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SUMMARY

Reduced water levels in inland waterways caused by the frequent and prolonged dry periods due to climate change could significantly hinder the inland waterway transport (IWT). Inland ships operating in shallow waterways face reduced efficiency due to hydrodynamic challenges such as increased resistance and propeller ventilation. This paper details the development of a twin-propeller Rhine vessel (GMS class), specially optimized for shallow water operation. Several hull designs focused on the aft section were iteratively optimized using computational fluid dynamics (CFD) simulations. The final hull design, appended with different configurations of three propulsion optimization devices—a flow separation plate, an outer tunnel, and a fixed inner tunnel—was tested in a towing tank. Their impact on propulsion efficiency and trade-off between performance in shallow and deep water were analyzed. With the capability to transport substantial amounts of cargo at drafts as low as 1.1 m, the proposed design appended with recommended propulsion improvement devices, could have carried over 10% additional cargo in 2018 compared to a conventional Rhine vessel.

NOMENCLATURE

Δ	Total mass displacement of the ship [t]
λ	Scaling factor [–]
B	Breadth (beam) of the ship [m]
C_{B}	Block coefficient [–]
DWT	Deadweight [t]
h	Water depth [m]
LOA	Length overall [m]
LCB	Longitudinal center of buoyancy [m]
P_{D}	Power demand [kW]
$P_{\mathrm{D,S}}$	Specific power demand [kW/t]
T	Draft [m]
T_{D}	Design draft [m]
T_{min}	Minimum draft [m]
U	Velocity of the ship [km/h]
U_{D}	Ship velocity at the design draft [km/h]

1 INTRODUCTION

Inland waterway transport (IWT) is a safer and more sustainable alternative to increasingly overloaded and congested rail and road transportation. Generally, it is considered that approximate demands of energy to carry a unit cargo weight [J/t-km] for inland water means are 17% lesser than that of road transportation and 50% less than that of rail transport, while being cost effective[1]. Owing to these favorable conditions, the European Union, in conjunction with European Green Deal and Sustainable and Smart Mobility Strategy projects, has already set goals to increase inland waterways and short sea

[1] Source: Official website of European Union, *Inland Waterways*, accessed January 3, 2025, https://transport.ec.europa.eu/transport-modes/inland-waterways_en.

transportation by 25% by 2030, and by 50% by 2050[2]. This underscores the importance of future-proofing the whole inland transportation system to keep up with the demand. This paper focuses on future-proofing of inland waterway cargo transport of the Rhine River, with particular emphasis on countering challenges faced by low water levels through improved ship design.

As one of the major rivers in Europe, the Rhine River runs through Switzerland, Liechtenstein, Austria, Germany, France and the Netherlands. With a fleet of close to 7000 ships, around 300 million tons of goods are transported on the Rhine every year (Woehrling, 2013). The portion of the river that spans through Germany traverses numerous cities that hold economic and industrial importance (Köln, Düsseldorf, Duisburg, etc.), signifying its importance to the country. Consequently, continuous improvement of IWT sector around Rhine River is of utmost importance when safeguarding the country's economic integrity for the future.

Even though inland water transportation must be adopted as a better alternative to land transportation in terms of sustainability and climate change, it is also the one worse affected by climate volatility in turn. These adverse effects are mostly linked to the vulnerability of ship operations to changing hydrological features of the river. For instance, the severe drought that prevailed during 2018 caused the river discharge volumes to plummet drastically, along with the water levels (Vinke et al., 2022). This consequently hindered a considerable portion of ship transportation through the river since most vessels in the current IWT fleet were not optimized for low draught operations, thus were susceptible to damages due to bottom contact and grounding. Also, as water levels decline, the navigable width of the river narrows.

Although dry periods have been natural occurrences in historical weather cycles, the concerns have arisen that these will become more prolonged, intense, and frequent due to climate change (Christidis and Stott, 2021). The general frequency of critical dry periods that lead to discharge volumes down to 2018 lows is 17.6 years, but this is projected to be uncertain and range between 6.5 – 22.6 years in the future (Brenk, 2021). Discharges are projected to continually increase in winter periods due to accelerated melting of mountainous ice caps. In summer periods, they are projected to gradually decline synonymous with frequent and prolonged dry periods (International Commission for the Protection of the Rhine, 2024). Contrary to the claims of climate change-based increased dry periods, a study conducted by Christodoulou et al. (2020) suggests that effects of climate change on inland waterways could be beneficial for IWT in some (Kaub on the Middle Rhine and Hofkirchen on the Upper Danube) since the utilized weather models have predicted overall increase in water levels. Yet, it is noteworthy that regions like Duisburg-Ruhrort were still projected to have lowered water levels, yielding net negative profits from IWT.

As described in coming sections, the current inland fleet operating on Rhine river consists to a major extent of the largest possible vessels to maximize profits. These vessels are far from being optimized to navigate at very low water levels. This is already factually proven from the experience gained through the 2018 dry period where economic momentum has been slowed down due to hindered IWT operations (Ademmer et al., 2019). Therefore, it is always prudent to maintain a universally capable vessel fleet that can perform well in either scenario. The burden of "future-proofing" the ships thus will be eased.

Various solutions can be proposed to address the problem of "future-proofing" the IWT sector against reducing water levels, encompassing aspects such as policy development, infrastructure improvements, logistical strategies and innovative design approaches (Hendrickx and Breemersch, 2012). Among the innovative design solutions proposed in the literature—such as reducing structural weight, designing smaller vessels, and adopting pusher-barge configurations—this paper specifically focuses on the promising aspect of improving the hydrodynamic performance of vessels in shallow water (Bačkalov et al., 2022, 2016; Radojčić et al., 2021). A new and optimized hull design is proposed, which will be evaluated with the integration of three shallow-water propulsion improvement devices that perform as hull appendages, namely, (a) flow-separation plate, (b) outer tunnel in retractable and fixed forms, and (c) fixed inner tunnels (see Figure 1). The ship configurations assessed were derived by alternatively appending these devices to the base hull. Systematic model tests were performed in the shallow water towing tank of Development Centre for Ship Technology and Transport Systems (DST).

[2] Source: Official website of European Union, *NAIADES III action plan*, accessed January 3, 2025, https://transport.ec.europa.eu/transport-modes/inland-waterways/promotion-inland-waterway-transport/naiades-iii-action-plan_en.

2 HULL DEVELOPMENT AND MODEL TESTS

2.1 DESIGN OBJECTIVES AND SPECIFICATION

In a collaborative meeting with inland shipping industry partners, key factors affecting ship operations in low water were identified. Analysis of hydrological and geographical data from the Rhine and its tributaries focused on water levels and flow characteristics. This analysis highlighted critical shallow areas and challenging river cross-sections, crucial for defining the ship's dimensions.

To accommodate the demand of increasing cargo volumes, IWT stakeholders throughout the past decade had resorted to developing increasingly larger ships. Larger ships were ultimately reducing the operational cost for unit cargo transported, thus remained favorable in economic terms too. During the period of 1996–2008, the average deadweight of new inland ships had nearly doubled (Hekkenberg, 2013). However, it remains doubtful whether advancements in ship design have kept pace with this rapid growth in size. The significant impairment of the inland traffic in Rhine during the 2018 dry season is a prominent example for this. It is also stated that the innovative vessels within the Rhine inland fleet make less than 0.2% (CCNR, 2024). Therefore, a mere maximization of dimensions would not make a compelling shallow-water efficient Rhine ship (Hekkenberg, 2016). Nevertheless, referring to these dimensions of current ships when deciding the dimensions of the intended ship design is prudent, as they have already been complying with the waterway constraints such as river locks.

The largest length and breadth dimensions of the vessels currently traversing the Rhine are 135 m and 22.90 m respectively. For pusher-barge configurations, these values could go up to 269.60 m in length and 34.35 m in breadth. However, the operability of these vessels is limited to specific sections of the river as steeply curved or narrow spans could hinder their maneuverability. The GMS (Großmotorgüterschiff) class on the other hand represents the most universally navigable ships with dimensions $110\ \text{m}\ \times\ 11.45\ \text{m}$ (length × breadth). This is classified under the CEMT class Va internationally. Some extra-long vessels that retain the breadth of the GMS class but extend its signature length up to 135 m have also become popular in the past decade (Bundesanstalt für Wasserbau, 2016). Typically, the carrying capacities for single Rhine vessels falls between $1{,}500 - 4{,}000$ t.

A comparison between numerous Rhine vessels led to the decision that the intended ship should be of GMS class with $110\ \text{m}\ \times\ 11.45\ \text{m}\ \times\ 2.8\ \text{m}$ (length × breadth × design draft) dimensions with the carrying capacity (deadweight) of about 2,300 t at the design draft. Further studies and discussions led to the discovery that a ship with the draft of 1.1 m could have managed to operate for 336 days in 2018, even during the dry period. Subsequently, 1.1 m was picked as the minimum operational draft. The static under-keel clearance was set at 0.3 m for improved safety measures with mitigated risk against ground contact and grounding avoidance (Renner and Bialonski, 2004). Furthermore, requirements for ship strength, stability, maneuvering, and other criteria were defined according to European standards and technical regulations for inland navigation (ES-TRIN).

Table 1. Summary of design objectives and specifications

Attribute	Value
Class	GMS (CEMT class Va internationally)
Length overall (LOA)	110 m
Beam (B)	11.45 m
Design draft (T_D)	2.8 m
Deadweight at design draft (DWT)	2370 t
Block coefficient at C_B	0.89
Cruising speed at T_D (U_D)	16 km/h
Minimum draft (T_min)	1.1 m

2.2 PROPULSION IMPROVEMENT DEVICES

The propeller diameter for CEMT class Va vessels is between 1.6 – 1.8 m (Bundesanstalt für Wasserbau, 2016, p. 15). Once a portion of the propeller has emerged in the air (partially immersed in water) due to low water, or when operating close to the water surface, air from the surface is sucked into its rotational volume, causing propeller ventilation. Subsequently, a number of adverse events are set off, such as main engine over speeding, excessive eccentric thrust, vibration and erosion due to cavitation. Altogether, the propulsion efficiency of the ship plummets drastically (Ghaemi and Zeraatgar, 2022; Taskar et al., 2016). Therefore, among other things, propeller ventilation is one of the reasons that makes shallow water navigation challenging for this vessel class. Scaling the propeller down in size while increasing its rotational speed to eliminate this issue is a suboptimal solution since this combination would generally result in propulsion efficiencies inferior to those of larger, slower propellers (Majumder and Maity, 2023; Tadros et al., 2021). Instead, the discussed propulsion enhancement devices (appendages) herein discussed are intended to counter ventilation by: (a) reconditioning the water flow into and around the partially-emerged propeller to cover it better through the flooding of tunnels, and (b) blocking the intruding air stream into the propeller volume even when it is operating near the surface. A visual arrangement of all three devices appended to the hull is presented in Figure 1.

2.2.1 Flow-separation plate

The flow separation plate is a horizontal plate that stems from the hull, located above the propeller and extends behind it. The rudder shafts are penetrated through it while allowed to rotate freely. Historically, the flow-separation plate was invented to support long rudder shafts against high bending moments. According to Zöllner (2015, 2006), the plate also possesses a drag-reducing effect since it modifies the flow both into and behind the propeller, as well as further downstream. Furthermore, by blocking the area above the propeller, the plate could help with propeller ventilation in shallow water.

2.2.2 Outer tunnel (fixed form and flex form)

Typical tunnels on inland vessels are pairs of side skirts fixed in front of the propellers. Their objective is to prevent air from being sucked into the propeller with the inlet waterflow, at low water levels and partially loaded conditions. The so called Flex-tunnel is an improved version of conventional fixed outer tunnels: firstly, it can be retracted into the hull at design draft; secondly, it can be folded-out in shallow water to benefit the water flow to the propeller (Förster, 2016; Zöllner, 2006). The flooding of the tunnel volume could reduce ventilation. In contrast to a fixed tunnel, a flexible tunnel offers the possibility of optimizing the entire aft section of a ship. This is possible because the ship's lines can initially be designed without a tunnel and the Flex Tunnel can be fitted later. Although this approach does not allow complete freedom in the design of the lines—due to the need to create a movable connection between the flex tunnel and the hull, usually using hinges that must be aligned on a single plane and line to function properly— it does offer considerable freedom in deciding on the design of the stern lines. In this way, the ship's design significantly reduces hull resistance, resulting in considerable fuel savings[3,4]. Mainly, the main functions of a Flex-tunnel are (Förster, 2016):

- Significantly improving the propeller inflow, particularly in shallow water, by ensuring more water is channeled into the propeller area. This results in an increase in propeller efficiency due to reduced ventilation.
- Reducing the flow resistance of the ship by optimizing the water flow around the propeller.
- Providing flexibility over fixed conventional tunnels by being able to hydraulically deploy/retract as the crew desired, allowing adaptation to various travelling conditions and water depths.
- Improving propeller inflow efficiency through the vacuum effect created at the connection between the tunnel and nozzle. This ensures optimal propeller operation even under minimal load and shallow water conditions.

2.2.3 Fixed inner tunnel

As with the outer tunnel, the inner tunnel is designed to work against ventilation. It is particularly needed for slender aft ship lines. Combined with the outer tunnel skirt, the inner tunnel skirt forms a complete tunnel section leading flow up to the inlet of the propeller duct. This completed tunnel section is supposed to be flooded more easily than a semi-tunnel section which is formed with just the outer tunnel skirt. This component would be permanently installed in the aft ship.

[3] Source: Official website of Damen, *Flex Tunnel*, accessed January 3, 2025, https://www.damenmc.com/flex-tunnel/#tab-1731943398133-10.
[4] Source: Official website of Damen, *FLEX Tunnelsystem*, accessed January 3, 2025, https://damenmc.com/wp-content/uploads/2023/04/FLEX_tunnel_system_DE-2.pdf

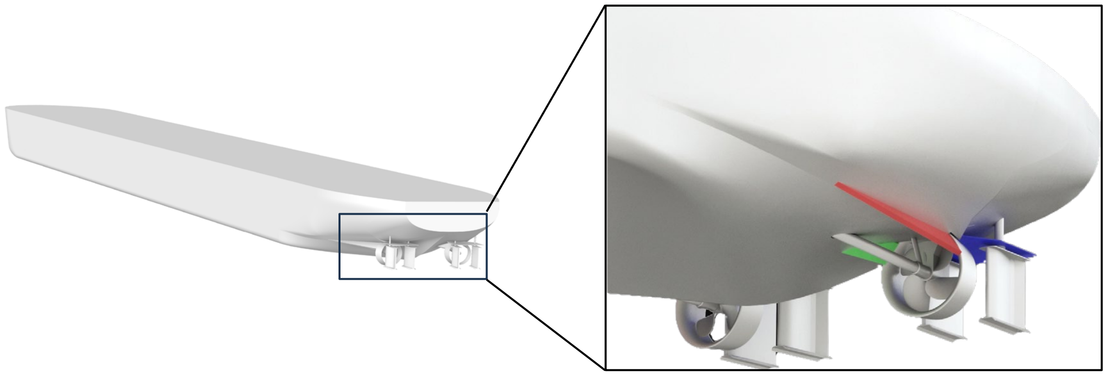


Figure 1. Visualization of the arrangement of considered propulsion improvement devices appended to a bare hull. Here, each device is depicted in different colors: (a) flow-separation plate in blue, (b) outer tunnel is red, and (c) fixed inner tunnel in green

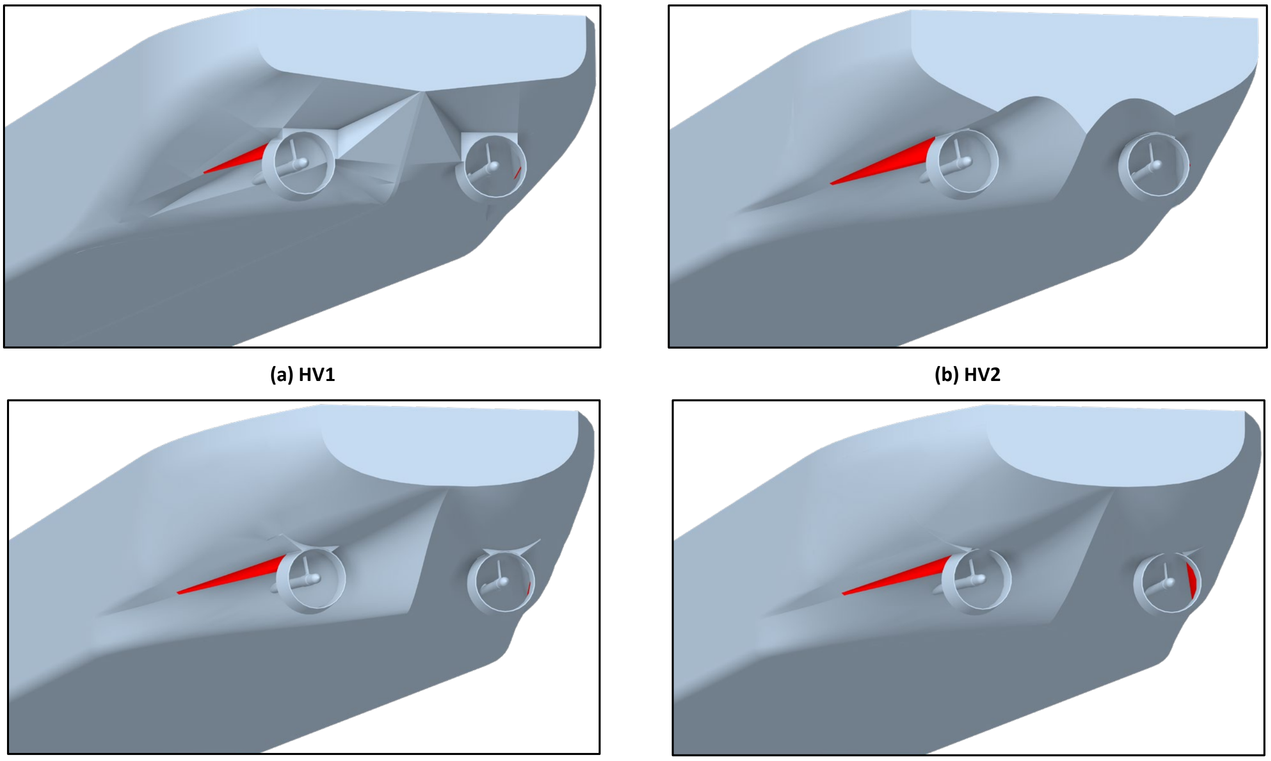
2.3 DEVELOPMENT OF THE HULL DESIGN

An iterative optimization process (see Figure 2), directed by the observations of CFD simulations at each step, was employed to develop the final hull design[5]. This process consisted of four distinct steps, each progressively refining the stern to enhance performance for efficient shallow water operation. Throughout the process, the signature dimensions and characteristics of the hull were kept unchanged: a Rhine ship measuring $110\ \mathrm{m} \times 11.45\ \mathrm{m}$ with a design draft of 2.8 m and two propellers.

- The first iterative version (HV1) closely resembled a typical GMS class vessel, directly inheriting many of its features. The water flow was found to be struggling to follow along the bulky stern portion in the forward motion. The flow separation caused by this led to additional resistance on the hull.
- Adopting the findings made by Friedhoff et al. (2018), the stern was refined with reduced volume and smoothly transitioning contour lines in the second iterative version (HV2). The shape of the propeller tunnel integrated into the hull was extended behind the propeller to minimize any discontinuities, leaving a semi-circular opening at the transom. The retractable tunnel skirt was reshaped to have a smooth transition with the hull lines. The aft ship lines were smoothed out.
- With HV3, a transom with a raised lowest edge was introduced to reduce the transom wetting that leads to increased resistance (Carlton, 2007).
- In HV4, the point where the bottom-most (base) hull edges converge together was moved forward compared to its location in HV3.

Consequently, further trimmed down stern volume and better directed flow into the propeller resulted in a further reduction in drag and improved the propulsion conditions. Ultimately, HV4 was declared as the final design with a drag reduction of about 12.7% and a power requirement reduction of about 21.5% compared to the initial design HV1, when sailing at the design draft and 16 km/h, in deep water. Figure 3 shows the lines plan of the selected design.

[5] The detailed CFD study is included in the final report of the research project “FlaBi”, which is being prepared for publication.



(a) HV1 (b) HV2

(c) HV3 (d) HV4

Figure 2. The optimization of stern shapes through the iterative process, shown with the corresponding outer tunnel flaps and without rudders

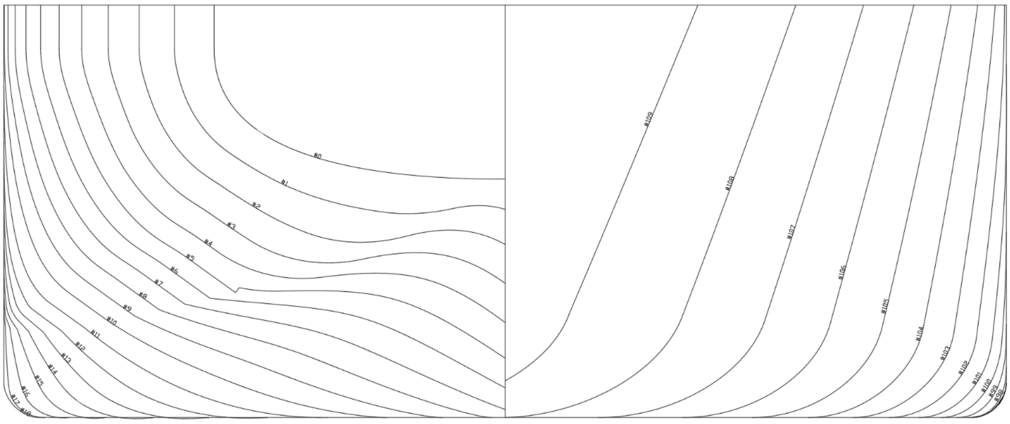


Figure 3. Hull lines of the finalized design HV4

The potential cargo capacity can be determined from the hydrostatics (see Table 2) of the ship and its calculated lightweight (660 t) (Hekkenberg, 2013).

Table 2. Hydrostatic table of the finalized HV4 hull design for drafts between T_{min} and T_{D}

T [m]	Δ [t]	LCB [m]	C_B [–]	Load carrying capacity (DWT) [t]
1.1	**1218.3**	**57.779**	**0.871**	**558.0**
1.5	1670.7	57.615	0.877	1010.4
2.0	2253.3	57.181	0.889	1593.0
2.5	2845.0	56.796	0.899	2184.7
2.8	**3204.2**	**56.579**	**0.904**	**2543.9**

2.4 MODEL TESTING OF HULL-APPENDAGE CONFIGURATIONS

The self-propulsion model tests with a 1:10 scale ratio were carried out in the shallow water towing tank at DST, which has a width of 10 m and a length of 200 m. The propeller is characterized by the following parameters: a scale factor λ = 10, a pitch-to-diameter ratio $\mathrm{P/D}$ = 0.955, a number of blades Z = 4, an expanded area ratio A_{E}/A_0 = 0.800, a diameter D = 0.110 m, and a chord length at 70% of the radius $\mathrm{C}_{0.7R}$ = 0.04965125 m.
Five distinct test configurations were established by attaching different combinations of aforementioned three propulsion improvement devices to the finalized hull HV4 (Figure 4). These configurations were then subjected to an extensive model testing phase to assess their hydrodynamic performance. The derived configurations are as follows. Note that the term 'base hull' is used for the hull assembly, including the twin propellers, propeller nozzles, and rudders.

K1: HV4 base hull appended with all three devices: flow-separation plate, outer tunnel, and inner tunnel

K2: HV4 base hull appended with flow-separation plate and outer tunnel

K3: HV4 base hull appended with flow-separation plate

K4: HV4 base hull appended with outer tunnel

K5: HV4 base hull without any propulsion improvement devices appended

Since the Flex-tunnel can be retracted in deep water, it essentially transforms the hull into the base configuration. Therefore, while configuration K4 represents the outer tunnel in both its fixed and folded-out (Flex) forms in shallow water, it exclusively represents the fixed form in deep water. Conversely, in deep water, the retracted Flex-tunnel is represented by configuration K5.

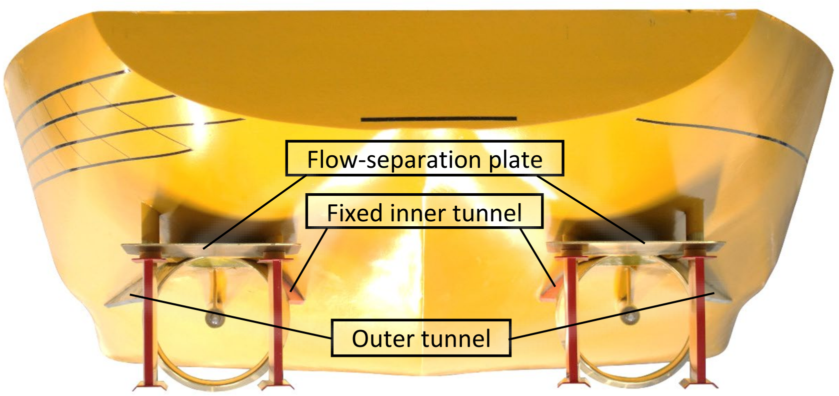


Figure 4. Test model of the K1 configuration, the base hull HV4 is appended with all three propulsion improvement devices (scaling factor $\lambda = 10$)

The model testing procedure was carried for each test configuration under varying combinations of draft (T), velocity (U), and depth (h) combinations (Table 3). Velocity in the range $U \in [4, 16]$ km/h, depth in the range $h \in [1.4, 7.5]$ m were considered with minimum and design draft values $T \in \{1.1, 2.8\}$ m. The minimum depth was determined based on the minimum draft and the required under-keel clearance, calculated as, ($h_{\min} = T_{\min} + 0.3$ m). However, the achievable velocity range was limited to low values at the minimum depth $U|_{h=1.4} \in [0, 5]$ km/h. This was a safety measure taken to prevent the model from getting damaged by bottom contact due to strong sinkage at higher speeds.

Table 3. Test matrix developed for model testing, with the considered draft (T), depth (h), and velocity (U) values in full-scale, for each configuration

Configuration	T [m]	h [m]	U [km/h]
K1	1.1, 2.8	[1.4, 5.0]	[5, 16]
K2	1.1, 2.8	[1.6, 5.0]	[5, 16]
K3	2.8	[3.5, 5.0]	[8, 16]
K4	1.1, 2.8	[1.6, 5.0]	[5, 16]
K5	2.8	[3.5, 7.5]	[7, 18]

2.5 MODEL TEST RESULTS

2.5.1 Results for $h = 5\ \mathrm{m}$ & $T = 2.8\ \mathrm{m}$

Table 4 summarizes the total power demand (P_{D}) corresponding to all velocities tested under the test condition, water depth h = 5 m and draft T = 2.8 m. The P_{D} values in model scale were measured without accounting for wind effects on the superstructure, roughness effects on the hull, or the impact of hull openings (e.g. bow thrusters). The model test results were then extrapolated to ship scale using Froude scaling based on the ITTC 1957 correlation line and DST's empirical correlation allowance (CA) including blockage correction. The power requirement clearly diminishes as the number of appendages decreases. Fully equipped K1 configuration demands the highest power, and a continuous decline can be seen as the appendages are stripped off. Ultimately, the completely stripped base hull configuration, which also resembles the base hull with retracted Flex-tunnel (K5), demonstrates the lowest power requirement, particularly at greater speeds.

In the tables dedicated to the test results, the relative change in power demand for each configuration is indicated with colored dots and arrows.

- Colored dots represent the change in power demand with respect to the base hull configuration (K5), for each velocity value
  - red: increased power demand w.r.t. K5
  - yellow: reference configuration K5
  - green: reduced power demand w.r.t. K5
- The direction of gray colored arrows below each case indicates the relative change in power demand with respect to the immediate preceding configuration (in Table 4, power demand of K2 has decreased by 3.1%, with respect to K1).

At this depth and draft level, flow-separation plate, fixed outer tunnel, and the inner tunnel merely burden the ship by increasing the power demand, most probably by introducing additional drag. At design draft, in absence of propeller ventilation to work against, they appear redundant. Subsequently, use of a Flex-tunnel proves beneficial in design draft as it can be retracted, effectively forming the base hull configuration (K5). According to the results, the opportunity cost of using a fixed tunnel instead of a retractable Flex-tunnel at design draft at the maximum speed of $U_{\max} = 16\ \mathrm{km/h}$ would be about 4% of increased power demand (K4→K5). However, the installation and maintenance costs of Flex-tunnel system are significantly higher than a fixed tunnel structure. To comprehensively evaluate the real economic benefits of a Flex Tunnel, these additional costs must be weighed against the cost benefit gained by lowered fuel consumption in deep water conditions. A comparison of the configurations K5→K1 shows that all three appendices together add 5.2% (at 16.1 km/h) to the power demand at design draft.

Table 4. Power demands recorded for the test cases with $h = 5\ \mathrm{m}$ and $T = 2.8\ \mathrm{m}$

U [km/h]	P_{D} [kW]					Trend visualization sparkline
	K1	K2	K3	K4	K5	
9.00	78	75.6 ↓ -3.1%	67.8 ↓ -10.3%	66.4 ↓ -2.1%	67.7 ↑ 2.0%	
11.60	162.5	163.9 ↑ 0.9%	156.2 ↓ -4.7%	151.4 ↓ -3.1%	148.4 ↓ -2.0%	
14.10	373	366.5 ↓ -1.7%	338.1 ↓ -7.7%	350 ↑ 3.5%	338.8 ↓ -3.2%	
15.10	513.4	479.1 ↓ -6.7%	491.1 ↑ 2.5%	492.3 ↑ 0.2%	478.9 ↓ -2.7%	
16.10	811.9	801 ↓ -1.3%	779.9 ↓ -2.6%	801.5 ↑ 2.8%	771.8 ↓ -3.7%	

2.5.2 Results for $h = 3.5\ \mathrm{m}$ & $T = 2.8\ \mathrm{m}$

A simple comparison of data given in Table 5 with data given in Table 4 reveals that the propulsion power for the same speed is consistently higher in shallower water, across all configurations. The comparison between configurations K1→K2 implies that the inner tunnel skirt has a negligible influence on performance at low speeds. However, this situation overturns at an increased speed of $U = 12.11$ km/h, where the presence of inner tunnel has significantly increased the power demand.

The comparison of configurations K4→K5 led to the observation that the outer tunnel results in an increased power requirement at all examined velocities. This assessment underscores that, removing the fixed outer tunnel or replacing it with a retractable Flex-tunnel at the design draft leads to a decreased resistance, improved propulsion conditions, and consequently a lower power requirement. The benefit at forward speeds between 11 and 12.11 km/h is reaching from about 4% to 7.7%. In comparison with the power demand reductions in the previous case at $h = 5$ m, the positive effect of retracting the tunnel seems to be even increased at $h = 3.5$ m; most likely because of improved propulsion conditions.

The effect of flow-separation plate cannot be clearly understood from the results. Even though the comparison between K3→K5, which is the removal of flow-separation plate is positive at some speeds, the general trend seems to an increase in power demand. However, the potential utility of this component under conditions of reduced water depths should be examined before hypothesizing its universal effectiveness or ineffectiveness.

Table 5. Power demands recorded for the test cases with $h = 3.5$ m and $T = 2.8$ m

U [km/h]	P_D [kW]					Trend visualization sparkline
	K1	K2	K3	K4	K5	
8.07	87.9	87.3 ↓ -0.7%	79.4 ↓ -9.0%	80.9 ↑ 1.9%	69.3 ↓ -14.3%	
10.07	196.7	192.5 ↓ -2.1%	165 ↓ -14.3%	189.7 ↑ 15.0%	185.1 ↓ -2.4%	
11.10	326.3	349.6 ↑ 7.1%	315.2 ↓ -9.8%	322 ↑ 2.2%	307.6 ↓ -4.5%	
11.60		425	407.5 ↓ -4.1%	424.5 ↑ 4.2%	391.8 ↓ -7.7%	
12.11	603.7	559.8 ↓ -7.3%	525.4 ↓ -6.1%	579.6 ↑ 10.3%	555.6 ↓ -4.1%	

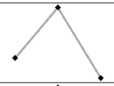
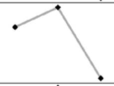
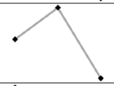
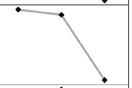
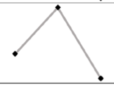
2.5.3 Results for $h = 1.6$ m and $T = 1.1$ m

Following the test runs at the design draft, the performance at the minimum draft T_{min} = 1.1m was investigated. The results made it clear that the shallow water effects significantly restrict operation. Particularly, the achievable maximum speeds were limited up to 8.6 km/h since any higher speeds caused the ship model to rapidly sink and collide with the tank bottom. Despite these limitations, it was possible to demonstrate that the ship was able to accelerate without additional assistance such as a bow thruster.

Table 6 lists the results of the tests. Note that the reference configuration here has been changed to K4 from K5. The propeller is 30% emerged from the water surface at the minimum draft. The ship was unable to move forward without the outer tunnel as very low thrust was generated by the propeller due to severe ventilation and the ventilated tunnel volume. Consequently, configurations that do not accommodate the outer tunnel were proven completely ineffective at the minimum draft and thus were omitted from the test runs. The inclusion of the fixed inner tunnel had a positive influence on the performance (K2→K1) at minimum draft, yet it is not significant.

The reduction in power demand after removing the flow-separation plate (K2→K4) is significant, even though the plate is positioned entirely above the water surface at the minimum draft. The plate does not contribute to any flow modification or assist against ventilation. One possible explanation is that the propeller jet above the water surface impacts on the underside of the flow-separation plate, altering the pressure difference in the propeller plane. Also, this may have generated additional resistance on the ship.

Table 6. Power demands recorded for the test cases with $h = 1.6$ m and $T = 1.1$ m

U [km/h]	P_D [kW] K1	P_D [kW] K2	P_D [kW] K4	Trend visualization sparkline
5.1	14.2	16.5 ↑ 16.2%	13.3 ↓ -19.4%	
6.1	28.9	30.3 ↑ 4.8%	25.3 ↓ -16.5%	
7.1	51.5	54.1 ↑ 5.0%	48.3 ↓ -10.7%	
8.1	106	105.2 ↓ -0.8%	95.3 ↓ -9.4%	
8.6	186.6	206.1 ↑ 10.5%	176.3 ↓ -14.5%	

3 DISCUSSION

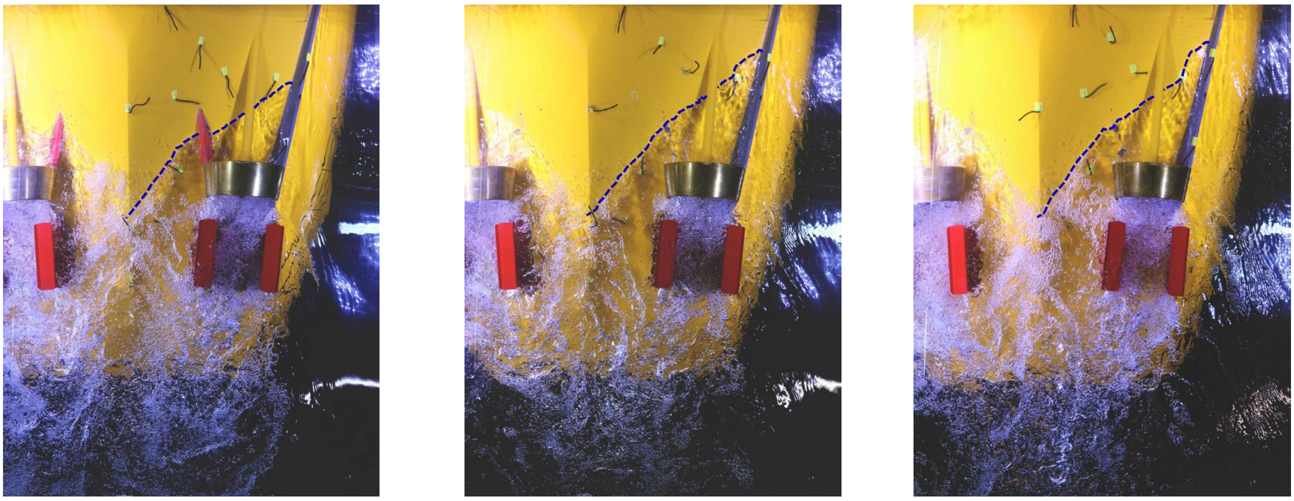
To decide whether the proposed ship design and shallow water propulsion improvement devices provide a sophisticated solution for 'future-proofing' the Rhine River IWT sector against extended period of shallow water, the decreased power demand and the extended operational days must be investigated.

3.1 PERFORMANCE IN SHALLOW WATER

It was technically not possible to operate the model at the minimum draft without the outer tunnel. This appendage is therefore essential for a ship that is optimized for shallow water.

Observations at the minimum draft further suggest that the inner tunnel can potentially reduce power consumption by around 10% (K2→K1). The photos shown with Figure 5 are taken from below the hull, through an observation window, during the minimum draft model tests. The dashed-blue line marks the boundary between the water and air. In K1, this boundary is pulled closer to the propeller inlet compared to the other two configurations. This means that more water is directed to the propeller when the inner tunnel is present. Boundary lines of K2 and K4 configurations without the inner tunnel are located at the same position relative to the propeller, indicating that the inner tunnel assisted against ventilation, ultimately improving the thrust generated.

Yet, the power demanded by the K4 configuration is the lowest for each speed, suggesting that positive effect of the inner tunnel may have been nullified. At the same time, the removal of the flow-separation plate (K2→K4) revealed a 14% reduction in power requirements (Table 6), showcasing its negative effect on the proposed ship design. Combination of this, and the additional resistance generated by the inner tunnel itself might have led the configuration K1 to have a higher power demand. This could have indeed been the reason that, even with an increased thrust provided by the inner tunnel, the configuration K1 shows a higher power demand compared to K4.



(a) K1 – all devices appended (b) K2 – outer tunnel + flow-separation plate (c) K4 - outer tunnel only

Figure 5. The photos captured during the model test at $h = 1.6$ m and $U = 8.1$ km/h, showcasing the state of ventilation of the partially emerged propeller for different configurations

In both water depth scenarios tested at the design draft ($h = 3.5$ m and $h = 5.0$ m), the flow separation plate, fixed inner tunnel, and outer tunnel proved to be detrimental to the performance of the proposed hull. When appended to the base hull, their protruding silhouettes appeared to disturb the flow around the hull, generating additional drag and adversely increasing the power demand. Therefore, the necessity of incorporating the flow-separation plate and the fixed inner tunnel to the proposed hull design is especially conflicted since they are not integral for shallow water operation. It is noted that the stern section of the proposed hull is explicitly optimized for shallow water through an iterative process. Hence, the effectiveness of these devices is not universally dismissed here, but it is simply implied that they are not necessary for the already optimized proposed hull. However, they might still serve as effective retrofitting options for existing, non-optimized hulls (Zöllner, 2006).

The outer tunnel on the other hand, was proven to be essential for shallow water operation based on the test runs conducted at the minimum draft. No thrust has been generated by any configuration without the outer tunnel. Any detrimental effect a fixed outer tunnel has on the ship performance at design draft can be easily circumvented by the usage of a Flex-tunnel. A Flex-tunnel can be simply retracted at the design draft, effectively transforming ship back to the base hull configuration (K4→K5), eliminating any added resistance. The retracted flex tunnel has a reduced power requirement of 4-7% at high speeds for both $h = 3.5$ m and $h = 5.0$ m cases (Table 4 and Table 5). For a new build, however, the question arises as to whether this performance enhancement justifies the significant capital investments for a Flex-tunnel over a relatively cheaper fixed tunnel.

To appraise the developed vessel design its competitiveness against the current Rhine fleet, a comparative analysis was conducted including a cohort of contemporary vessels. The evaluation, depicted in Figure 6, focuses on the propulsion power requirement for a unit displacement relative to the total displacement. The specific power requirement per displacement matrix serves as an indicator of efficiency, as both are directly proportional. To ensure the validity, uniform conditions were maintained across all assessments, including the water level ($h = 5$ m), vessel speed ($U = 16$ km/h), and the channel width. Yet, this approach may not be perfectly standardized in the absence of information on other potentially influential factors, such as the exact vessel's lightweight or specific ship type. The new design for a Rhine vessel, represented by the red dot, demonstrated a commendable specific performance per unit volumetric displacement. This achievement not only highlights the design's efficiency but also its potential to stand competitively in the market, affirming the design's viability under the standardized test conditions employed in this analysis.

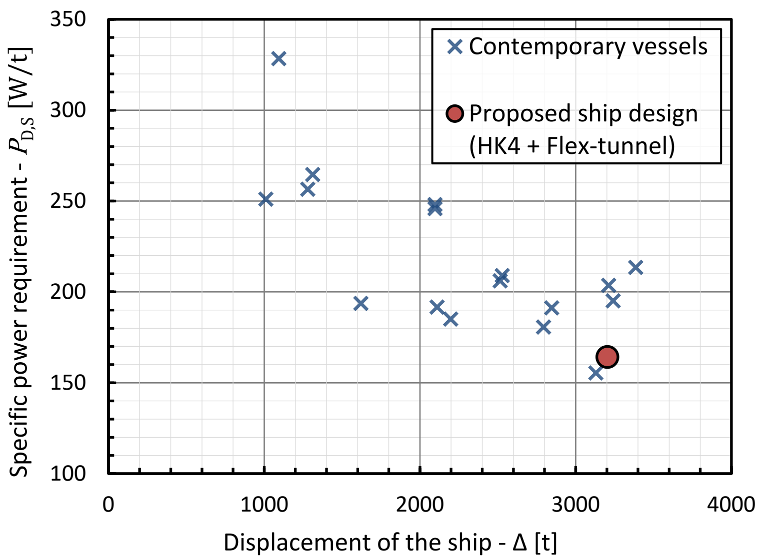


Figure 6. The comparison of specific power requirement against the cargo carrying capacity of the proposed ship design with respect to several Rhine vessels in operation (Source: the inland vessel database of Development Centre for Ship Technology and Transport Systems - DST, Germany)

3.2 INCREASED CARGO CARRYING DAYS

The German Federal Institute of Hydrology (BfG) collected water level data along the Rhine in 2018 (German Federal Institute of Hydrology, 2018). The data set includes recordings of the water levels at intervals of 100 m. The specific data corresponding to the German section of the Rhine (362.3 km to 865.4 km) can be utilized to calculate the number of days the vessel would experience downtime. For the vessel proposed in this study, a minimum allowable under keel clearance of 0.3 m results in an operable minimum depth of $h_{\text{min}}|_{T_D} = 3.1$ m at the design draft $T_{\text{D}} = 2.8$ m. In 2018, water levels below this depth persisted for 237 days. However, if the minimum draft $T_{\text{min}} = 1.1$ m is taken into consideration, the minimum operable water depth reduces to $h_{\text{min}}|_{T_{\text{min}}} = 1.4$ m, leading to only 10 days of downtime for the vessel.

Table 7 provides information on cargo that can be transported at various drafts of the proposed ship. Here, it is assumed that the proposed ship would operate as same as a typical GMS vessel, accounting for about 60 journeys annually. Some existing Rhine vessels in the GMS class can attain drafts as low as 1.4 m, requiring a minimum water level of 1.7 m. This water level was not reached for 90 days in 2018. This indicates that a significant portion of the German Rhine fleet remained idle for at least 25% of the year, unable to transport goods due to insufficient water levels. Smaller ships could be operated, but the loading capacity of these ships was not sufficient to adequately supply all the industrial sites along the Rhine. This situation has compelled the IWT stakeholders to adopt alternative modes of transport, namely rail and road, which consequently imposed significant operational pressures and financial challenges. With the reduced downtime (additional 80 operational days) with nearly 10% extra cargo with respect to the existing Rhine GMS fleet, the proposed ship design poses as a promising solution to mitigate the challenges faced by the industry. However, it is important to recognize that a reduced draft, while offering increased operational days, comes with the trade-off of reduced cargo capacity. Also, the speed attainable at lower h/T ratios is limited. This analysis does not account for this reduction in speed because it is based on the assumption of possible number of journeys annually through the Middle Rhine. Note that the cargo capacity of an existing GMS ship is assumed to be the same as the cargo capacity of the proposed vessel at the same draft since they have similar overall dimensions.

Table 7. Cargo carrying capacity of the proposed vessel for water depths seen in Rhine during 2018

Water depth [m]	Draft [m]	Load carrying capacity at draft [t]	Annual days operable [-]	Tonnage for 60 journeys per year [t]	Remarks
> 3.1	2.8	2543.9	140 (38.4%)	58544.5	- Load carrying capacities for each draft were extracted from the hydrostatic table (Table 2) - Total possible cargo for an existing GMS ship= 94891.2 t
3	2.7	2424.0	16 (4.4%)	6375.5	
2.9	2.6	2304.2	14 (3.8%)	5302.8	
2.8	2.5	2184.7	6 (1.6%)	2154.8	
2.7	2.4	2065.5	11 (3%)	3734.9	
2.6	2.3	1946.8	6 (1.6%)	1920.1	
2.5	2.2	1828.5	7 (1.9%)	2104.0	
2.4	2.1	1710.5	7 (1.9%)	1968.2	
2.3	2	1593.0	5 (1.4%)	1309.3	
2.2	1.9	1475.6	9 (2.5%)	2183.1	
2.1	1.8	1358.7	3 (0.8%)	670.0	
2	1.7	1242.1	8 (2.2%)	1633.4	
1.9	1.6	1126.2	13 (3.6%)	2406.7	
1.8	1.5	1010.4	9 (2.5%)	1494.8	
1.7	1.4	894.8	21 (5.8%)	3088.9	
1.6	1.3	780.5	28 (7.7%)	3592.4	- Additional cargo gained by the proposed ship optimized for low draft and shallow water= 8973.6
1.5	1.2	670.7	33 (9%)	3638.3	
1.4	1.1	558.0	19 (5.2%)	1742.8	
1.3	1	–	–	–	- Inoperable water depth
		∑ 365	97.3%	∑ 103864	

4 CONCLUSIONS

Inland waterway transportation (IWT) is a sustainable and efficient alternative to road and rail transport. Europe boasts a comprehensive inland shipping network, with the Rhine River serving as one of its most vital corridors. However, the inland shipping sector is projected to face significant challenges due to climate change, particularly from disruptions caused by declining water levels. For example, the prolonged dry period in 2018 resulted in substantial economic losses for the unprepared inland shipping industry as most of the vessels were unable to operate in shallow water. As a solution for this, in order to "future proof" the industry against climate change, a new ship design optimized for low-draft, shallow water operations was proposed. The proposed design was further evaluated with the attachment of three different propulsion improvement devices, especially intended to counter propeller ventilation. The three devices were, (a) flow separation plate, (b) outer tunnel attachment in retractable and fixed forms, and (c) fixed inner tunnel.

- The hull was designed through a four-step iterative optimization process, with a particular focus on improving the stern shape for shallow water operations. The finalized design retained the characteristic dimensions of a typical GMS-class vessel. Compared to the initial design, which closely resembled a contemporary GMS vessel, it demonstrated a 12.7% reduction in drag and a 21.5% decrease in power demand to achieve a 16 km/h speed at the design draft.
- The self-propulsion model tests were conducted at a scale of 1:10 for five configurations of base hull appended with different combinations of shallow water improvement devices. The last configuration was the base hull without the shallow water appendages.
- In deepest water depth investigated, at design draft, no propeller ventilation was seen. All three appendages were found to exert extra drag on the hull and lower the ship's performance.
- In the shallow water scenario, the configurations with inner tunnel and flow-separation plate did not improve in overall performance. In contrast, the outer tunnel was absolutely necessary to operate the ship at minimum draft. And addition to that, the Flex Tunnel can decrease the power demand by extra 4-7% at design draft.

- The developed vessel design was compared against a number of vessels within the current Rhine fleet, focusing on the propulsion power requirement per unit displacement as an indicator of efficiency, where a sufficient improvement was found to have achieved.
- In addition, the ship design is capable of operating in extremely shallow water due to its low minimum draft. Utilizing it during the dry period of 2018 could have resulted in uninterrupted operation of an additional 80 days compared to an existing GMS class vessel. This would have accounted for close to a 10% increment in total cargo transported.
- All in all, the proposed ship appended with the outer tunnel provides a robust solution for 'future-proofing' the Rhine IWT sector against reducing water levels.

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