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Towards Climate Resilient Inland Waterway Vessel Design: Concept of Distributed Thrust for Shallow Water Conditions

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Abstract. Inland waterway vessels are critical to the hinterland transportation network, offering an environmentally friendly alternative to road and rail transport. However, climate change poses significant challenges, such as fluctuating water levels and extreme shallow water conditions that lead to increased resistance and reduced propulsive efficiency. These conditions necessitate innovative design and operational strategies to ensure the efficiency and sustainability of propulsion systems. Given the increase in resistance and risk of propeller emergence in shallow water conditions, this study explores the development of climate-resilient inland vessels, by implementing the distributed thrust concept, where multiple smaller propellers replace conventional single relatively large units, offering superior maneuverability, propeller load distribution, and adaptability to varying water depths and conditions. Utilising state-of-the-art resistance approximation and a robust optimisation method, this research proposes a novel shallow-water model that enables optimal configuration of propeller size, number, and placement, considering key performance metrics such as thrust efficiency and ventilation mitigation, contributing to sustainable inland waterway transportation. Results from a case study demonstrate that the distributed propulsion system can effectively shift the operational threshold for propulsion, extending the navigational capabilities and performance in water depths where conventional design would face limitations. The findings highlight the potential of integrating distributed propulsion with advanced optimisation techniques to address climate-induced challenges while ensuring operational reliability.

Key words: *shallow water, inland waterway vessel, propulsion, climate-resilience, robust optimisation*

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1. Introduction

Waterborne transport plays a crucial role in hinterland transportation, offering a more environmentally sustainable and cost-effective alternative compared to other transport modalities. However, this competitive advantage is increasingly threatened by extended periods of droughts and floods that result in both low and high water levels [1]. Inland vessels operate in environments already constrained by water depth, channel width, and the presence of bridges and locks, making navigation a key factor in determining the transport efficiency of inland waterway transport.

Climate change exacerbates these challenges, undermining the reliability and competitiveness of inland navigation. This also hampers the achievement of objectives outlined in the EU's NAIADES III action plan [2], which seeks to shift a significant share of freight transport from road to more sustainable modes, such as inland waterways and rail transport. Numerous studies have examined the impact of climate change on inland water transport, with a particular focus on the effects of reduced water depth in navigable fairways. Given the expectation that prolonged droughts will occur more frequently in the future, these conditions are anticipated to have more severe consequences on transport efficiency, safety, and reliability compared to the challenges posed by high water levels or discharge fluctuations [3].

In a recent review of the literature [4], two primary challenges facing inland waterway transport in achieving sustainability and reliability were identified. The first concerns the adverse impact of extreme shallow-water conditions on both hydrodynamic efficiency and cargo-carrying capacity, which impedes efforts to increase the modal share of inland waterway transport, already underutilised. The second relates to the challenges of integrating suitable green energy solutions onboard.

This study focuses on addressing the first challenge by improving the propulsion performance of inland vessels to ensure sufficient thrust under extremely low water conditions. By extending the technical tipping point or operational limits, the research aims to enhance the technical resilience and effectiveness of inland waterway transport in adverse environmental conditions. Achieving this requires understanding the critical interaction between the vessel hull, propeller(s), and waterway, which influences the hydrodynamic characteristics and efficiency in extreme waterway conditions.

This study advances beyond conventional hydrodynamic analysis by applying computationally efficient optimisation techniques that account for the performance of the worst-case scenario, enabling enhanced operational resilience for these challenging conditions.

The rest of this paper is structured as follows; section 2., presents the theoretical framework and background literature relevant to this study, section 3. describes the research methodology, key findings are analysed in section 4. and section 5. concludes with contributions and future directions.

2. Theoritical background

2.1. Confined waterway effect

Vessel navigating in waterways with restricted width and depth, the flow around it is substantially influenced by the confined environment. In such conditions, the boundary layer around the flat bottom plate becomes thinner, resulting in higher friction resistance. The flow around the hull is accelerated, leading to a pressure reduction according to Bernoulli's principle. This pressure decrease contributes to the squat effect of the ship [5]. The increase in squat also accounts for increased resistance and loss of speed [6].

[7] summarised the threshold for the effects of waterway cross-section relative to the ship dimension on the hydrodynamic effect in table 1.. The main parameters are the blockage factor (A_c/A_s), the depth to draft ratio (h/T) and the channel width to beam ratio (W/B).

Table 1.: Confinement Effect Parameters [7]

Parameters	Start of confinement effect	Important confinement	Highly confined
A_c/A_s	50	7–8	4
h/T	15	3–4	1.5
W/B	50–200	10–15	4

In addition to the confinement effect, the flow regime plays a critical role in influencing the increased resistance experienced by ships. Specifically, the flow regime significantly affects the wave-making resistance component of inland vessels [8]. Flow regimes are characterized by the vessel's speed relative to the water depth, expressed as the depth Froude number ($F_{nh} = \frac{V}{\sqrt{gh}}$). As highlighted by [9], the shallow water effect becomes more pronounced as the vessel approaches the critical flow regime ($F_{nh} \approx 1$). However, this condition is typically not so common for inland vessels, as they are low-speed vessels operating predominantly within the subcritical flow regime.

In the design of the propulsion system of the ship, the interactions of the hull-propeller (s)-waterways play an important role in accurately determining the propulsive coefficients (thrust t and wake w factors). Where the wake fraction coefficient describes actual inflow to the propeller, and the thrust deduction factor describes the additional resistance due to the suction pressure by the propeller(s) in action and is used to determine the thrust required to overcome the resistance. These factors have been theoretically investigated by [10], where it was observed that, reduction in water depth weakens the wake (w) and intensifies the propeller suction (t). In conventional ship propulsion systems, vessels typically rely on single or twin-screw large-diameter propellers. However, this configuration has notable limitations, particularly in shallow-water operations, where the risk of propeller ventilation becomes a significant concern. The loss of propulsion thrust and inefficiencies caused by high propeller loading, resulting from increased resistance, highlight the need for a paradigm shift in the design of propulsion systems for inland waterway vessels.

Moreover, when operating in shallow water conditions, the propeller is also highly loaded due to the increase in thrust required to meet the increased resistance. When this happens and, therefore, the propeller is highly loaded, the operating rotational speed will have to be increased to maintain the required thrust. The high rotational speed creates conditions that lower the local pressure on the suction side of the blades, which is lower than the vapor pressure, leading to propeller cavitation. The variation in open-water efficiency is highly dependent on the change in propeller loading, which in essence is related to the thrust deduction factor [11]. Advancements have been made in improving the propulsion efficiency of inland vessels for shallow-water conditions. Rotteveel in [12] investigated the different stern shapes, including tunnels, to improve the inflow to the propeller in shallow water.

In recent years, numerical methods using CFD simulation tools have been used to predict and optimise inland vessel propulsion performance. However, these are computationally expensive for early design concept exploration. Hence, models that estimate resistance and propulsion performance based on the vessel's and the waterway's specific characteristics are essential during the early design stages.

To address these challenges and meet the demands of current and future operations, innovative approaches to propulsion system design must be considered. To benefit from the available beam of the vessel in the stern region, a propulsion concept called the distributed thrust has notably been investigated by [13], [14]. As highlighted by Hagesteijn [13], one of the key advantages of distributed thrust using multiple smaller propellers is the redundancy it provides. In the event of failure of one or more propellers, the system can maintain functionality, thereby minimizing downtime. Furthermore, distributed thrust allows for the use of smaller, more modular power drive trains instead of larger, centralized systems. For inland vessels, this approach enables the use of easily serviceable and replaceable truck engines as an alternative to specialized marine engines [13], significantly simplifying maintenance and reducing operational costs.

2.2. Robust optimisation

In today's complex technological landscape, integrating diverse disciplines has become essential for addressing engineering challenges. Operations Research (OR), a field of applied mathematics, employs analytical methods to support informed decision-making. A key approach within OR is robust optimization, which specifically focuses on decision-making in uncertain environments by accounting for the worst possible scenarios.

The efforts to implement robust optimisation to help in decision making in shipping are not new, recent advancements in maritime transport research have leveraged robust optimization in various applications, such as a robust optimization model for ship traffic scheduling presented by [15] and vessel maneuvering control, as explored by [16]. [17] applied robust optimization for fleet deployment and tactical ship assignments, as well as capacity allocation, to account for the volatility of shipping markets and seasonal variations, ultimately aiming to maximize revenue.

In ship design, robust optimization has made significant advancements by enhancing design methodologies while minimizing the computational demands associated with high-fidelity, resource-intensive simulations, such as those in computational fluid dynamics. Additionally, the ship design process is becoming increasingly complex, driven by numerous conflicting design objectives that are mutually interdependent, coupled with increasing number of design or operational constraints and decision variables. Accounting for this increasing complexity poses a challenge commonly known as the so-called ”curse of dimensionality”. As such optimisation models have become integral part of ship design workflow. For example, [18] applied robust design optimization to determine optimal hull geometries and floating system configurations, ensuring adaptability to uncertain design requirements.

Considering the inherent uncertainties in the operational conditions of inland vessels, robust optimisation in the authors' view, provides a powerful framework for designing vessels that are resilient to the worst possible conditions they may encounter throughout their operational lifetime. As demonstrated in this study, applying robust optimisation informed by physics to extreme shallow-water scenarios facilitates the development of propulsion systems that ensure both efficiency and reliability, even under variable water depths and challenging constraints.

This approach allows for exploration of resilient vessels that can operate effectively across a range of unpredictable environmental conditions.

3. Approach

3.1. Optimisation modelling - adversarial robust optimisation

A well-known approach in robust optimisation is the adversarial approach. The main idea of the adversarial approach is to explicitly model the uncertainty by considering the deterministic ”worst-case” scenario [19]. This method seeks to optimise the system’s performance while ensuring it remains robust and effective under the most unfavourable conditions the system might encounter, here-in an *inland waterway vessel*. The optimization process iteratively adjusts the design or decision variables to minimize the impact of these adversarial uncertainties. This ensures the solution is not only optimal under nominal conditions but also resilient under extreme variations.

3.1.1. resistance

- *uncertainty sets*
  The uncertainties are modelled as a set $\mathcal{U}$ of possible waterway conditions, and in this case, related to the confinement effects of the waterway.

$$\mathcal{U} = \left\{ \mathbf{u} = \left(\frac{h}{T}, \frac{W}{B}, d_b \right) \;\middle|\; \frac{h}{T} \in [1.1, 10],\ \frac{W}{B} \in [2.0, 10],\ d_b \in [0.1 \cdot W, 1.0 \cdot W] \right\} \tag{1}$$

where:

$$\begin{aligned} h/T &: \quad \text{(water depth-to-draft ratio)}, \\ W/B &: \quad \text{(channel width-to-beam ratio)}, \\ d_b &: \quad \text{(proximity of vessel to sides of channel wall)}. \end{aligned}$$

- *worst case for vessel resistance*
  The worst possible scenario would result in increased resistance as given below;

$$R_T = f(V_s, u) \mid_{u \in \mathcal{U}} \tag{2}$$

- *resistance estimation*
  Estimating the resistance of the vessel, the state-of-the-art friction correction for shallow water used in this work is adopted from [5]. This is a correction for the ITTC friction line, accounting for shallow-water effect;

$$C_\mathrm{f} = \frac{0.08468}{(\log Re - 1.631)^2} \cdot \left(1 + \frac{1.168}{\log Re - 0.5238} \cdot \left(\frac{h}{T} \right)^{-1.472} \right) \tag{3}$$

The additional resistance due to the squat effect is calculated from [20] empirical ship squat formula, which is corrected for waterway conditions such as the width of the channel, the slope of the channel, and the proximity of the vessel to the sides.

$$z = 0.0065 \cdot e^{5.2 \cdot F_{nh}} + (0.95 \cdot F_{nh}^6 - 0.065) \tag{4}$$

$$z_{final} = z \cdot (\alpha_W \cdot \alpha_M \cdot \alpha_{W'}) \tag{5}$$

where $F_{nh} = \frac{V}{\sqrt{gh}}$ is the depth froude number and $(\alpha_w, \alpha_m, \alpha_w')$ are correction factors for the width of the waterway, slope of bank, and the proximity of the vessel to sides.

3.1.2. propulsion

Thrust loss in case of propeller emergence has been assumed to be proportional to the out-of-water area of the propeller disc. Ventilation is a phenomenon that occurs when the propeller operates close to the dynamic free surface and drawing air into the propeller stream or when the blades pierce the free surface, leading to sudden loss in propeller thrust and torque. This becomes more pronounced when the propeller loading is high and the submergence is limited. Load can be distributed among multiple propellers to reduce loading on one or two propellers, which is the focus of this research. To improve submergence below the surface, a smaller-diameter propeller can be used. Hence, to mitigate the risk of propeller ventilation. The thrust loss factor β is given empirically as a function of the shaft submergence ratio $\frac{h}{R}$ given by eq. (6). This was proposed by [21], accounting for the combined effects of loss of disk area, wave, and wagener effect.

$$\beta = \begin{cases} 1, & \text{if } \frac{h}{R} \geq 1.3 \\ 1 - 0.675 \cdot (1 - 0.769 \cdot \frac{h}{R})^{1.258}, & \text{otherwise} \end{cases} \tag{6}$$

The shaft immersion ratio, which is modelled as a function of the propeller diameter accounting for hull-propeller blade clearance, is given by eq. (7).

$$\frac{h}{R} = 2\left(\frac{T_e}{D} - 0.65\right) \tag{7}$$

where T_e is the vessel draft and D is propeller diameter.

- *worse case for propulsion*
  Worse possible scenario for propulsion would be the potential breakdown in thrust given below.

  $$T_F = \beta \cdot T \tag{8}$$

  where T_F and T are the effective propeller thrust and openwater propeller thrust, respectively.

In this study, Wageningen B-series propeller, a conventional propeller series widely used in the design and optimisation of propulsion system, is used. Originally developed through systematic model testing by MARIN [22], this propeller series provides comprehensive open-water performance charateristics for conventional fixed pitch propeller across parametric variations in *pitch-diameter ratio, expanded area ratio, number of blades, and advance number*.
Recent advances have represented the open-water characteristic as high-order multivariate polynomials as a functions of these variables, given in eq. (9) and eq. (10).

$$K_{\mathrm{T}} = f_1(J, P_D, A_{ER}, Z) = \sum C^{T}_{s,t,u,v} (J)^s \cdot (P_D)^t \cdot (A_{\mathrm{ER}})^u \cdot (Z)^v \tag{9}$$

$$K_{\mathrm{Q}} = f_2(J, P_D, A_{ER}, Z) = \sum C^{Q}_{s,t,u,v} (J)^s \cdot (P_D)^t \cdot (A_{\mathrm{ER}})^u \cdot (Z)^v \tag{10}$$

$$J = \frac{V_a}{n \cdot D} \tag{11}$$

The coefficients of the high-order B-series polynomial functions are published in [23]

3.2. MINLP formulation

The problem, as formulated, is a mixed-integer non-linear (*MINLP*) optimisation problem. This is a non-linear problem because the objective function, which is the open water efficiency, is non-linear, and some constraints, such as the $(Kt - Kq)$, are polynomial functions of the pitch-diameter ratio, expanded area ratio, and number of blades. The thrust loss factor (β) is an empirical hydrodynamic function, as described in reference [3], and acts as a penalty factor that reduces the thrust generated by the propeller. This thrust loss factor increases with the propeller size as discussed in the previous subsection. Consequently, the optimisation process aims to minimise this penalty factor by distributing the thrust across multiple smaller-diameter propellers, thereby reducing the overall impact of the thrust loss factor. Hence, to maximise the benefit from the entire beam (B_{max}) of a vessel in the stern region, the constraint illustrated in fig. 1. and defined in eq. (12) must be considered.

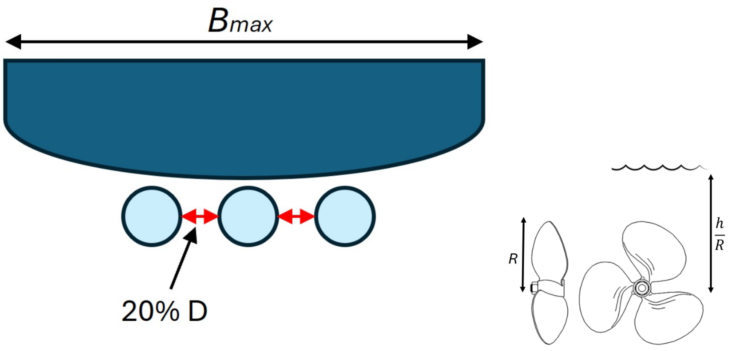
$$\sum_{n_{\text{p}}=1}^{N} (n_p \cdot D + (n_{\text{p}} - 1) \cdot (0.2 \cdot D)) \leq B_{\text{max}} \tag{12}$$

The total thrust produced is modelled to account for the worst-case scenario, where the total propeller(s) thrust ($n_p \cdot T$) should overcome the resistance in the worst-case (shallow water condition) R_T.

$$n_{\text{p}} \cdot (T \cdot \beta) \geq R_T, \tag{13}$$

The thrust loss factor negatively impacts the total thrust, primarily a function of the submergence of the propeller. This submergence, in turn, depends on the propeller's size (diameter).
The formulation of the optimisation problem is summarised below;

$$\begin{aligned}
&\textit{maximise}: && \eta = \frac{J}{2\pi} \cdot \frac{K_{\text{T}}}{K_{\text{Q}}}, \\
&\textit{subject to}: && n_{\text{p}} \cdot (T \cdot \beta) \geq R_T, \\
& && \sum_{n_{\text{p}}=1}^{N} (n_p \cdot D + (n_{\text{p}} - 1) \cdot (0.2 \cdot D)) \leq B_{\text{max}}, \\
& && K_{\text{T}} = f_1(J, P_D, A_{ER}, Z), \\
& && K_{\text{Q}} = f_2(J, P_D, A_{ER}, Z), \\
& && T = K_{\text{T}} \cdot n^2 \cdot D^4, \\
& && Q = K_{\text{Q}} \cdot n^2 \cdot D^5, \\
&\textit{decision variables}: && \\
& && D \in [0.5 \cdot T_e, 1 \cdot T_e], \\
& && P_D \in [0.7, 1.4], \\
& && A_{ER} \in [0.5, 1.0], \\
& && J \in [0.1, 1.6], \\
& && Z \in [3, 6] \\
& && n_{\text{p}} \in \mathbb{Z}^+
\end{aligned}$$



(a) propeller spacing

(b) propeller submergence

Figure 1.: *Propeller Configuration Constraints*

This method estimates the diameter, pitch, number of propeller(s), and efficiency required to achieve sufficient total thrust for inland waterway vessels operating in shallow waters. This program was implemented in Python, with the optimisation model formulated using Pyomo (Python Optimisation Modeling Objects), an open-source Python library designed for modeling a wide range of optimisation problems. Pyomo provides a flexible framework that supports linear, nonlinear, and mixed-integer optimisation, allowing users to interface with various solvers depending on the problem's requirements. For this specific problem, which is classified as a Mixed-Integer Nonlinear Programming (MINLP) problem, the open source solver BONMIN *(Basic Open Source Nonlinear Mixed INteger Programming)* was employed. BONMIN is designed to efficiently handle MINLP problems by integrating nonlinear and integer programming techniques.

4. Results and Discussions

4.1. Resistance and propulsion

Implementing this method on a use case with characteristics in the table table 2., this is the CEMT Class VI, a typical vessel of Rhine class. For this vessel, the resistance it may encounter is decomposed into the three main components: the viscous resistance and the wave making resistance and ship squat effects, as illustrated in the 1^{st}, 2^{nd} and 3^{rd} frames of fig. 3.. The viscous resistance is made up of the resistance due to friction (C_f) and the resistance due to the form of the vessel ($1 + k^*$). The wave-making resistance exhibits an increasing trend with water depth, as illustrated in the second frame of fig. 3.. Its dominance remains relatively limited. This is because wave-making resistance is primarily governed by the flow regime, characterized by the depth Froude number ($F_{nd} = \frac{V}{\sqrt{gh}}$). Notably, significant wave-making resistance occurs when F_{nd} approaches the critical flow regime $F_{nd} \approx 1$, However, this condition is generally not encountered in inland vessels, as they predominantly operate within the subcritical flow regime ($F_{nd} < 0.6$).

Table 2.: Vessel Characteristics

Parameters		value
C_b	[-]	0.86
L	[m]	110
B	[m]	11.4
T_l	[m]	3.5
T_e	[m]	1.8
S_w	[m^2]	2974.96
∇	[m^3]	3795.2
lcb	[m]	55.28
lcg	[m]	56.27

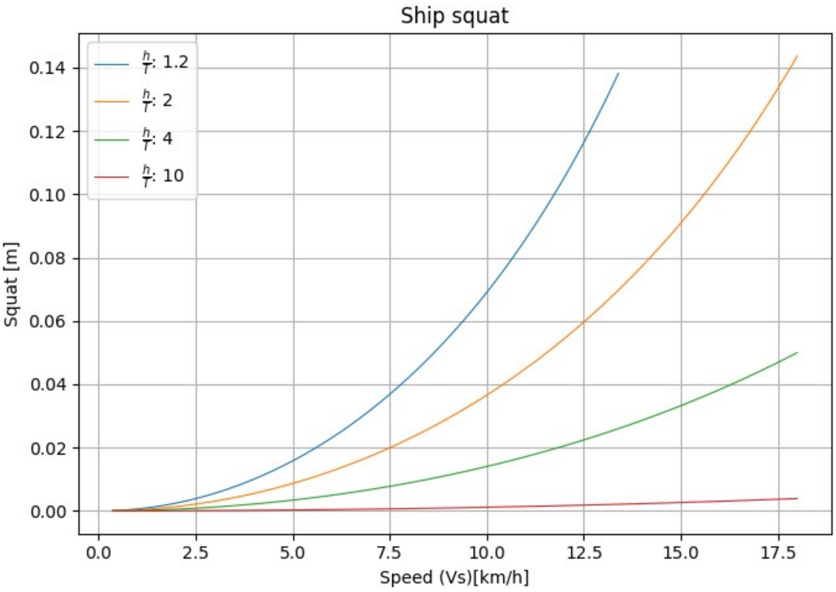


Figure 2.: *Ship squat*

However, resistance due to squat must also be considered, as it arises from the additional ship draft or sinkage when the vessel moves in shallow water. This effect occurs due to a pressure drop beneath the keel,

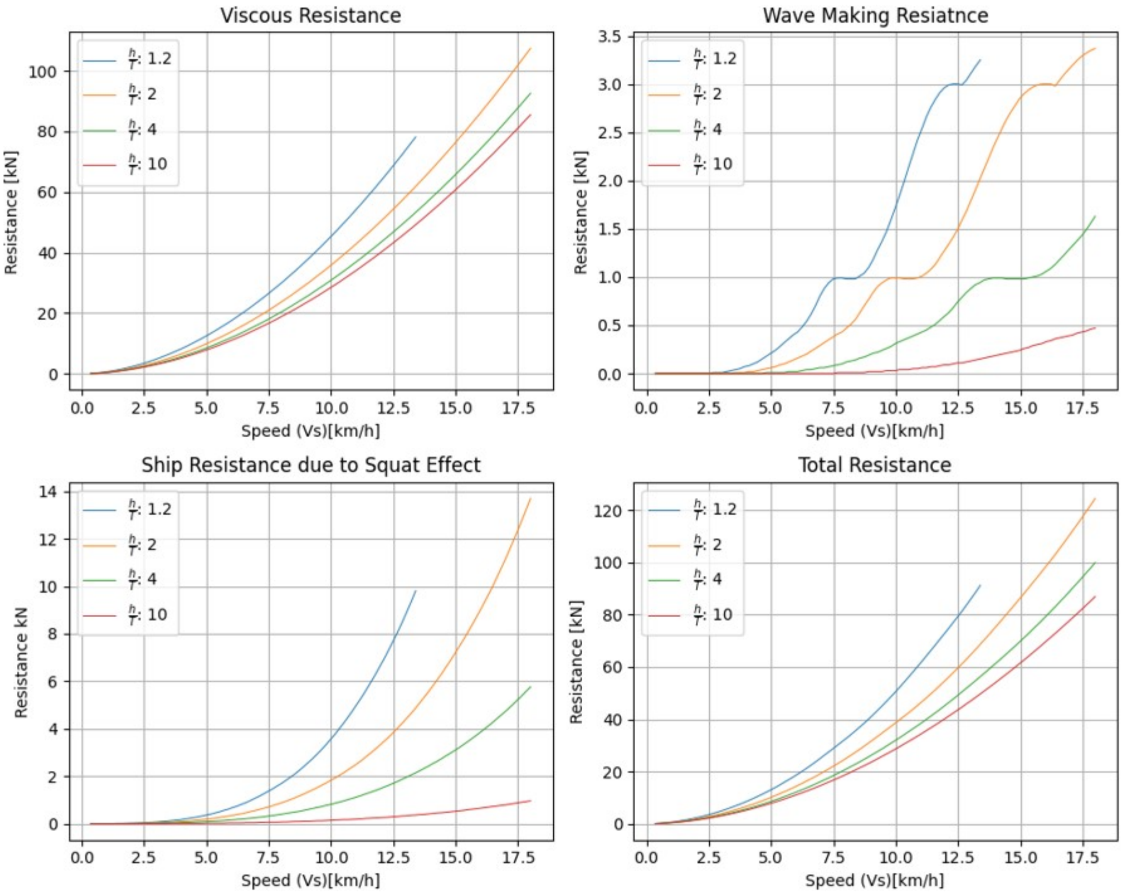


Figure 3.: *Resistance Components*

which draws the vessel closer to the bottom. As illustrated in fig. 2., ship squat or sinkage increases with vessel speed and becomes even more pronounced as the water depth decreases.

4.2. Conventional vs unconventional propulsion configuration

Here we compare the propeller performance in shallow of the optimised propeller configuration with a conventional propeller configuration of twin screw from [24] as can be seen in the fig. 4. and table 3.. Given the constraints and penalty for larger diameter propellers formulated in the problem, to maintain performance, as part of the solution space exploration, the diameter of the propeller is reduced, and the number of propeller(s) is increased to compensate for the required thrust, also determining the propeller characteristics.

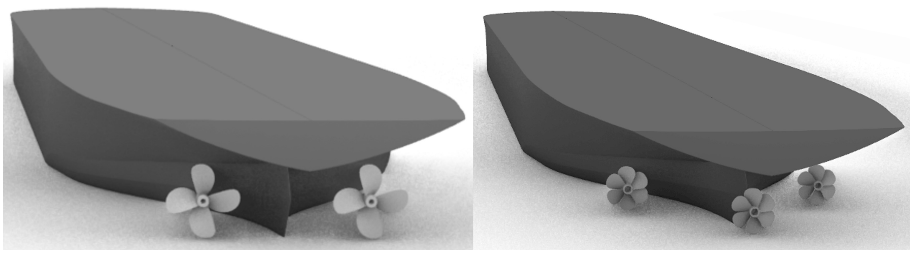


Figure 4.: *Conventional vessel with 2 propellers (left) and Unconventional vessel with 3 propellers (right)*

Table 3.: Comparison of propeller characteristics of conventional and unconventional (results of this study) propeller configuration of the same class of vessel

Parameters		Conventional	Unconventional (from this study)
type of propeller [-]		*ducted*	*non-ducted*
Number of propellers [-]	n_p	2	3
Number of blades [-]	Z	4	6
Propeller Diameter [m]	D	1.8	1.57
Pitch ratio [-]	P_D	1.052	0.88
Expanded Area Ratio [-]	A_{ER}	0.71	0.5
Thrust Coefficient [-]	K_T	0.1856	0.27
Torque Coefficient [-]	$10K_Q$	0.3387	0.38
Advance ratio [-]	J	0.595	0.4
Rotational speed [s^{-1}]	n	9.72	5.69

As it can be seen in fig. 5., the thrust requirement represented by the red curve increases with decreasing water depth for the given ship speed. The horizontal dashed lines represent the thrust produced by the two configurations. We can observe that for the unconventional three-propeller configuration, we can meet the thrust requirement until a water depth of about 2.3 m, which is not the case for the conventional two-propeller configuration, which can only meet the thrust requirement at a water depth of 3.1 m. A shift of approximately 0.7 meters in the navigable depth threshold enables transportation operations in significantly shallower waters than would be feasible with a conventional twin-screw configuration using two large propellers. However, this improvement comes at the cost of increased total installed power capacity, although with the benefit of system redundancy since not all propellers are in use in normal operating conditions.

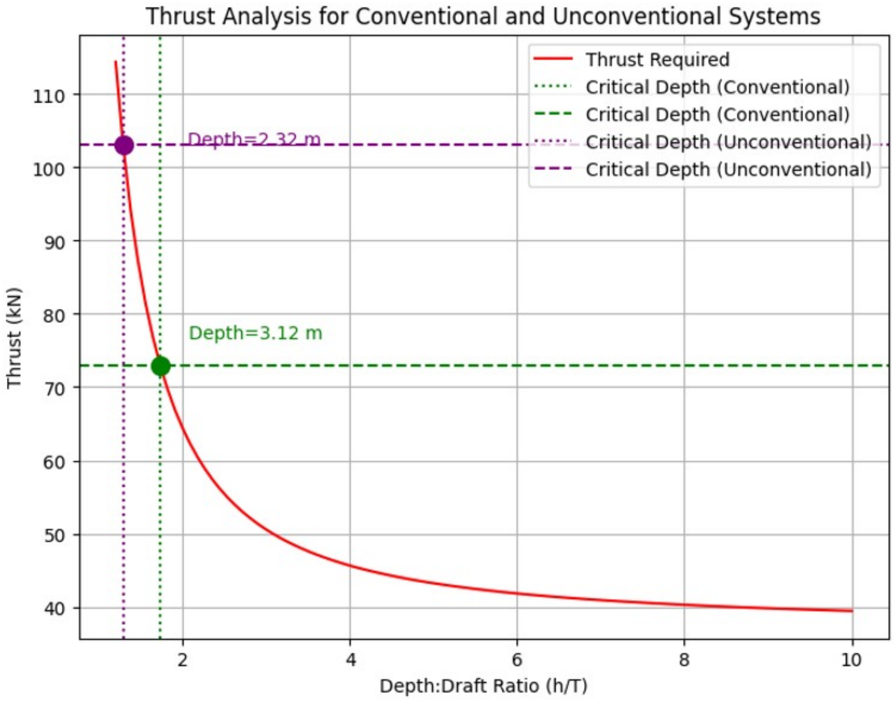


Figure 5.: *Thrust Analysis*

4.3. Near optimal solutions from optimisation solver

Here we present and compare near-optimal solutions produced from the solution pool option of the optimisation solver table 4..

Table 4.: Propeller performance characteristics for different near-optimal solutions

Soln.	D (m)	n_p	Z	P/D	A_{ER}	J	n (s^{-1})	K_T	$10K_Q$	T (kN)	Q (kNm)	β	h/R
1	**1.57**	**3**	**6**	**0.88**	**0.50**	**0.40**	**4.69**	**0.27**	**0.04**	**37.13**	**8.28**	**0.89**	**0.98**
2	1.66	5	6	0.88	0.50	0.40	4.46	0.27	0.04	41.09	9.64	0.83	0.87
3	1.75	2	6	0.88	0.50	0.40	4.22	0.27	0.04	45.86	11.37	0.77	0.75
4	1.78	4	6	0.88	0.50	0.40	4.16	0.27	0.04	47.25	11.89	0.76	0.72
5	1.78	2	5	0.79	0.50	0.36	4.69	0.24	0.03	52.59	12.09	0.75	0.72
6	1.67	3	5	0.79	0.50	0.36	5.02	0.24	0.03	45.95	9.87	0.83	0.86
7	1.41	6	6	0.88	0.50	0.40	5.26	0.27	0.04	29.50	5.86	0.99	1.26
8	1.42	6	5	0.79	0.50	0.36	5.90	0.24	0.03	33.30	6.09	0.98	1.24
9	1.45	4	5	0.79	0.50	0.36	5.76	0.24	0.03	34.88	6.53	0.97	1.18
10	1.73	5	5	0.79	0.50	0.36	4.83	0.24	0.03	49.54	11.05	0.79	0.78

n_p: number of propellers
Z: blade number
P_D: pitch ratio
A_{ER}: expanded area ratio
J: advance coefficient
n: rotational speed
K_T: thrust coefficient
K_Q: torque coefficient
T: thrust
Q: torque
β: thrust loss factor
h/R: immersion ratio

A particularly interesting comparison is the relationship between the thrust loss factor and the immersion ratio, as shown in fig. 6., which depends on the propeller size. This relationship is further illustrated in fig. 7., where the thrust produced and the thrust loss factor for each solution are compared. As observed, solutions exhibiting higher thrust loss are primarily influenced by their propeller sizes. Notable examples include solutions 3, 4, and 5, with diameters of 1.75 m, 1.78 m, and 1.78 m, respectively. These solutions are more susceptible to thrust breakdown due to their tendency to operate partially out of the water or above the surface, a consequence of their larger diameters. Conversely, solutions with smaller propeller diameters exhibit a lower susceptibility to thrust breakdown; examples include solutions 7, 8, and 9, as presented in table 3.. However, to compensate for the reduced thrust per propeller, these solutions employ a greater number of propellers to achieve the required thrust.

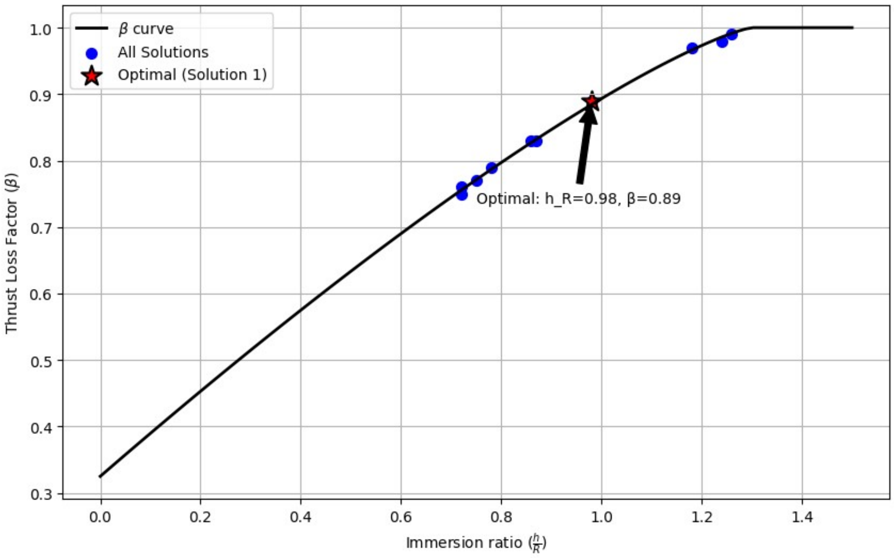


Figure 6.: *Thrust Loss Factor against immersion ratio*

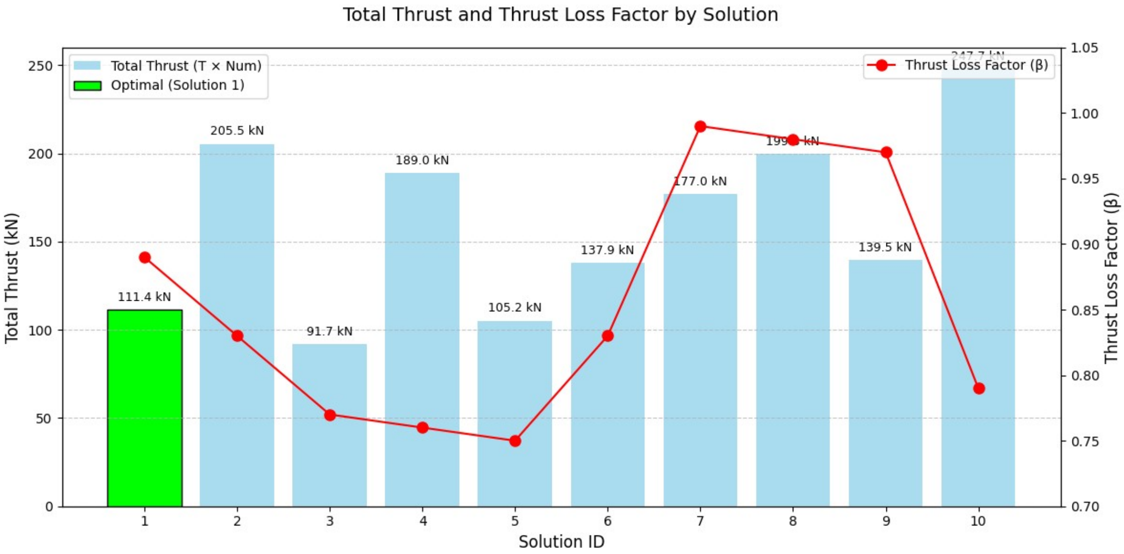


Figure 7.: *Total Thrust and Thrust Loss by Solution*

5. Conclusion and Recommendation

This study presents an optimisation study of the propulsion design of inland ships. It has been confirmed that shallow water impacts the hydrodynamic performance of inland ship. Also conventional propulsion design for inland ship can not suffice the growing need to adapt to the effect of climate change on waterways, allowing for transportation in these extreme circumstances.

From this study the following conclusions were drawn and confirmed;

- The distributed thrust concept for inland vessels offers greater adaptability to extreme shallow-water conditions by extending the navigable depth limit (*water depth*). This is particularly important as larger-diameter propellers, typically used in conventional configurations, are more susceptible to thrust breakdown in shallow water due to their increased risk of emergence, which are already highly loaded.
- Robust optimisation at the early design phase, is an efficient approach for accounting for uncertainties in waterway characteristics due to climate change. This approach enables a more reliable preliminary estimation of vessel propulsion design requirements.

Further investigation will involve validating this use case with computational fluid dynamics to simulate the actual working of the propeller(s) in the behind condition. Assessing the changing inflow condition in shallow water and how this alters the wake and thrust deduction factors. Although this work considered only the Wageningen B series propeller for this optimisation, adopting and integrating the use of other propeller series in the optimisation framework would enable better decision-making.

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References

[1] O. Jonkeren et al. "Climate change and economic consequences for inland waterway transport in Europe". In: *Regional Environmental Change* (2013). DOI: `10.1007/s10113-013-0441-7`.

[2] C. Sys et al. "Pathways for a sustainable future inland water transport: A case study for the European inland navigation sector". In: *Case Studies on Transport Policy* 8.3 (2020), pp. 686–699. DOI: `10.1016/j.cstp.2020.07.013`.

[3] O. Jonkeren. *Adaption to climate change in inland waterway transport*. Tinbergen Institute research series 460. Amsterdam: PhD Thesis - Vrije Universiteit Amsterdam, 2009. 153 pp.

[4] R. Anku et al. "A review of the state-of-the-art Sustainable and Climate-resilient inland waterway vessels". In: *International Marine Design Conference* (2024). DOI: `doi.org/10.59490/imdc.2024.826`.

[5] Q. Zeng et al. "A modification of the ITTC57 correlation line for shallow water". In: *Journal of Marine Science and Technology* 24.2 (2019), pp. 642–657. DOI: `10.1007/s00773-018-0578-7`.

[6] P. Du et al. "Resistance and wave characterizations of inland vessels in the fully-confined waterway". In: *Ocean Engineering* 210 (2020), p. 107580. DOI: `10.1016/j.oceaneng.2020.107580`.

[7] P.-J. Pompée. "About modelling inland vessels resistance and propulsion and interaction vessel - waterway Key parameters driving restricted/shallow water effects". In: (2015).

[8] D. Radojčić. *Environmentally friendly Inland Waterway Ship design for the Danube River*. Tech. rep. 2009.

[9] L. Zentari et al. "Experimental and numerical investigation of shallow water effects on resistance and propulsion of coupled pusher-barge convoys". In: *Applied Ocean Research* 121 (2022), p. 103048. DOI: `10.1016/j.apor.2022.103048`.

[10] J. Kulczyk and T. Tabaczek. "Coefficients of Propeller-hull Interaction in Propulsion System of Inland Waterway Vessels with Stern Tunnels". In: *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation* 8.3 (2014), pp. 377–384. DOI: `10.12716/1001.08.03.08`.

[11] S. Saettone et al. "Experimental Measure of propulsive factor in following and head waves". In: *Applied Ocean Research* (2021). DOI: `10.1016/j.apor.2021.102639`.

[12] E. Rotteveel et al. "Inland ship stern optimization in shallow water". In: *Ocean Engineering* 141 (2017), pp. 555–569. DOI: `10.1016/j.oceaneng.2017.06.028`.

[13] G. Hagesteijn et al. "Distributed Propuslion: A Novel Concept for Inland Vessels". In: *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering OMAE2015 - Canada*. 2015.

[14] A. Sánchez-Caja et al. "A New Propulsion Concept for High Propulsive Hydrodynamic Efficiency". In: *Ocean Engineering* 243 (2022), p. 110298. DOI: `10.1016/j.oceaneng.2021.110298`.

[15] X. Zhang et al. "Robust Optimization for a Class of Ship Traffic Scheduling Problem with Uncertain Arrival and Departure Times". In: *Engineering Applications of Artificial Intelligence* 133 (2024), p. 108257. DOI: `10.1016/j.engappai.2024.108257`.

[16] A. I. Jambak and I. Bayezit. "Robust Optimal Control of a Nonlinear Surface Vessel Model with Parametric Uncertainties". In: *Brodogradnja* 74.3 (2023), pp. 131–143. DOI: `10.21278/brod74307`.

[17] X. Lai et al. “Robust Ship Fleet Deployment with Shipping Revenue Management”. In: *Transportation Research Part B: Methodological* 161 (2022), pp. 169–196. DOI: 10.1016/j.trb.2022.05.005.

[18] P. Gallagher. “Novel Approach to Robust Concept Development for Offshore Floating Systems”. In: *International Journal of Maritime Engineering* 164.A4 (2023). DOI: 10.5750/ijme.v164iA4.1206.

[19] J. Thürauf. “Adjustable Robust Nonlinear Network Design under Demand Uncertainties”. In: (2024). DOI: 10.48550/arXiv.2405.17867.

[20] A. Gronarz. “Development of a Squat Formula Based on Numerical Calculations”. In: (2016). DOI: 10.18451/978-3-939230-38-0_13.

[21] K. Minsaas et al. “On the Importance of Addedd Resistance, Propeller Immersion and Propeller Ventilation for Large Ships in a Seaway”. In: *Proceedings of PRADS-83 2nd International Symposium on Practical Design in Shipbuilding*. 1983.

[22] G. Kuiper. *The Wageningen Propeller Series*. Tech. rep. Maritime Research Institute Netherlands (MARIN), 1992.

[23] M. Bernitsas. *Kt Kq and Efficiency curves for the Wageningen B-series Propellers*. Tech. rep. University of Michigan, 1981.

[24] P. Mucha et al. “An experimental study on the effect of confined water on resistance and propulsion of an inland waterway ship”. In: *Ocean Engineering* 167 (2018), pp. 11–22. DOI: 10.1016/j.oceaneng.2018.08.009.