport routes, port facilities and available pusher tugs.

4. Conclusions

One goal of our study was to identify design options, which enhance the navigability of container barges on the Danube River. We identified in total six new barge designs, which fit to the boundaries we decided on (i.e., the barges should serve the Danube stretch between Enns, Austria and Giurgiu, Romania; they should be optimized to carry 45′ pallet-wide high-cube containers used for intermodal transport; barges should not exceed the dimensions of 97,50 m x 11,45 m). The new barge designs are able to foster up 90 45′ pallet-wide high-cube containers in three layers, compared to a traditional Europa 2a barge, which is able to carry only up to 45 containers in three layers. Nevertheless, after assessing stability and sightlines of each barge designs, we observed that a three layers transport is not feasible in each case. A two layers transport is in most cases possible. There is hardly a general answer, which can be given regarding the best suitable barge design for transporting 45′ pallet-wide high-cube containers. For this reason, each transport situation needs to be evaluated separately, to determine the best suitable barge design for this specific transport situation.

The study contributes to the theoretical understanding by identifying six new barge designs tailored for enhanced navigability on the Danube River, specifically optimized for transporting 45′ pallet-wide high-cube containers within defined boundaries. Our study provides practical contributions by offering stakeholders involved in container transport along the Danube River viable barge designs optimized for specific operational requirements. The identification of feasible designs, along with considerations of stability and sightlines, furthermore, enables practical enhancements in barge design aimed at improving efficiency and safety in container transport operations on the Danube.

As limitations of our study there could be named the geographical scope, which limits the generalizability of the results for other rivers. Another limitation concerns the container type. The study focused solely on 45′ pallet-wide high cube containers, omitting other possible container types. Further research on this topic could imply broadening the geographical scope and the utilization of other possible container types. Other fields for further research would be investigating the operational feasibility of the fix new barge designs developed or utilizing dynamic simulation modeling techniques to simulate various loading scenarios.

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