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AUTOFLEX

[D4.2] Uncrewed Vessel concept

Work Package	WP4	Developing small automated Zero-emission Vessels
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EXECUTIVE SUMMARY

Deliverable D4.2 presents the concept design of the AUTOFLEX vessel – a fully electric, uncrewed container vessel tailored for CEMT Class II inland waterways, including segments classified as Zone 2. The document outlines the design process, development methodology, and key technical outcomes that demonstrate the feasibility of a zero-emission, automated vessel aligned with European decarbonisation and digitalisation goals.

Concept Development and Design Methodology

The design was developed in response to the operational and regulatory requirements defined in Tasks 2.1 (Design Parameters and Boundary Conditions) and Task 4.1 (Impact of Automation and Containerization). These included navigational constraints such as maximum vessel dimensions, lock widths, bridge clearance, and shallow draft limits. These inputs were translated into specific design features covering hull geometry, propulsion layout, structural architecture, and cargo configuration.

Rhino3D and Orca3D were used to support the 3D arrangement validation and lightship weight estimation, while NAPA was applied for the hydrostatic assessments and stability analyses. This ensured that the concept remained technically sound, practically deployable, and compliant with relevant regulations.

Key Technical Features and Achievements

- Fully electric propulsion based on modular ZES battery units (ZESpacks)
- Autonomous operation aligned with CCNR Autonomy Level 3
- Hull and structure optimised for shallow-draft navigation and Zone 2 operations
- Compatibility with 20-ft ISO and pallet-wide (PW) container formats
- Compliance with requirements of ES-TRIN, Bureau Veritas, and UNECE Resolution No. 61

These features demonstrate that the AUTOFLEX concept meets the project's primary goals: supporting emission-free transport, enabling uncrewed operation, and integrating seamlessly into existing waterway infrastructure.

Challenges and Design Considerations

Design challenges included ensuring vessel stability while maintaining cargo capacity, accommodating battery modules without reducing container slots, and designing redundant electric systems. Another specific requirement was the hull adaptation to suit the azimuth propulsion units.

An additional design consideration addressed in Task 4.2 was the evaluation of lightweight structural solutions. As described in chapters 8.1 and 8.2 , the analysis demonstrated that such technologies may not be well suited for small, autonomous inland vessels without accommodation areas.

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Their potential impact on performance, cost, and practical implementation would be limited, and they were therefore not recommended for integration into the final concept.

Broader Impact and Strategic Value

The AUTOFLEX concept provides a strong reference for future inland vessel development. It illustrates how digital design methods and modular energy systems can support automation and emission reduction while complying with operational and legal requirements. The design is scalable and applicable beyond the current use case, supporting EU-wide efforts to modernise and decarbonise inland shipping.

Outlook: Path Toward Further Development

The design serves as a technical foundation for upcoming work in Task 4.3 (Basic design and optimization of hull and propulsion), which will focus on:

- Optimize the hydrodynamic performance of the vessel while maximizing cargo capacity and minimizing total cost of ownership (TCO)
- Investigate hull-propulsor-waterway interaction and banking effects under normal and low water conditions for both use cases
- Employ a simulation-driven design approach based on a parametric model built in CAESES
- Validate CFD results through model testing using a scale model of the vessel
- Quantify power demand and energy efficiency across a matrix of speeds, load cases, and waterway conditions

Partner Contributions

This concept is the result of coordinated input from the AUTOFLEX consortium:

- **DST** – Hull form development, hydrostatics and intact stability analysis
- **SO** – Design of propulsion systems and energy architecture

These combined contributions enabled the development of a technically mature, forward-looking vessel concept ready for refinement and validation in the next project phase.

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LIST OF ABBREVIATIONS

Abbreviation	Description
AAB	AUTOFLEX Advisory Board
AIS	Automatic Identification System
BV	Bureau Veritas
CA	Consortium Agreement
CAD	Computer-Aided Design
CCNR	Central Commission for Navigation on the Rhine
CEMT	Conférence Européenne des Ministres des Transports
CESNI	European Committee for Drawing up Standards in Inland Navigation
CFD	Computational Fluid Dynamics
D2.1	Deliverable 2.1 of AUTOFLEX Project
D4.1	Deliverable 4.1 of AUTOFLEX Project
DST	Development Centre for Ship Technology and Transport Systems
ECE	Economic Commission for Europe
ES-TRIN	European Standard laying down Technical Requirements for Inland Navigation vessels
GA	General Arrangement
GAP	General Arrangement Plan
GM	Metacentric Height
GZ	Righting Lever
HM	Hekkenberg Method
HP	Holland Profile (structural profile type used in shipbuilding)
HVAC	Heating, Ventilation and Air Conditioning
ISE	Institut für Strukturleichtbau und Energieeffizienz gGmbH
IWT	Inland Waterway Transport
JRG2	Steel grade S235 JRG2 (material standard)
LC1 – LC9-1	Loading Conditions 1 to 9-1
LCG	Longitudinal Centre of Gravity
MDC	Mobile Distribution Centre
MR	Maritime Robotics
NR	Naval Rules (Bureau Veritas)
PW	Pallet-Wide Container Format
OA	Overall
S&C	Swap & Charge
S235	Structural steel, standard grade (EN 10025)
S355	High-strength structural steel (EN 10025)
SFAZ	Small, Flexible, Automated, Zero-emission
SO	SINTEF Ocean
SOTA	State-of-the-art
SPR	Schottel Rudder Propeller
TCO	Total Cost of Ownership
TCG	Transverse Centre of Gravity

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TEU	Twenty-foot Equivalent Unit
VCG	Vertical Centre of Gravity
WB	Water Ballast
WF	Wake Fraction
WP	Work Package
ZES	Zero Emission Services

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1 INTRODUCTION

1.1 AUTOFLEX PROJECT OVERVIEW

The AUTOFLEX project, funded under the European Union's Horizon Europe research and innovation programme (Grant Agreement No. 101136257), seeks to revolutionize inland waterway transport (IWT) through the development of small, flexible, zero-emission, and automated vessels. These uncrewed vessels are designed to navigate shallow and constrained inland waterways, offering an environmentally sustainable and logistically efficient alternative to traditional road-based freight transport [1].

By integrating cutting-edge technologies such as autonomous navigation systems, fully electric propulsion, and modular energy storage AUTOFLEX proposes a new class of inland cargo carriers that are not only cost-effective and operationally flexible but also fully aligned with the EU's broader goals for green and digital transitions, as outlined in the European Green Deal [2] and Sustainable and Smart Mobility Strategy [3]. These vessels are tailored to the specific challenges of Europe's inland waterways, where infrastructure limitations and environmental concerns require innovative and adaptable solutions.

One of the central aims of AUTOFLEX is the development of a CEMT Class II uncrewed vessel concepts, engineered to operate autonomously in environments that are typically inaccessible to larger ships. The project envisions a future where inland shipping is fully integrated into multimodal transport chains, reducing road congestion and contributing significantly to the decarbonisation of freight transport across Europe [4].

1.2 OBJECTIVES AND SCOPE OF THIS DELIVERABLE

Deliverable D4.2 presents the conceptual development and preliminary structural design of the AUTOFLEX vessel. As the first comprehensive design iteration within WP4, this report which is dedicated to the development of small, uncrewed, zero-emission inland vessels establishes the technical and architectural foundation for an autonomous inland vessel optimized for energy efficiency, cargo capacity, and environmental performance.

This deliverable focuses on the design activities conducted in Task 4.2, encompassing:

- Definition of operational requirements and regulatory constraints
- Determination of principal vessel dimensions and general arrangement
- Hull form development and preliminary 3D modelling
- Structural layout and scantling calculations in line with classification society standards
- Weight estimation, including lightship weight and centres of gravity
- Evaluation of functional adaptations required for automation and zero-emission operation

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In addition to documenting the concept design process, this deliverable draws on findings from prior tasks - Task 2.1 and Task 4.1 - to ensure consistency with real-world constraints and strategic project goals.

By delivering a technically validated concept design, D4.2 sets the stage for subsequent refinement in Task 4.3 (Basic design and optimisation of hull and propulsion), where simulation, optimization, and stakeholder input will further evolve the vessel architecture.

1.3 REPORT STRUCTURE AND METHODOLOGICAL APPROACH

This report is structured to follow the logic of a systematic and iterative vessel design process. It begins with a review of key inputs from Task 2.1 and Task 4.1, which define the design space based on infrastructural, environmental, and regulatory conditions.

Subsequent chapters document the concept development of the AUTOFLEX vessel:

- Chapter 2–3 establish the linkage to previous tasks and define the design methodology, including reference vessel benchmarking and parameter normalization
- Chapter 4–6 describe the technical evolution of the hull form, layout, and structural components, supported by 3D modelling and design simulations
- Chapter 7–9 detail scantling calculations, strategies for weight optimization, and the resulting lightship weight estimation
- Chapter 10–11 present propulsion integration, CFD validation, and stability assessments
- Chapter 12 concludes with a summary of findings and a roadmap for future design activities

Together, these chapters offer a comprehensive and coherent overview of the AUTOFLEX concept development. The document is intended as a technical reference for project partners, reviewers, and stakeholders, and provides a robust foundation for the transition from concept to optimized design in the following project phases.

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2 LINKAGE TO PREVIOS TASKS

2.1 TASK 2.1 – DESIGN PARAMETERS AND BOUNDARY CONDITIONS

Task 2.1 established the foundational design framework for the AUTOFLEX vessel by conducting a comprehensive assessment of the infrastructural, environmental, and operational factors that shape inland waterway transport. The results of this task are documented in Deliverable D2.1: "Design Parameters and Boundary Conditions"[1]. For the AUTOFLEX vessel by conducting a comprehensive assessment of the infrastructural, environmental, and operational factors that shape inland waterway transport. This analysis was essential for identifying constraints and opportunities relevant to vessel design, particularly in the context of autonomous and zero-emission operation.

The task included an in-depth evaluation of the physical characteristics of European inland waterways, drawing on data from national authorities, infrastructure plans of European inland waterways, focusing on key parameters such as:

- Channel depth, navigable width, and under-keel clearance
- Lock dimensions, gate types, and operational procedures
- Vertical clearance under bridges and overhead structures
- Port infrastructure, berthing configurations, and terminal accessibility
- Traffic density, navigation rules, and speed regulations
- Seasonal variations in water levels and associated draft restrictions
- Influence of tidal flows and current velocities on propulsion and control

This data was collected from national waterway authorities, classification societies and was systematically analysed to define the design envelope for the vessel concept. One of the outputs was the classification of relevant navigation zones, particularly Zone 2, as part of the intended operational routes in which the AUTOFLEX vessel is partially intended to operate. The specific hydrological and regulatory conditions in this zone were used to establish freeboard requirements, hull dimensions, and minimum safety margins.

A critical distinction made during the analysis was between tide-dependent and tide-independent waterway segments. This affects vessel scheduling, trim control, energy consumption, and hull shaping. For example, vessels operating in tidal areas must adapt dynamically to changing current patterns, while those in stable inland basins can rely on more predictable behaviour. Accordingly, Task 2.1 influenced the sizing of propulsion units and the integration of trim and stability control systems such as ballast tanks.

Compatibility with CEMT Class II waterway infrastructure emerged as a guiding constraint. Task 2.1 confirmed that locks and bridges on these routes impose strict upper bounds on

[1] *AUTOFLEX Deliverable D2.1: Design Parameters and Boundary Conditions, 2024*

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vessel dimensions, which in turn affect cargo capacity, container arrangement, and propulsion. The resulting dimensional framework including maximum beam, length, draft, and air draft was carried forward into Task 4.2 and serves as the basis for hull geometry and general arrangement planning (see Chapter 4.2 in this report).

Beyond geometric constraints, Task 2.1 also provided essential input on infrastructure and environmental conditions relevant to vessel resistance and energy consumption, such as shallow water depths, narrow canals, and typical cruising speeds. Although no detailed resistance curves were calculated in this task, the identification of operating environments with restricted under-keel clearance and proximity to canal banks helped define the boundary conditions for power demand estimation and battery sizing in the concept design phase. These insights also highlighted the need for maneuverability and robust control systems, which are central to the autonomous capabilities of the AUTOFLEX vessel.

In summary, Task 2.1 provided essential context for developing a regulation-compliant and technically feasible uncrewed vessel. Its findings guided conceptual decisions from hull shaping to energy storage layout within the physical and legal constraints of the targeted inland transport network. These insights are embedded in the methodologies and parameters applied throughout this deliverable (see Chapter 3).

2.2 TASK 4.1 – IMPACT OF AUTOMATION AND CONTAINERIZATION

Task 4.1 investigated the design implications of the following AUTOFLEX vessel concept aspects: automation, electrification, and container-carrying capability. These elements are essential enablers of a flexible, zero-emission, and uncrewed inland vessel suited for navigation in European waterways particularly in constrained or low-traffic environments where traditional manned operations offer limited economic viability.

The analysis conducted in this task was also informed by the findings from Deliverable D4.1, which assessed the modernization potential of CEMT class reference vessels. In that context, it was shown that the CEMT II reference vessel is particularly well suited for conversion into an autonomous, containerized platform, as it requires minimal structural changes while offering operational benefits such as improved manoeuvrability and preserved cargo capacity. These findings reinforced the decision to base the AUTOFLEX concept on a vessel of similar scale and characteristics.

Automation and Its Design Impact

Autonomous operation significantly influences the vessel's architectural layout, equipment integration, and safety requirements. Traditional components such as wheelhouses, accommodation quarters, sanitary facilities, and other crew-related infrastructure could be reduced or fully omitted. This shift enables greater flexibility in deck planning, machinery arrangement, and cargo space utilization. As a result, volume formerly reserved for accommodation and working spaces can be reallocated to technical systems or payload, potentially improving efficiency and simplifying the overall structure.

However, operating without onboard personnel introduces new technical demands. Redundant communication systems, autonomous navigation sensors, backup energy solutions, as well as provisions for mooring operations, fire safety, and emergency intervention etc. must be incorporated to guarantee operational safety and resilience.

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Key design considerations included:

- Strategic placement and protection of GNSS, LiDAR, radar, and camera systems
- Integration of antenna arrays for communication and remote monitoring by land-based control centres
- Secure compartments for mission-critical electronics with provisions for remote access and inspection, supported by reserve batteries to ensure redundancy and uninterrupted operation

These systems must also be designed for maintainability by external mobile crews or through remote diagnostics and support from land-based control centres, influencing spatial planning and access routes within the vessel's structure.

Containerization and Modular Cargo Concepts

Parallel to automation, Task 4.1 evaluated containerization as a strategy for improving cargo handling, intermodal compatibility, and logistical adaptability. Multiple cargo types and loading concepts were analysed, including ISO containers, palletized goods, and standardized module units. A modular container-based approach was identified as the most efficient solution for integrating the vessel with existing inland terminal infrastructure.

This strategy imposed several direct requirements on structural design, including:

- Reinforced deck areas for container loads
- Defined spacing for optimal weight distribution and handling access

The uniformity of cargo units simplified the vessel's structural grid and zoning. Container height, weight, and position influenced the hull profile, transverse framing, and placement of watertight bulkheads. These structural implications were carried forward and addressed in the scantling calculations of Task 4.2.

Insights from D4.1 showed that containerizing small general cargo vessels can be challenging, especially for the smallest CEMT I ships. However, the CEMT II class design required least modifications; removal of the accommodation, facilitated by automation, enabled additional space for battery packs which, in turn, facilitated electrification of the vessel without compromising the payload. This was one of the key results which supported: a) further development of the CEMT II vessel, and b) development of a container carrier.

Conclusion and Integration into WP4

The results of Task 4.1 serve as a critical link between the conceptual vision of WP2 and the practical engineering implementation in WP4. The insights gathered informed the spatial configuration, control system integration, structural layout, and operational logic of the vessel. The successful integration of automation and modularity defines the innovation character of AUTOFLEX and enables it to serve as a scalable, cost-efficient, and sustainable inland shipping solution. The findings of D4.1 emphasize that innovations like automation and electrification should be considered as part of the overall vessel system, including aspects such as structure, operations, logistics, and energy use. According to D4.1, looking at these technologies separately can lead to incorrect conclusions. Task 4.1 takes this into account by combining all these aspects into a clear and consistent vessel design.

References to Task 4.1 inputs can be found throughout Chapters 3, 4, and 10 of this deliverable report, particularly where system arrangements, containerization features, and automation interfaces are addressed.

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3 METHODOLOGY FOR THE DESIGN OF AUTOFLEX VESSEL CONCEPT

The design methodology for the CEMT Class II vessel within the AUTOFLEX project follows a structured and iterative approach that integrates technical research, performance benchmarking, concept development, and simulation-based validation. This ensures that the final vessel design complies with regulatory constraints, meets operational needs, and supports the project's innovation goals including the adoption of zero-emission propulsion, autonomous navigation, and modular logistics.

At the core of this methodology is the ship design spiral, a well-established concept in naval architecture described in various academic sources (see Figure 3-1). The spiral enables a continuous improvement loop across all design aspects from layout and hull form to system integration and structural performance. Each design iteration builds on feedback from simulations, partner inputs, and rule compliance assessments.

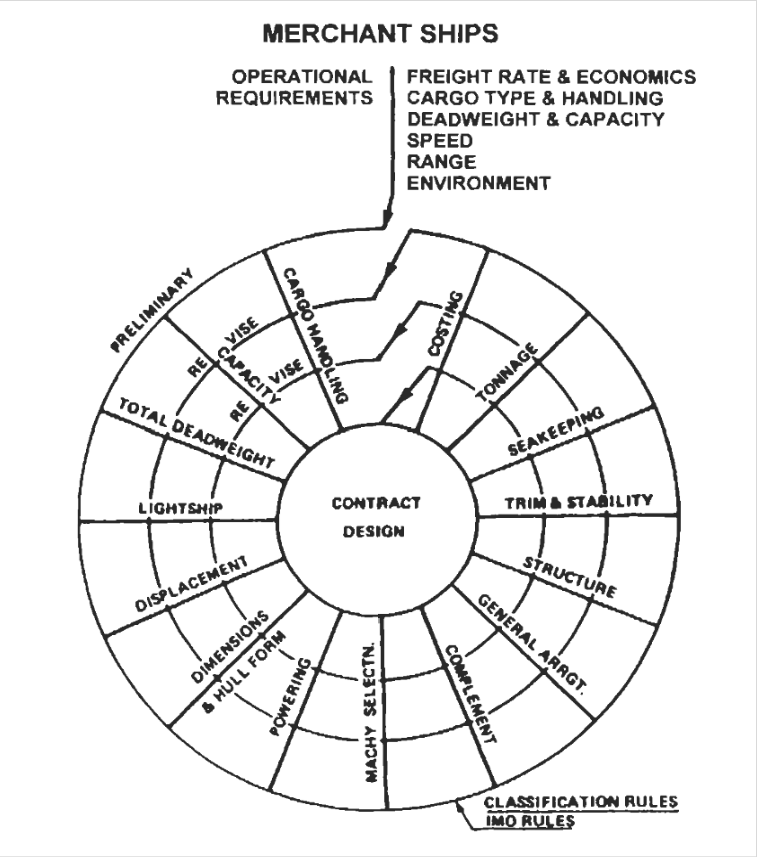

Figure 3-1: Ship design spiral [5]

Literature Review and Framework Development

To establish a solid foundation for the design process, an extensive literature review was carried out. This included classification society regulations [6], [7], [8], [9] existing inland vessel designs, propulsion technologies, and trends in autonomous and electric shipping.

Operational constraints such as maximum draught, lock dimensions, and bridge clearance were also carefully considered. Particular attention was paid to manoeuvrability in confined waterways and tidal conditions, as these heavily influence hull design and ballast tank functionality.

A principal component of the methodology was the development of a reference vessel dataset. Key parameters such as length, beam, draught, tonnage, TEU capacity, and installed propulsion power were compiled. From this data, normalized unit parameters (e.g., *L/B, L/T, B/T, L/P*) were derived to support meaningful comparisons across vessel types. These unit values were visualized and evaluated to identify trends in hull form efficiency, energy consumption, and capacity utilization. This benchmarking process, combined with the analytical insights and technical recommendations outlined in Deliverable D4.1, played a pivotal role in validating the AUTOFLEX concept. D4.1 provided structured guidance for interpreting variations in performance metrics across reference vessels and assessing the implications of new propulsion arrangements and hull designs. The comparison with established vessels enabled a precise evaluation of where the AUTOFLEX configuration stood in terms of design innovation versus traditional performance boundaries.

Reference Vessels and Benchmarking

Several benchmark vessels were analysed to determine unit values, with the Neo-Kemp II BV class vessel (see Figure 3-2) selected as the primary reference due to its alignment with the project's design objectives. The Neo-Kemp II BV is a specialized inland cargo vessel optimized for container transport on European waterways, particularly in regions like the Netherlands and Belgium. Measuring approximately 63 m in length, 7 m in beam, and with a draught of around 2 m, it is well-suited for navigating shallow waters and narrow canals. Its design prioritizes efficient container handling, offering a capacity of 32 TEU. A defining characteristic of the vessel is its forward-positioned wheelhouse, enhancing visibility when manoeuvring under bridges and in confined areas. Structurally, the vessel features a double bottom and double hull, ensuring additional safety and integrating ballast tanks for improved stability. The propulsion system consists of diesel engines, two azimuth thrusters, and a bow thruster, enabling precise manoeuvrability even in constrained waterways [10]. This vessel served as a crucial reference in determining optimal design parameters for the new CEMT Class II vessel, ensuring its compatibility with existing infrastructure while maintaining efficiency and safety. Its container capacity, double-hull structure with ballast tanks, and propulsion system featuring diesel engines, azimuth thrusters, and a bow thruster provided a robust basis for developing a new vessel.

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Figure 3-2: Neo-Kemp II BV: a 32 TEU inland container vessel [10], [11]

Initial Design Development

Using insights from benchmarking and regulatory frameworks, an initial concept framework was built. The cargo hold was sized to carry 24 TEU with appropriate clearances. Structural elements such as bulkheads and framing systems etc. were defined in accordance with classification standards. The layout ensured access to maintenance zones and compliance with loading safety criteria.

A series of design loops was carried out, adjusting main dimensions and system layout based on simulated hydrostatic performance, weight distribution, and internal volume constraints. The overall vessel dimensions including length, beam, draught, and freeboard were optimized using a spiral design approach. This approach enabled ongoing adjustments based on input from simulation, structural analysis, and partner feedback. Deliverable D2.1 was instrumental in defining the design envelope, ensuring compatibility with real-world navigation routes, port infrastructure, and bridge heights.

A major consideration was the accommodation of all propulsion and navigation equipment within the vessel geometry. Inputs from partners SO and MR specifically regarding the dimensions and arrangement of switch cabinets, inverters, converters, and thrusters were essential for designing the aft and fore ship sections with sufficient clearances and access for maintenance service. This allowed the integration of full-electric propulsion without compromising container capacity.

Structural Design

A transverse framing system was selected to ensure material efficiency and strength, especially in the cargo hold where alignment with container corners was crucial. Frame spacing and scantlings were adapted from reference vessels and cross-checked against

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Bureau Veritas and ES-TRIN regulations. The floor and girder spacing were optimized to support container loads while achieving an efficient weight-to-strength ratio.

The hull form was refined iteratively to optimize hydrodynamic performance. A 3D model was developed in Rhino 3D [12], and hydrodynamic assessments using Orca3D [13] focused on evaluating hydrostatics, estimating weight distribution, and performing preliminary stability assessments. The bow shape was optimized to reduce wave-making resistance and improve flow entry, while the stern geometry was tailored to ensure smooth water inflow to the azimuth thrusters, minimizing turbulence and maximizing propulsion efficiency. Using the spiral methodology, the hull design was progressively adjusted through performance evaluations. The results of this phase formed the baseline for further CFD simulation and optimization tasks to be conducted in Task 4.3.

Ballast Tank Functionality and Adaptation

The double bottom and double side structures were dimensioned by comparing with similar vessels. Multiple ballast tanks were integrated to support stability management during varying load conditions. These tanks also enable air draft reduction when passing under bridges in tidal waterways - a specific operational scenario for which the vessel was optimized. Ballasting strategies were tested using Orca3D.

3D - modelling and Structural Evaluation

The detailed 3D model played a central role in guiding the development of the vessel concept. It enabled the continuous assessment of compartment layouts, structural reinforcements, and system integration throughout the entire design process. Early iterations of the model served as a spatial validation tool to ensure that all components including propulsion equipment, batteries, and control cabinets could be positioned with appropriate access for maintenance and inspection. The 3D model also supported progressive updates to key structural features, such as bulkhead spacing, deck reinforcement zones, and ballast tank arrangement. These updates were essential for validating system fit, verifying compartmentalization for fire safety, and ensuring effective structural continuity.

Simulations conducted in Orca3D formed a critical feedback loop, allowing for real-time evaluation of design changes. At each major design iteration, hydrostatics, stability, resistance, and load distribution analyses were carried out. These simulations were essential not only for validating safety margins and loading conditions, but also for tracking changes in displacement, centre of gravity, and overall trim behaviour as the vessel concept evolved.

Scantling calculations were performed using the latest Bureau Veritas rules for inland navigation vessels [6]. Structural requirements were evaluated for decks, shell, side- and bottom plating, girders, frames, bulkheads, girders, hatch coamings, stiffeners, etc. In addition, reinforcement zones were defined around openings, and battery container interfaces to ensure structural integrity under operational and accidental load cases. Plate thicknesses and stiffener profiles were selected based on load-bearing demands, corrosion margins, and fatigue considerations. Both conventional and high-tensile steel options were assessed, with final selections guided by a balance between strength, weight efficiency, and cost-effectiveness. Plate thicknesses were optimized for areas under high stress, with both standard and high-strength steel options evaluated for cost-effectiveness.

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Collaborative Design and Feedback Integration

The concept design process was carried out in close collaboration with project partners, ensuring that the vessel architecture reflected technical, operational, and regulatory inputs. Regular design review meetings and shared access to digital models facilitated a continuous exchange of information and ideas.

Partner SO contributed propulsion system layouts, including detailed spatial and interface requirements for thrusters, inverters, and control cabinets. These inputs were critical for optimizing the aft section layout. DST played a central role in stability analysis and simulation-based validation. This included assessing the effects of container loading schemes, ballast tank operation, and ZES battery packs placement on hydrostatic balance, GM, and trim. Recommendations from DST led to several key adjustments in tank configuration and load distribution strategy.

This collaborative and iterative process ensured that technical feasibility, automation integration, and operational realism were fully embedded in the vessel concept. It also allowed early identification of potential design conflicts, enabling proactive solutions through coordinated refinements. As a result, the vessel configuration emerging from Task 4.2 reflects a comprehensive, cross-disciplinary approach to modern inland vessel design.

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4 DEVELOPMENT OF VESSEL CONCEPT

4.1 INTRODUCTION

The development of the AUTOFLEX vessel concept is based on a structured and iterative process tailored to meet the complex demands of future inland waterway transport - namely, full electrification, uncrewed operation, modular cargo flexibility, and infrastructure compatibility. This chapter outlines how a design concept evolves from abstract constraints and operational targets into a concrete, technically validated proposal.

The chapter builds directly on the methodological framework introduced in Chapter 3 and expands it into the conceptual phase of vessel definition. It integrates regulatory guidelines (e.g., ES-TRIN [7], Bureau Veritas [6]), functional requirements (e.g., remote operability, cargo modularity, energy efficiency), and logistical constraints (e.g., lock and bridge dimensions within CEMT Class II corridors) into a consistent design logic.

The process begins with the identification of key boundary conditions, derived from previous work packages (notably D2.1 and D4.1), and translates them into principal design parameters such as main dimensions, weight distribution, and the required space for technical systems such as batteries, propulsion units, and control equipment. Reference vessel benchmarking (see Chapter4.2) provides a tangible starting point for dimensioning, while the subsequent concept development follows the steps of the ship design spiral, emphasizing refinement through simulation and comparison.

The concept is developed step by step in different technical areas: the hull and structure, the layout of the electric drive system, the automation components, and the placement of battery containers. During this phase, the design must remain technically practical, follow the relevant rules, and use space efficiently. Project partners supported this process with key inputs - SO helped with the propulsion layout, MR with battery integration, and DST with stability checks. Their contributions were important to make the design both innovative and realistic for actual use.

The final part of the chapter highlights how the concept integrates into the broader context of inland shipping logistics. It demonstrates the vessel's potential for scalable and flexible deployment in underutilized waterway networks, aligning with the AUTOFLEX objective of reactivating small-scale cargo routes with zero-emission, smart vessels.

Through this chapter, the reader is provided with a detailed account of how the AUTOFLEX design has evolved into a mature and technically consistent vessel configuration ready for further optimization in Task 4.3.

4.2 REQUIREMENTS DEFINITION

The conceptual design of the AUTOFLEX vessel is based on a set of clearly defined requirements derived from stakeholder expectations, regulatory constraints, and operational needs. These requirements were identified through the analyses conducted in Task 2.1 – (Design Basics) and Task 4.1 (Design Impacts) and were further refined and confirmed during coordination meetings with project partners. They form the foundation for all subsequent design activities.

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Functionally, the vessel must support full uncrewed operation at CCNR Autonomy Level 3 and offer a flexible cargo configuration that accommodates both standard ISO containers and swappable ZES battery modules. To enable sustainable transport, the vessel must minimize energy consumption and be capable of long-range missions powered entirely by batteries. Digital integration with fleet management systems and reliable remote control are also considered essential features.

From an operational perspective, the vessel is designed for use on small inland waterways, specifically those classified as CEMT Class II (see Table 4-1). This includes navigation through narrow canals, locks, and under bridges often with restricted clearance. As defined in D2.1, this also includes operation in Zone 2 waterways (see Figure 4-1), particularly in estuary navigation routes, characterized by wave heights of up to 1.2 m [9].

To operate effectively in such conditions, the vessel must feature:

- A compact overall footprint
- Minimal draught for shallow water access
- A favourable length-to-beam ratio for increased manoeuvrability
- Compatibility with temporary terminals, mobile distribution centres (MDCs), and swap-and-charge hubs (S&C)
- Structurally adapted features for operation in Zone 2, including increased freeboard, a raised and reinforcement bow section and bulwark (Schanzkleid) for improved safety and seaworthiness in exposed sections of the waterway

These characteristics were further refined through scenario-based evaluations (Use Cases) in Task 2.1.

Regulatory Requirements

Compliance with regulatory standards is a fundamental requirement in the AUTOFLEX concept. The following frameworks were used:

- ES-TRIN 2025 - Technical standards for inland vessels issued by CESNI [7]
- ECE/TRANS/SC.3/172/Rev.1 - United Nations recommendations for inland navigation vessels [9]
- Bureau Veritas NR 217 (2021) - Rules for structural design, material selection, and safety systems [6]

In addition, automation-related features were aligned with CCNR [14] and CESNI guidelines [15] for autonomous vessels, ensuring that safety and control elements are appropriately integrated into the concept.

Freeboard Determination

For regulatory purposes, the vessel is classified as a Type C vessel according to ECE/TRANS/SC.3/172/Rev.1. Type C vessels are open-type vessels, including those with uncovered or partially covered cargo hatches. According to Article 4-4.2.4 of the standard, the minimum freeboard required for vessels operating in Zone 2 is:

- Minimum freeboard: 600 mm

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- Minimum combined height of freeboard and coaming for open-deck vessels: 1000 mm [9]

These requirements were applied as critical constraints during hull development and were used to determine the vertical position of the main deck and container base level. The freeboard specification also informed the decision to raise the bow and integrate bulwarks in the forward area, ensuring compliance with wave impact and operational safety criteria in Zone 2 conditions. It also guided the configuration of ballast tanks and the overall hull height, ensuring sufficient air draft clearance under bridges. These decisions reflect the regulatory demands set by ECE/TRANS/SC.3/172/Rev.1 as well as operational safety for navigation in Zone 2 areas.

Together, these functional, operational, and regulatory requirements define the design envelope for the AUTOFLEX vessel and guide the integration of all major systems and features.

Table 4-1: Classification of European inland waterways [16]

Classification of European inland waterways – Classification des voies navigables européennes – Классификация европейских внутренних водных путей

Waterway type / Type de voies navigables / Тип водных путей	Waterway class / Classes de voies navigables / Класс водных путей		Designation / Dénomination / Наименование	Motor vessels and barges – type of vessel: general characteristics / Automoteurs ou chalands – type de bateau : caractéristiques générales / Самоходные суда и баржи – тип судна: общие характеристики: Max. length / Longueur max. / Максим. длина L(m)	Max. beam / Largeur max. / Максим. ширина B (m)	Draught / Tirant d'eau / Осадка d (m)[7]	Tonnage / Tonnage / Тоннаж T (t)	Pushed convoys – type of convoy: general characteristics / Convois poussés – type de convoi : caractéristiques générales / Толкаемые составы – тип состава: общие характеристики	Length / Longueur / Длина L(m)	Beam / Largeur / Ширина B (m)	Draught / Tirant d'eau / Осадка d (m)[7]	Tonnage / Tonnage / Тоннаж T (t)	Min. height under bridges / Hauteur minimale sous les ponts / Миним. высота под мостами H (m)[2]	Symbol on maps / Symboles sur les cartes / Обозначение на карте
of regional importance / d'intérêt régional / Регионального значения	west of Elbe / à l'Ouest de l'Elbe / к западу от Эльбы	I	Barge - Péniche - Баржа	38.50	5.05	1.80-2.20	250-400						4.00	
		II	Kampine - Campinois - 'Кампин'	50-55	6.60	2.50	400-650						4.00-5.00	
		III	Gustav Kœnigs - 'Густав Кёнигс'	67-80	8.20	2.50	650-1000						4.00-5.00	
	east of Elbe / à l'Est de l'Elbe / к востоку от Эльбы	I	Gross Finow - 'Гросс Финоу'	41	4.70	1.40	180						3.00	
		II	Type BM-500 - Типа БМ-500	57	7.50-9.00	1.60	500-630						3.00	
		III	[6]	67-70	8.20-9.00	1.60-2.00	470-700		118-132	8.20-9.00	1.60-2.00	1000-1200	4.00	
of international importance / d'intérêt international / Международного значения		IV	Johann Welker - 'Йоганн Велкер'	80-85	9.50	2.50	1000-1500		85	9.50[5]	2.50-2.80	1250-1450	5.25/7.00[4]	
		Va	Large Rhine vessels-Grands rhénans-большие рейнские	95-110	11.40	2.50-2.80	1500-3000		95-110[1]	11.40	2.50-4.50	1600-3000	5.25/7.00/9.10[4]	
		Vb							172-185[1]	11.40	2.50-4.50	3200-6000		
		VIa							95-110[1]	22.80	2.50-4.50	3200-6000	7.00/9.10[4]	
		VIb	[3]	140.00	15.00				185-195[1]	22.80	2.50-4.50	6400-12000	7.00/9.10[4]	
		VIc							270-280[1] 195-200[1]	22.80 33.00-34.20[1]	2.50-4.50	9600-18000	9.10[4]	
		VII						[8]	285	33.00-34.20[1]	2.50-4.50	14500-27000	9.10[4]	

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Figure 4-1: Overview of Zone 2 navigation areas relevant to Use Case 1 and Use Case 2, based on data from Deliverable D2.1 (p. 38)

4.3 REFERENCE VESSEL DATA AND DERIVATION OF MAIN PARTICULARS

To support the development and validation of the AUTOFLEX vessel, a comprehensive dataset of existing inland vessels was compiled. This dataset includes 12 representative vessels that span a range of conventional and modern CEMT Class II designs, including several from the Neo-kemp II type series (see Figure 3-2). Among these is also the AUTOFLEX reference designs itself. The selection was made to reflect variation in shipbuilding strategies, cargo capacities, propulsion systems, and structural layouts (see Table 4-2).

The dataset enables a comparative approach that reveals where the AUTOFLEX design falls within or diverges from established industry norms. It provides a basis for understanding typical hull proportions and for evaluating how the AUTOFLEX vessel aligns with standard practice regarding size, power, capacity, and geometry.

Key Parameters and Dataset Composition

The main parameters captured for each vessel include:

- Length [m], L
- Beam [m], B
- Draught [m], T

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- Tonnage[2] [t], $Tonnage$
- TEU capacity (where available)
- Installed propulsion power [kW]

These parameters offer a representative profile of vessel dimensions, loading capacity, and power installation. They also form the basis for further normalization through the calculation of unit values.

Table 4-2: Reference vessels data

Vessel Name	Class	Length [m]	Beam [m]	Draught [m]	Tonnage [t]	Power [kW]	Capacity TEU	Links
AUTOFLEX CEMT II vessel (initial design)	CEMT II	53.00	6.28	2.00	485	380	24	Ch. 5
AUTOFLEX CEMT II vessel (improved design)	CEMT II	53.00	6.60	1.93	506	380	24	Ch. 10
Alcor	CEMT II	63.00	7.04	2.54	625	447	24	[17]
Anna	CEMT II	49.50	6.60	2.44	513	223		[18]
Elsa	CEMT II	60.00	7.08	2.31	641	395		[19]
Empresa	CEMT II	62.80	7.15	2.50	650	447	N/A	[20]
Kempenaar standard	CEMT II	55.00	6.60	2.59	655	287	24	[21]
Oskar Teubert	CEMT II	53.00	6.30	2.00	562	200	N/A	[22]
Schavuit	CEMT II	66.98	7.44	2.50	697	521	N/A	[23]
Neo- Kemp	Neo-kemp	63.00	7.00	2.50	550	400	32	[21]
HKH Prinses Maxima	Neo-kemp II BV	62.90	7.03	2.11	649	601	48	[24]
Kreefeld	Neo-kemp II BV	63.00	7.03	2.30	552	604	48	[25]
Sjors	Neo-kemp II BV	62.90	7.03	2.92	849	550	48	[26]
Versteijnen	Neo-kemp II BV	63.00	7.03	2.11	553	472	48	[27]

Derivation and Use of Unit Values

To enable a consistent comparison across vessels of different sizes and configurations, the following dimensionless unit values were calculated:

- L/B – Length-to-Beam ratio
- L/T – Length-to-Draught ratio
- B/T– Beam-to-Draught ratio
- $L/Tonnage$ – Length-to-Tonnage ratio

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[2] *The term "tonnage" in this report refers to the vessel's deadweight. The term "tonnage" is commonly used in inland navigation to indicate loading capacity.*

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- *L/P* – Length-to-installed Power ratio

Interpretation of Unit Value Diagrams

These ratios transform main particulars of the vessels into meaningful relationships that indicate key aspects of hull form efficiency, cargo space utilization, and propulsion performance. For example, the *L/B* ratio describes the vessel's slenderness relative to its beam, which affects both water resistance and manoeuvrability. The *L/T* ratio reflects the relation between vessel length and draught, which is important for balancing cargo capacity with shallow-water capability. The *L/P* ratio shows how much propulsion power is installed per metre of vessel length, helping to assess whether the propulsion system is appropriately dimensioned relative to other inland vessels etc. The unit values were plotted against ship length to assess their statistical distribution and identify relevant design trends across existing inland vessels. Outliers in the dataset were also reviewed to identify deviations caused by historical design strategies or vessel specialization. Some older ships deviate due to dated construction norms or different propulsion paradigms, while more recent examples often reflect optimisations for container handling, bulk cargo, or hybrid operations. Understanding these deviations helps define the boundaries of feasible design space and informs whether a departure from current norms supports or hinders innovation.

***L/B* Ratio:** The AUTOFLEX designs - both initial and improved - lie near the middle of the observed distribution of *L/B* values for inland vessels of similar lengths (see Figure 4-2). This confirms that the design maintains a balance between hull slenderness and hydrodynamic resistance. The trendline indicates that most vessels in the 60–70 m length range cluster around *L/B* values between 7.5 and 9.0. The AUTOFLEX values fall comfortably within this band, suggesting appropriate resistance characteristics and manoeuvrability for confined waterways. The improved design-version shows a slight increase in beam, which slightly reduces *L/B*, improving both stability and handling in tight canals while remaining within efficient hull form proportions.

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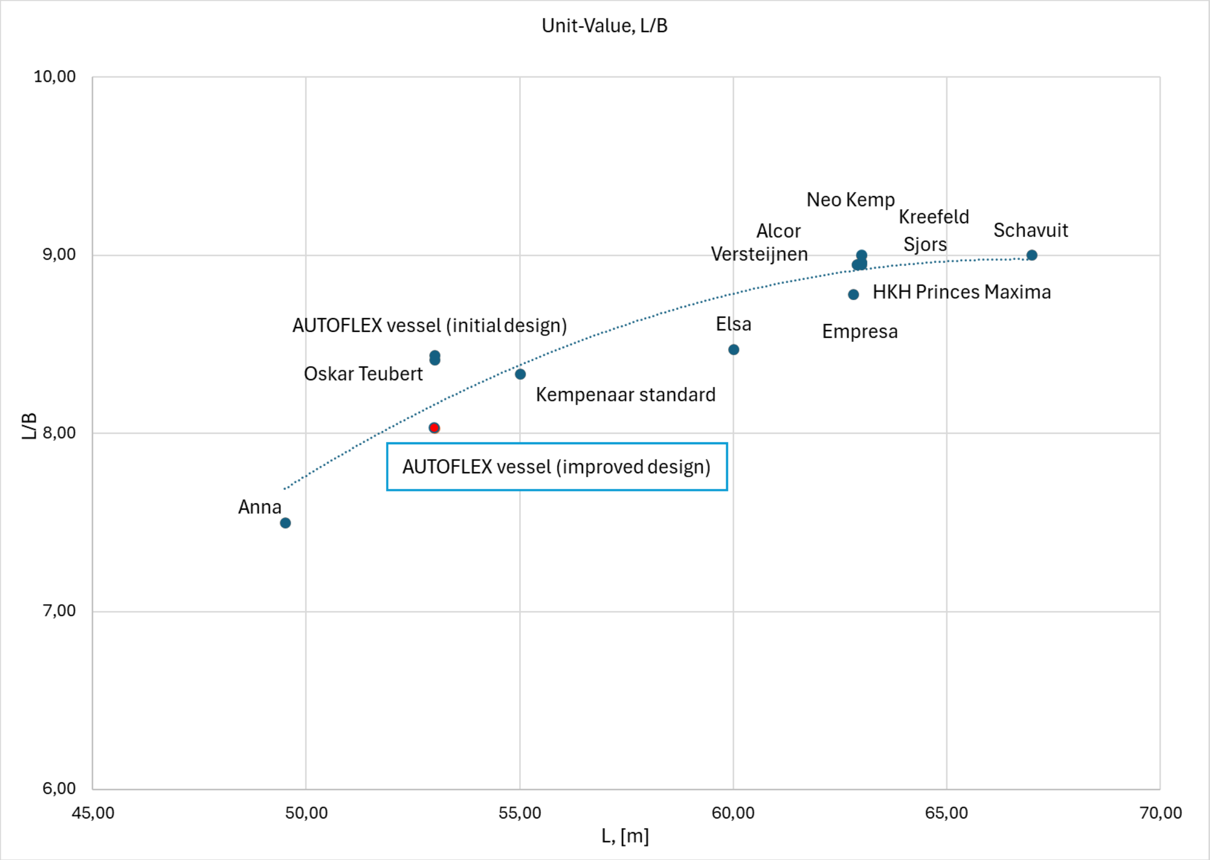

Figure 4-2: *L/B* – Length-to-Beam ratio

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***L/T* Ratio:** The AUTOFLEX concept shows *L/T* values for both the initial and improved designs that lie above the trendline, which indicates a relatively low draught in proportion to length (see Figure 4-3). This confirms the vessel's suitability for shallow-water operations, where a lower draught is crucial for safe and flexible navigation. Compared to conventional inland vessels shown in the dataset, this outcome appears to be enabled by a reduction in lightship weight. That reduction was made possible through the vessel's autonomous design approach, which eliminates the need for onboard accommodation structures, such as a crew cabin or bridge deck. As a result, structural weight is minimized, and draught can be kept low without compromising cargo space or stability.

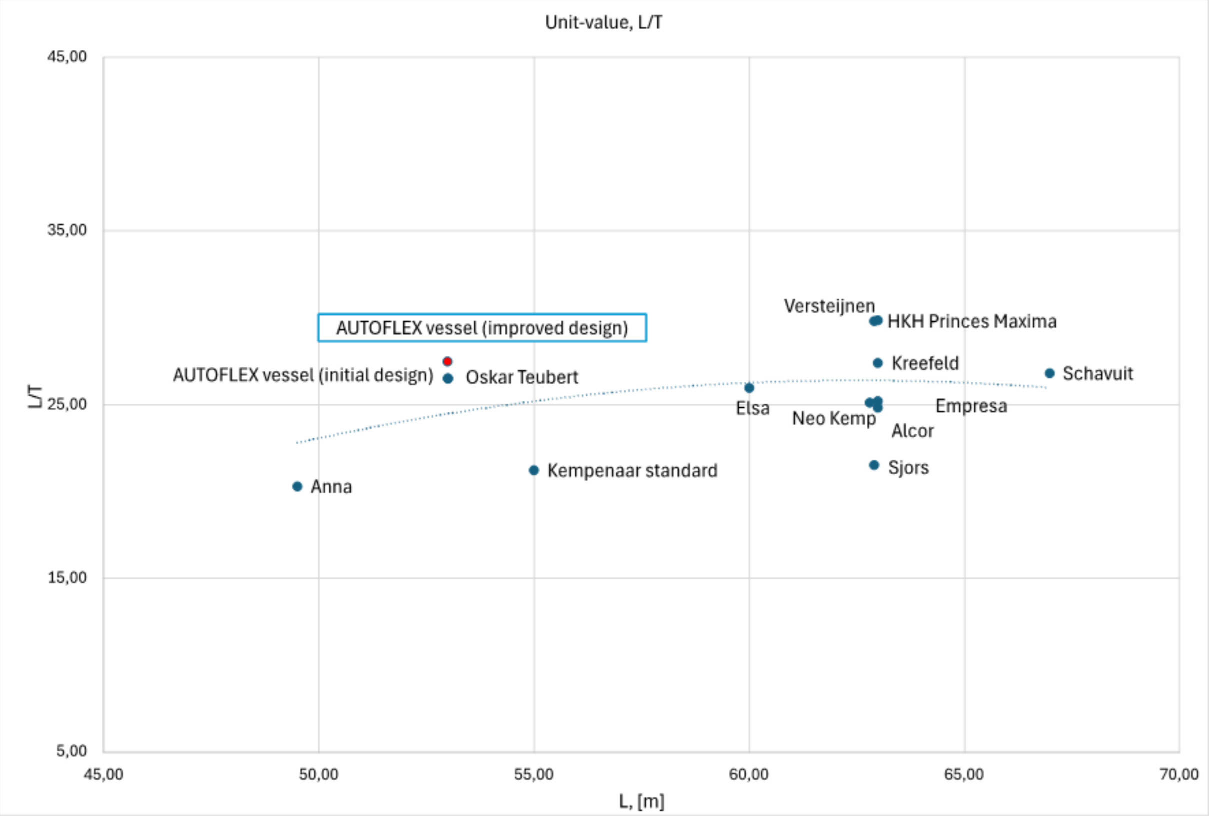

Figure 4-3: *L/T* – Length-to-Draught ratio

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***B/T* Ratio:** This metric shows a wider variation across the dataset, but AUTOFLEX designs remain well within the central distribution (see Figure 4-4). The improved AUTOFLEX vessel appears slightly more stable in transverse direction, potentially due to a broader beam or marginally reduced draught. This is consistent with the operational need for enhanced transverse stability, especially in Zone 2 navigation and under partial loading. Higher *B/T* values may indicate greater safety margins against rolling moments, which are important in autonomous operation where real-time correction may be less dynamic.

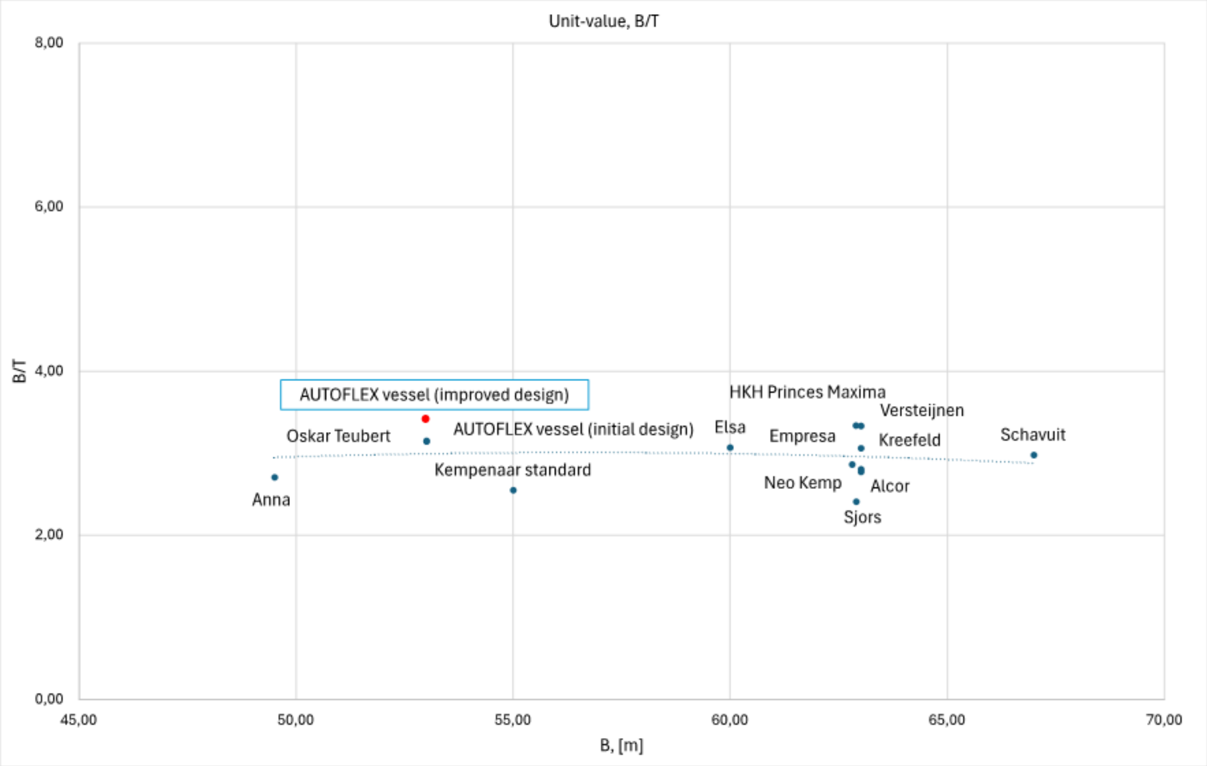

Figure 4-4: *B/T* – Beam-to-Draught ratio

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***L/Tonnage* Ratio:** The AUTOFLEX initial and improved designs lie just above the trendline, suggesting that for their length, the vessels carry slightly less tonnage than many reference ships (see Figure 4-5). While this might suggest a reduction in cargo efficiency, the design was primarily driven by the goal of minimizing draught for shallow-water operation. This was achieved by lowering the lightship weight, made possible through the omission of conventional superstructure and by designing the layout to accommodate battery containers efficiently. The result is a vessel that sacrifices some payload for improved accessibility and manoeuvrability in depth-limited waterways.

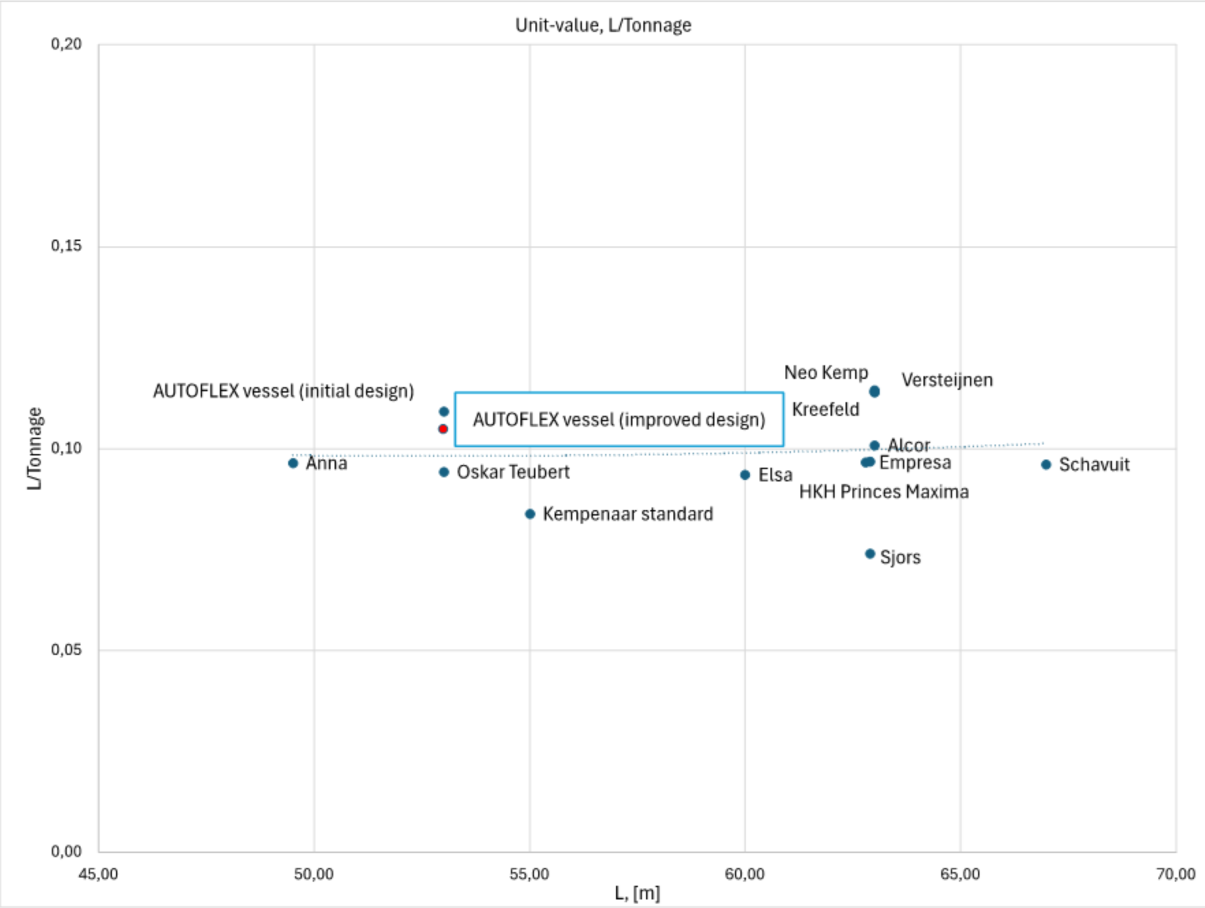

Figure 4-5: *L/Tonnage* – Length-to-Tonnage ratio

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***L/P* Ratio:** This chart reveals one of the most significant insights (see Figure 4-6). The AUTOFLEX initial and improved designs are positioned well below the trendline, indicating a noticeably lower *L/P* ratio than comparable vessels. This means that, for its length, AUTOFLEX has a relatively high level of installed propulsion power. This may reflect that, during the initial design phase, the selected propulsion power was simply chosen too high - possibly as a cautious estimate to ensure increased redundancy and reliable manoeuvrability in tidal or remote-operation scenarios. However, the deviation from the fleet trendline suggests that this oversizing may no longer be justified and presents a clear opportunity for refinement. Task 4.3 offers a good chance to revisit this decision and adjust the propulsion power based on better resistance data and real use scenarios, aiming for more efficient performance.

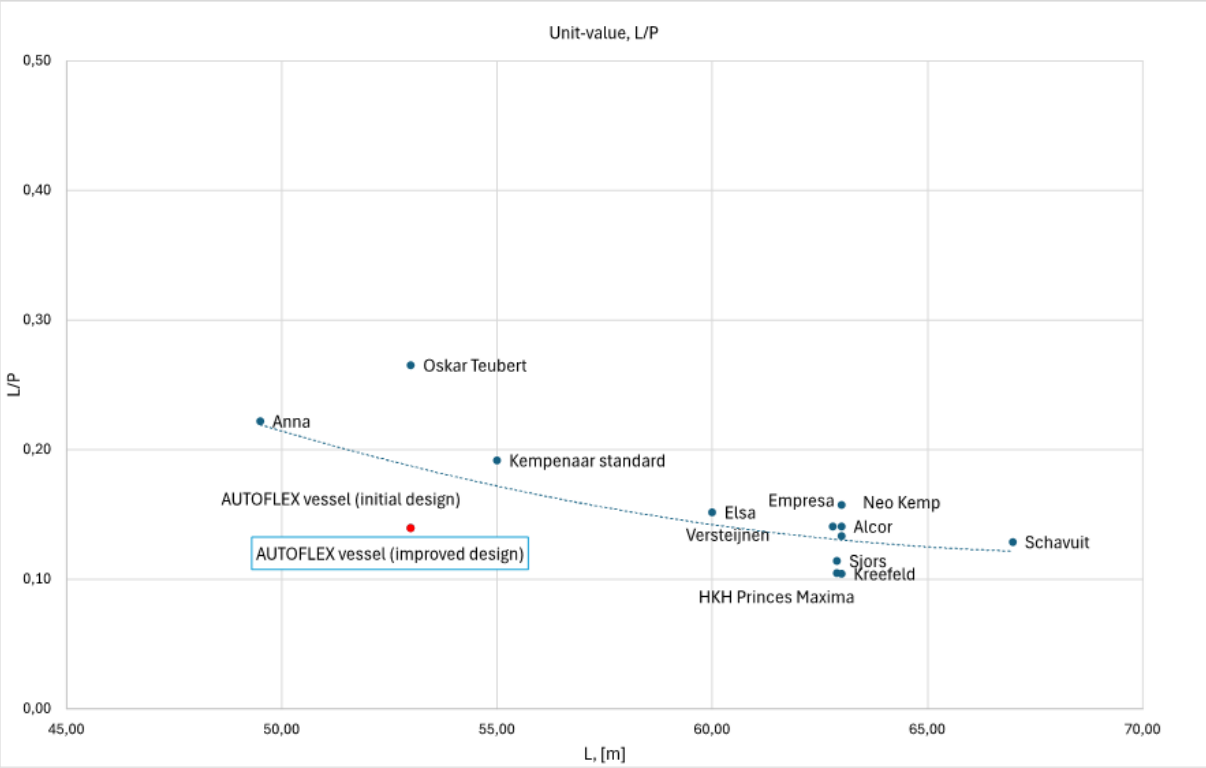

Figure 4-6: *L/P* – Length-to-Installed Power ratio

In conclusion, the AUTOFLEX vessel lies within technically and operationally credible boundaries for all considered unit values. The diagrams confirm that its hull dimensions, draught, stability etc. are well-matched to the requirements of inland navigation. At the same time, the unit value analysis clearly highlights propulsion power as a key area where future optimization is both possible and desirable. These diagrams not only validate current design decisions but will continue to be updated as more vessel data becomes available, serving as practical tools for guiding refinement.

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5 3D MODELING AND CALCULATION PROCESS

5.1 FROM CONCEPT SKETCH TO DETAILED CAD-MODEL

This section presents the early design phase that laid the foundation for the technical development of the AUTOFLEX vessel. The initial concept was first visualized through a hand-drawn sketch created during the early evaluation of operational requirements and design constraints (see Figure 5-3). This preliminary drawing captured the basic layout and proportions of the vessel, including a long, parallel midship section for container cargo, and clearly designated zones for propulsion, energy, and navigation systems.

The early sketch was influenced by several reference vessel types as well as international concept studies of autonomous cargo vessels, such as the ASKO autonomous barge (see Figure 5-1), AEGIS vessels (see Figure 5-2) and the SEAFAR initiative [28]. These references helped guide the spatial layout, particularly with respect to modular battery placement, automation zones, and integration of remote operation systems.

Figure 5-1: ASKO Autonomous barge [29]

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Figure 5-2: Vessel designs of the AEGIS project [30]

The hand-drawn layout served as both a creative and technical communication tool during the early design meetings. It acted as a visual anchor and shared reference throughout the development of the 3D CAD model, ensuring consistency in dimensions and spatial logic. Furthermore, the sketch reflects a preliminary but deliberate balance between hydrodynamic constraints (e.g., low resistance, compact waterplane) and the operational necessities of uncrewed, electrically driven inland navigation.

This early visualization ultimately informed the structured development of the detailed design model and demonstrated how technical planning and functional goals were already well aligned from the initial project stages.

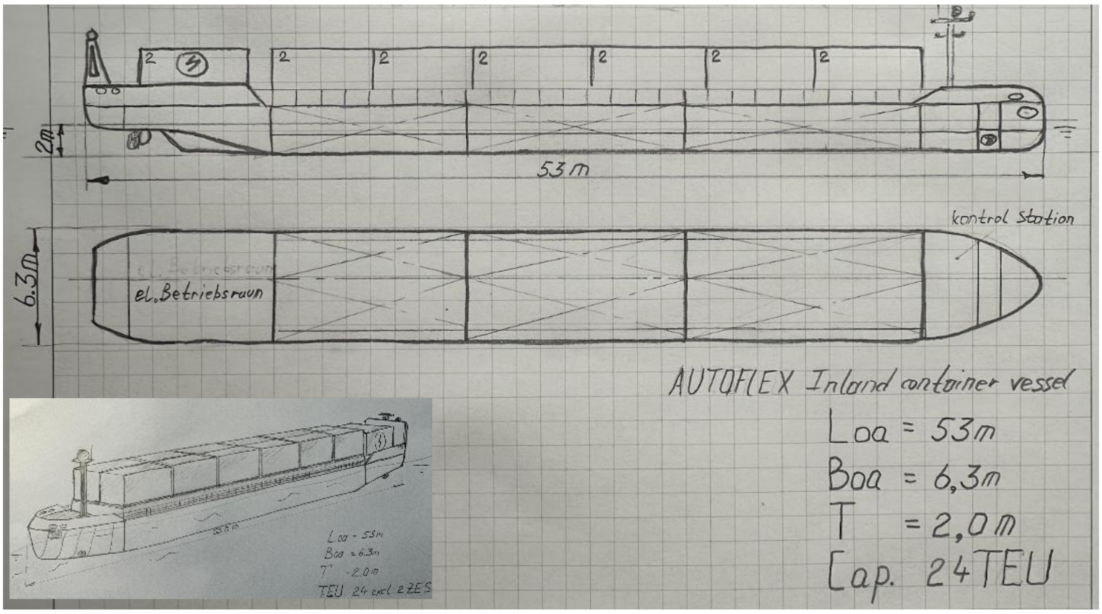

Figure 5-3: Preliminary concept sketch of AUTOFLEX CEMT II vessel

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5.2 INITIAL DESIGN

The initial 3D vessel design was developed based on findings from Deliverable D4.1 and dimensional benchmarks derived from the reference dataset (see Chapter 4.3). The concept featured a compact hull with a streamlined V-shaped bow, an overall length of 53.0 meters, and a beam of 6.3 meters - values within the CEMT Class II profile (see Figure 5-4).

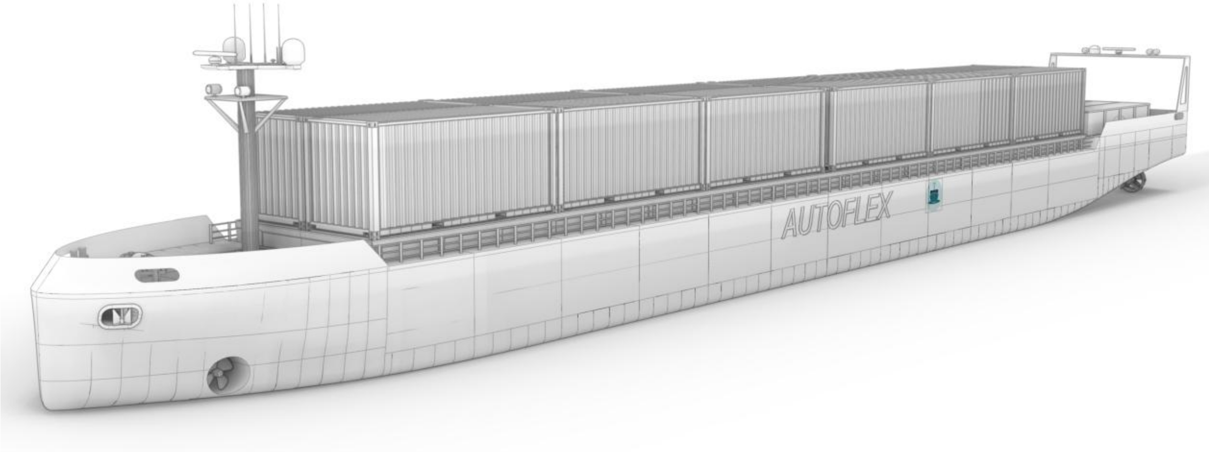

Figure 5-4: Initial design of AUTOFLEX CEMT II vessel

The structural design incorporated an elevated double bottom and double side structure to house integrated ballast water tanks (see Figure 5-5). This arrangement supports dynamic stability control in both empty and partially loaded states, which is particularly important for uncrewed operations and automated trim management.

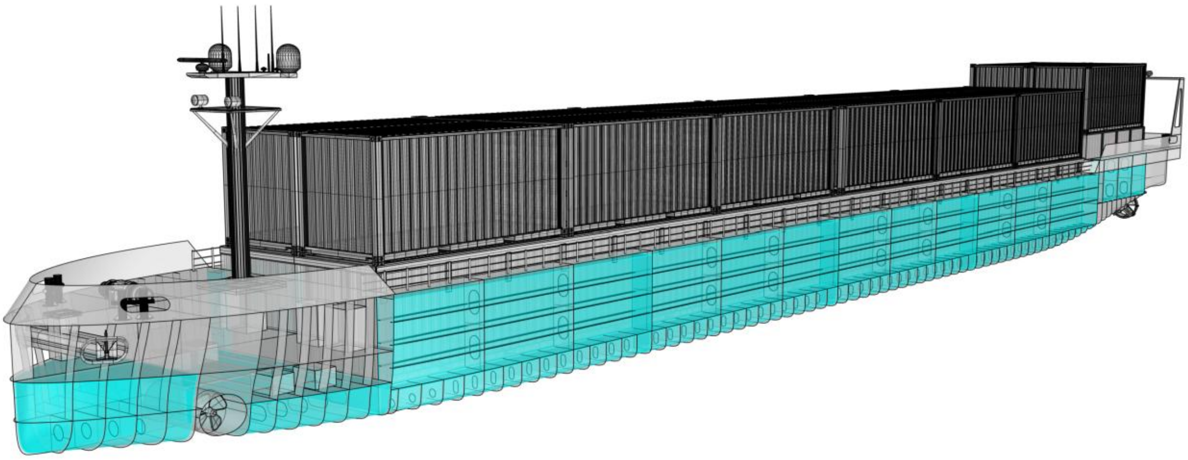

Figure 5-5: Representation of double bottom and double side structures with ballast tanks arrangement of initial design

Two options for battery placement were evaluated:

- External placement: ZESpacks mounted visibly on the poop deck (Figure 5-6)
- Internal placement: ZESpacks enclosed within a dedicated compartment on the tween deck (Figure 5-7)

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Figure 5-6: ZESpacks mounted on poop deck

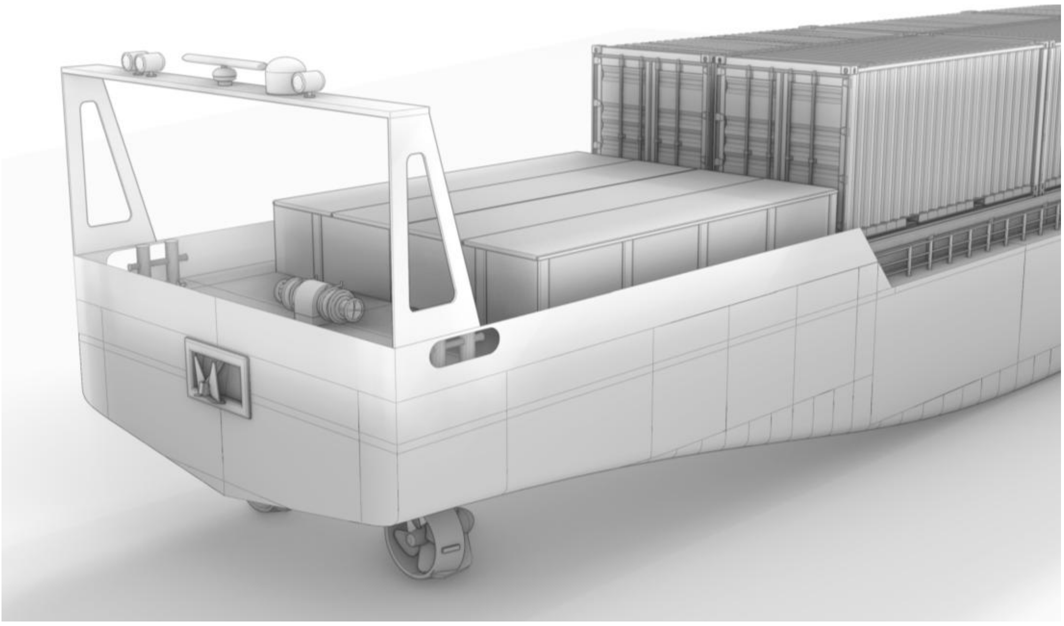

Figure 5-7: ZESpacks mounted on tween deck in enclosed compartment

The latter configuration was preferred from a stability perspective, as it improved the metacentric height by lowering the centre of gravity, particularly when the vessel is fully loaded with containers.

Cargo hold, located in the parallel midship section of the vessel, was optimized for 20-foot ISO containers and designed around a standard load distribution of 17 t/TEU [6], Pt D, Ch 2, Sec 3, p. 106. The arrangement allowed for 24 TEU, with two rows, six bays and two tears of containers stowed in the open cargo hold. Special attention was given to maintaining transverse and longitudinal stability when operating with stacked containers and ZESpacks installed in the aft section. A forward ballast tank was included to enable trim correction (see Figure 5-8).

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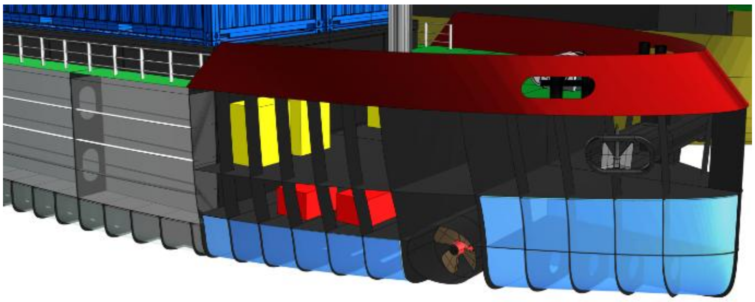

Figure 5-8: Forward ballast tanks arrangement at the bow of the vessel

The full structure was developed in 3D CAD software, including structural components, internal arrangements, and access zones. Preliminary scantling calculations followed Bureau Veritas standards [6]. Hydrostatic calculations and intact stability evaluations including *GM* assessment and trim under varying loading conditions were also performed. Resistance prediction modelling supported early estimates of propulsion power requirements.

Lightship weight was determined based on the defined structural components and preliminary outfitting assumptions.

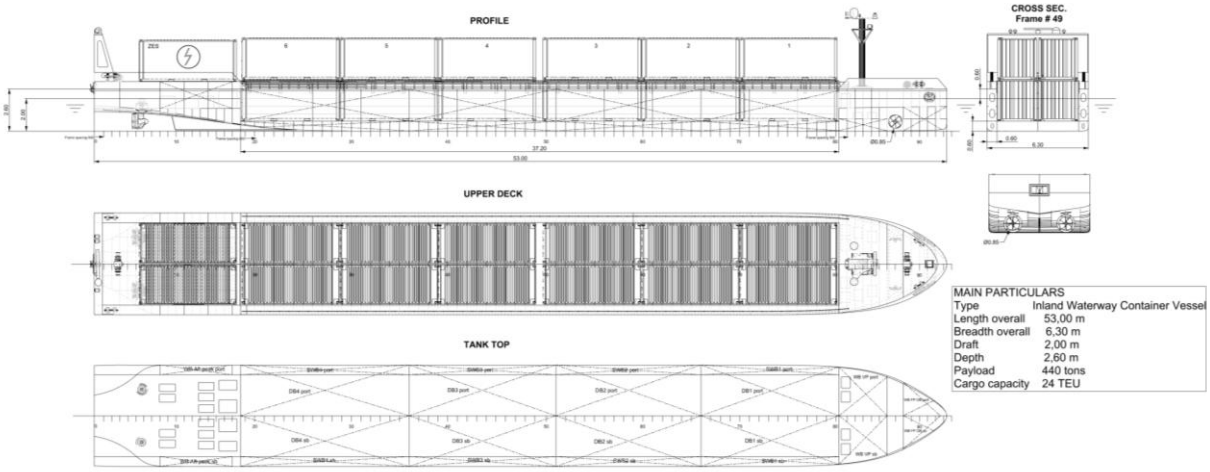

Figure 5-9: General arrangements plan of initial design of AUTOFLEX CEMT II vessel

This complete preliminary design iteration served as a foundation for evaluating space allocation, structural feasibility, and system integration. It represented the first fully developed 3D vessel model for AUTOFLEX project, including defined structural components, stability calculations, and early resistance predictions forming the basis for more refined versions developed in the following design stages.

5.3 IMPROVED DESIGN

The concept development phase included a series of refinements based on input from key project partners, as already mentioned, particularly SO and DST. SO contributed with propulsion system proposals, including specification of the required propeller diameter, which directly influenced the design of the aft section. In parallel, DST provided in-depth

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support for the assessment of stability, cargo distribution, integration of ZES battery systems, and overall structural layout (see Chapter 10).

To meet these technical requirements, the vessel design underwent multiple iterations. DST developed and provided an improved hull form (see Figure 5-10), which was subsequently adopted as the foundation for the final concept.

The refined design introduced several important changes to improve vessel stability, trim behaviour, and loading efficiency:

- The beam was increased from 6.3 m to 6.6 m to enhance transverse stability
- A fuller U-shaped bow was introduced to provide sufficient space for cargo hold
- The underwater hull volume at the aft section was expanded to provide additional buoyancy and achieve (near-)zero trim at the design draught without additional ballast

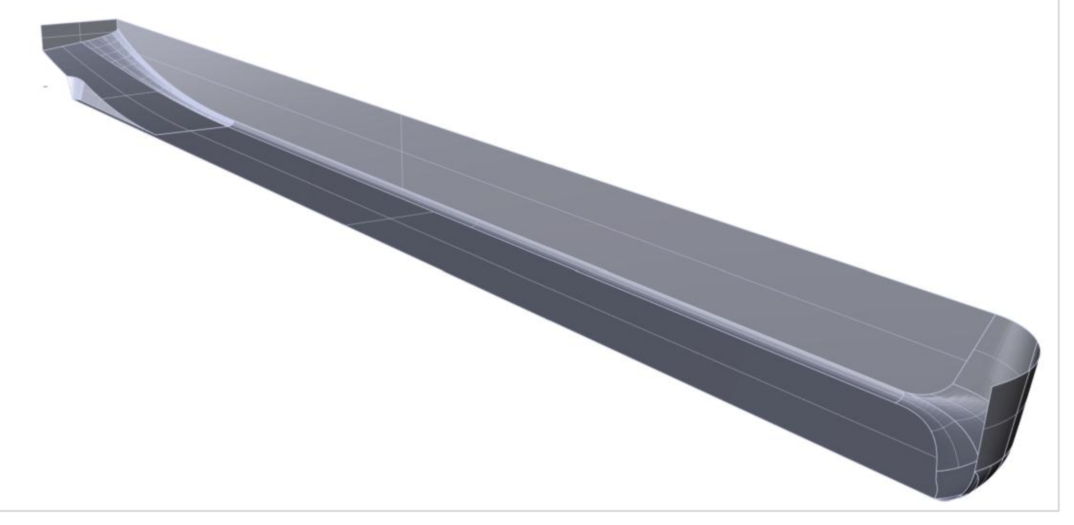

Figure 5-10: Improved hull form delivered by DST

Due to the relocation of ZES battery packs into the lower hold, containers can no longer be stacked above them. As a result, the container capacity was reduced from 24 TEU to 22 TEU. The internal layout was adapted accordingly, with adjusted structural framing to align with the hull geometry and ensure safe and efficient integration of all systems.

From this point onward, all subsequent calculations, evaluations, and technical analyses presented in this report refer exclusively to the improved design.

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6 STRUCTURAL DESIGN AND LAYOUT

Following the finalization of the improved hull form (see Chapter 5.3), the structural layout of the AUTOFLEX vessel was refined to meet the functional, regulatory, and operational requirements of an uncrewed, fully electric inland container vessel. The structure follows modern inland shipbuilding practices and integrates key zones, including cargo spaces, propulsion compartments, ballast tanks, and equipment rooms. All components are configured to support zero-emission operation, modular battery integration, and compliance with classification society regulations (e.g., ES-TRIN and Bureau Veritas).

Fore-Section Configuration

The forebody includes a forecastle deck with anchor chain box, bollards, winches, and a telescopic mast for navigation and communication systems. Below forecastle deck, tank top and stringer levels accommodate communication- and navigational electronics and an emergency battery units for redundancy [31], Sec 4, p. 31. The section is bounded by a transverse collision bulkhead and an integrated bulkhead enclosing the tunnel thruster compartment, both ensuring watertight subdivision as per classification rules [7].

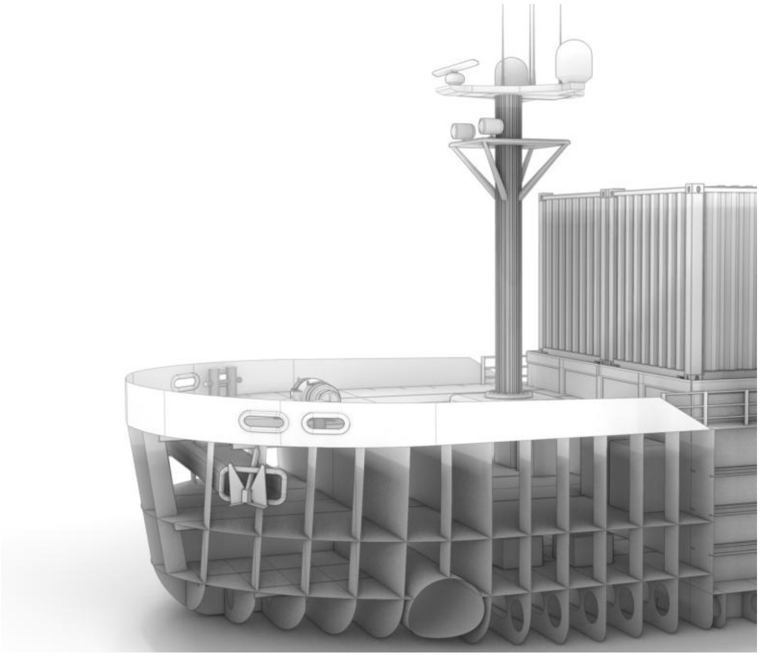

Figure 6-1: Fore-section of the vessel

Additional information on bulkheads layout is provided in Chapter 6.3 .

Cargo Hold Arrangement

The cargo hold extends from the fore-section to the aft-section and is enclosed by watertight bulkheads on all sides. It is designed as a rectangular space with smooth inner surfaces to maximize usable volume. The cargo hold is designed without hatch covers, ensuring a simplified and low-maintenance structure. Hatch coamings are set at 560 mm, in accordance with class standards [9], balancing hold accessibility and safety. The cargo hold is designed

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with clearances of 10 cm between containers in the transverse direction and 5 cm in the longitudinal direction. The clearance at the sides is ca. 20 cm, which allows for the optional placement of pallet-wide (PW) containers [32], specifically designed to fit two EUR pallets side by side. The 20-foot PW container has external dimensions of *L*: 6.058 m, *B*: 2.462 m, *H*: 2.591 m.

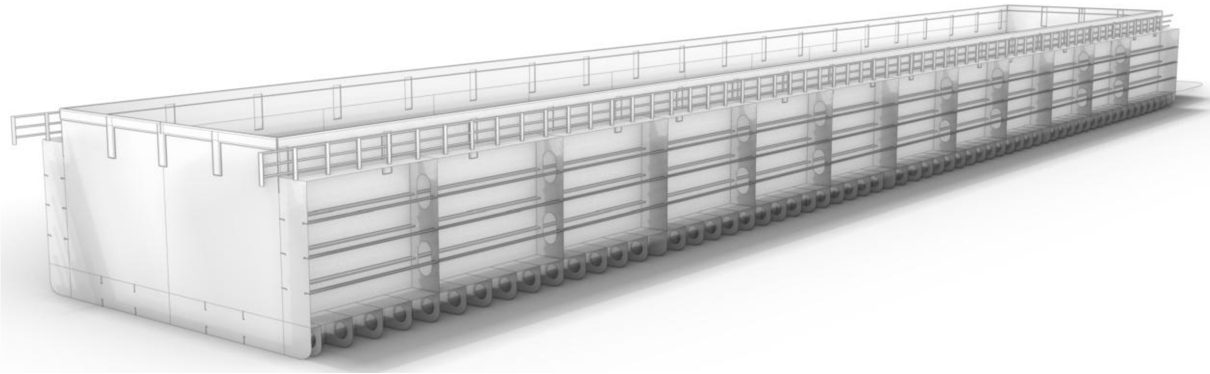

Figure 6-2: Cargo hold of the vessel

For more details, see Chapter 6.2 .

Aft-Section and Machinery Compartments

The aft section integrates two separate machinery spaces for azimuth thrusters and a compartment dedicated to power electronics, including switchboards, converters, inverters, and transformers. This configuration ensures system redundancy in line with ES-TRIN [7], Art. 11.01, p. 73 , increasing operational safety in the event of localized failures particularly relevant for electric and uncrewed vessels.

As the vessel uses azimuth thrusters for both propulsion and steering, no traditional rudder or steering gear is required. The system enables precise manoeuvrability and compact system integration.

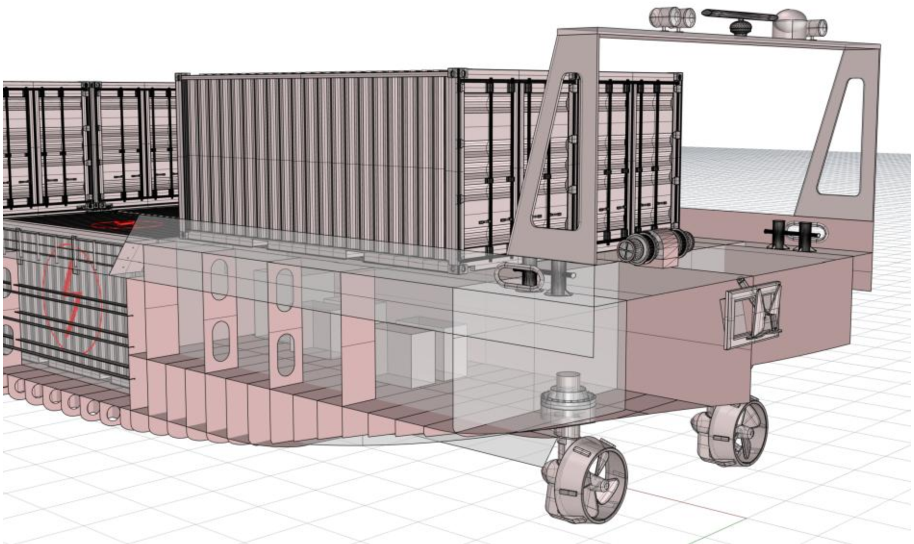

Figure 6-3: The aft section of the vessel

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Double-Bottom and Double-Side Structures

The vessel incorporates a full double-bottom and double-side construction (see Figure 6-4), integrating bottom ballast tanks and wing tanks (see Figure 6-5). This arrangement provides increased structural safety and enables flexible trim control in light-load or bridge-clearance conditions. Ballast tanks located in the bottom and wing sections are controlled automatically, enabling adaptive draft and trim regulation depending on operational conditions.

These elements are essential for navigating tidal estuaries and low-infrastructure inland corridors (see Chapter 4.2).

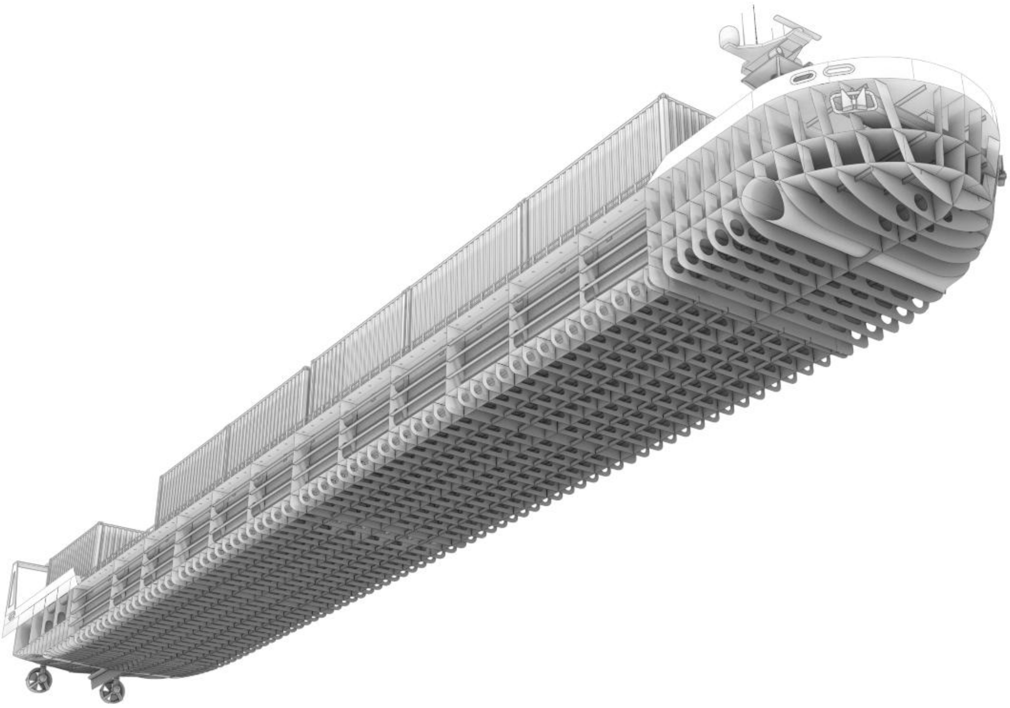

Figure 6-4: Double-bottom and double-side structures of the vessel

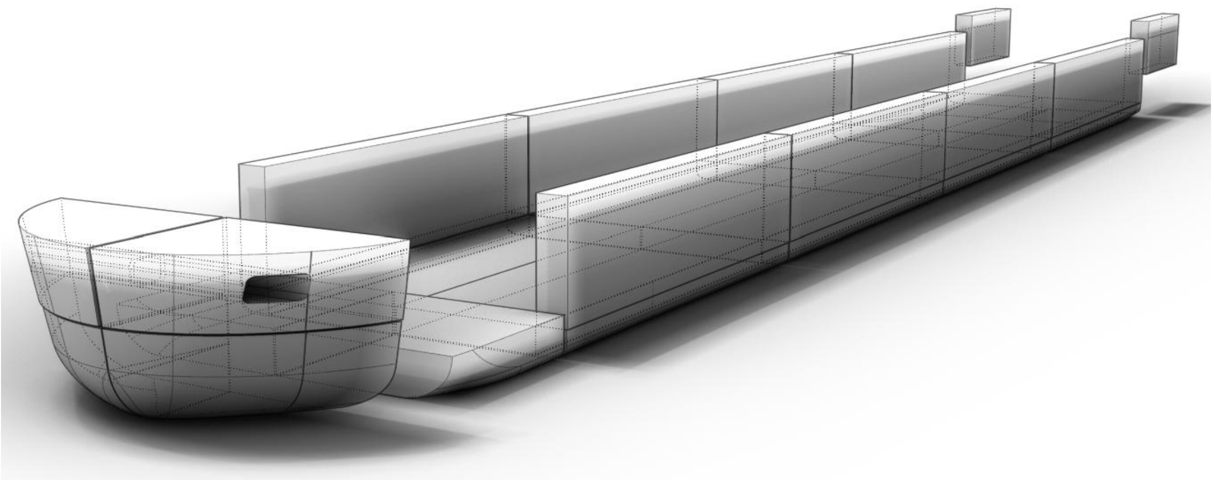

Figure 6-5: Arrangement of water ballast (WB) tanks in the vessel

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For more details, see Chapter 6.3.3.

Framing and Structural Reinforcement

Frame spacing is defined as:

- 600 mm in the cargo hold section
- 500 mm in fore and aft compartments

Floors are placed at every frame; watertight floors are installed at intersections with ballast tanks. A centre girder runs along the full vessel length. Web frames are included at 3-meter intervals to reinforce the double sides.

For more details, see Chapter 6.1 .

Propulsion System

The vessel is equipped with a fully electric propulsion system composed of:

- Two azimuth thrusters (combined 380 kW)
- One bow thruster (115 kW) for low-speed manoeuvring

The primary energy source is a 5.6 MWh supplied via two modular ZESpacks. The modularity allows for rapid battery exchange, minimizing operational downtime and enabling efficient turnaround at ports.

The fully electric propulsion system is engineered for maximum energy efficiency, extending operational range and supports noise-free, vibration-free, and emission-free navigation, aligned with inland waterway environmental standards.

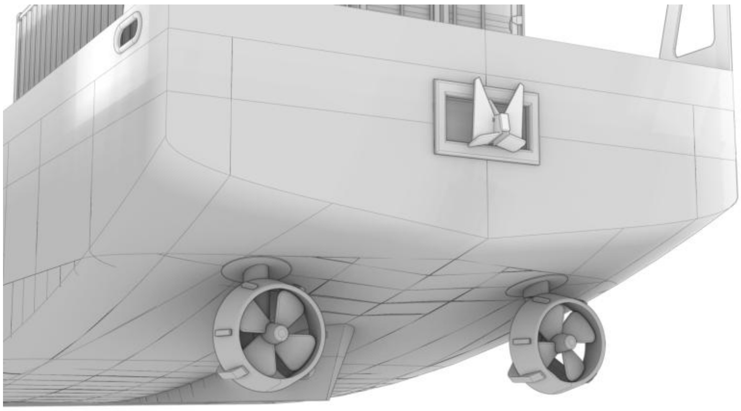

Figure 6-6: Main propulsion system. Two azimuth thrusters with total power of 380 kW and propeller diameter of 0.85 m

Cargo Handling and Logistics Integration

No onboard cargo handling systems are installed. Instead, cargo operations rely on land-based automation systems, including mobile cranes, reach stackers, and port-integrated logistics hubs. This approach simplifies onboard layout, reduces maintenance requirements, and supports streamlined intermodal transshipment. It aligns with the automation objectives of WP4 and reinforces compatibility with modular port operations.

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6.1 SELECTION OF FRAMING SYSTEM

For the design of AUTOFLEX vessel, a transverse double-bottom and double-side structure has been selected. This decision is based on the specific operational environment, expected loads, vessel performance requirements, and common practices in comparable vessels. Transverse framing (see Figure 6-7) is primarily used for ships less than 120 meters in length [33]. For a AUTOFLEX vessel, which frequently performs docking manoeuvres and often experiences side contact with the quay, this framing system provides significant advantages by absorbing lateral forces and minimizing structural stress during operations.

Frame Spacing Considerations

The frame spacing has been determined based on comparative vessel studies:

- 600 mm frame spacing in the cargo hold area
- 500 mm frame spacing in the fore and aft ship sections to reinforce areas exposed to greater structural loads and dynamic forces

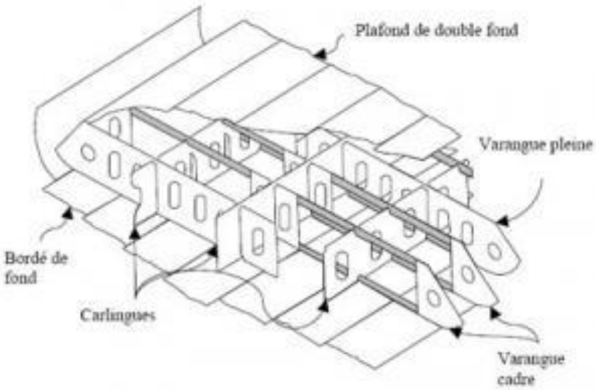

Figure 6-7: Transversely framed double bottom [33]

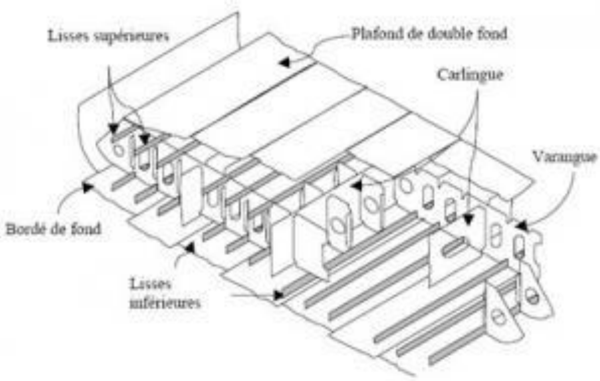

Figure 6-8: For comparison purposes: longitudinally framed double bottom [33]

6.2 DEFINITION OF CARGO HOLD AND STRUCTURAL LAYOUT

The cargo hold plays a central role in determining the overall layout and performance of an inland container vessel. Since these vessels are designed primarily for cargo transport, maximizing cargo space while ensuring structural integrity and hydrodynamic efficiency is

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crucial. The hull shape is often adapted to fit container arrangements optimally, balancing storage capacity with minimal resistance in water. While minimizing unused space does not always guarantee cost savings, it significantly enhances cargo-handling efficiency and overall vessel stability. Defining the cargo hold layout starts with analysing the longitudinal and transverse dimensional chains. The longitudinal arrangement considers the total number of container bays, spacing between them, and structural elements like bulkheads and frame spacing. The transverse dimension ensures the vessel can accommodate the required number of containers in width while maintaining sufficient clearance for securing and handling of the cargo and allowing operational flexibility. To increase cargo versatility, adequate side clearance is included, allowing for the placement of WP containers designed for euro pallets.

Longitudinal Dimensional Chain of Cargo Hold

The longitudinal dimension is determined by considering the standard length of a TEU container, which is approximately 6.06 meters. To facilitate handling and safety, a clearance of 0.05 meters between containers is maintained, along with an end clearance (between containers and cargo hold bulkheads) of 0.1 meters. The total cargo hold length is calculated as follows:

$$L_{cargo\ hold} = n \cdot Container\ length + (n-1) \cdot Clearance\ between\ container + 2 \cdot Clearance\ at\ ends$$
$$= 6 \cdot 6.06m + 5 \cdot 0.05m + 2 \cdot 0.1m = 36.81\ m$$

To align the cargo hold with a frame spacing of 600 mm - derived from analysis of reference vessels such as the CDS 532 [34] (see Figure 6-9) and similar inland vessels - the length of the cargo hold in the AUTOFLEX vessel was extended accordingly. The adjusted cargo hold length was determined as follows:

Frame spacing within cargo hold = 600 mm

Number of frames = 63

$$Length_{cargo\ hold\ new} = 62 \cdot 0.6\ m = 37.20\ m$$

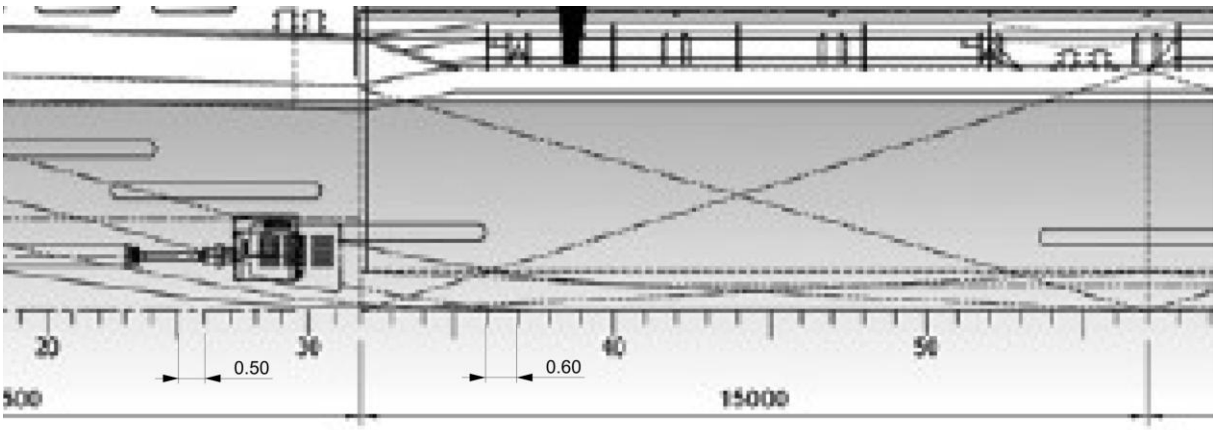

Figure 6-9: Frame spacing of 600 mm in cargo hold area of reference vessel [34]

Transverse Dimensional Chain of Cargo Hold

The transverse dimension chain is calculated by considering the standard TEU container width of 2.44 meters. A clearance of 0.1 meters between containers and clearance of ca. 0.2 meters at the sides of the cargo hold ensure sufficient spacing:

$$W_{cargo\ hold} = m \times Container\ width + (m-1) \times Clearance\ between\ containers + 2 \times Clearance\ at\ sides = 2 \times 2.44m + 1 \times 0.1m + 2 \times 0.21m = 5.40m$$

These calculations define an optimized cargo hold that maximizes storage capacity while maintaining adequate structural clearance. The clearance of 0.21 meters between containers and cargo hold walls on each side allows for the placement of two 20' PW containers ($W_{PW} = 2{,}462$ mm) in every bay [32], expanding the vessel's cargo versatility. To ensure safety and structural integrity, the cargo hold is fully enclosed by watertight bulkheads at the forward, aft, and lateral sides, preventing water ingress and enhancing overall vessel stability. The coaming height is set at 560 mm, in accordance with classification requirements, ensuring structural protection and facilitating secure cargo arrangements [9], p. 32.

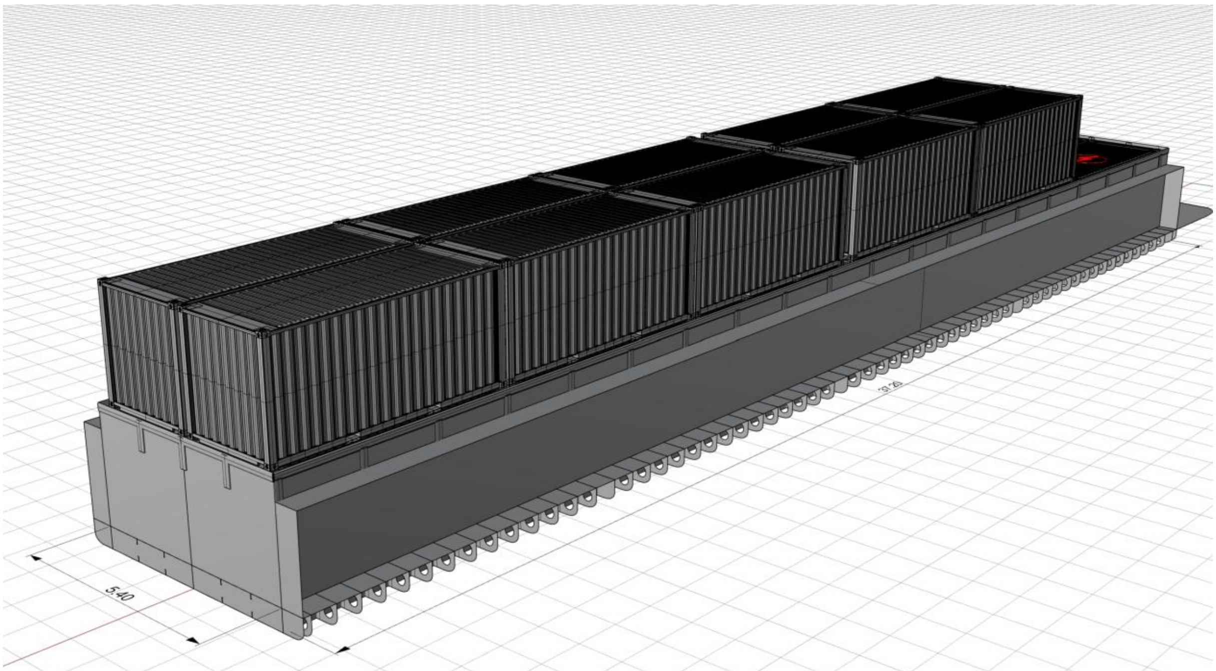

Figure 6-10: Main dimensions of the cargo hold section, bounded by watertight bulkheads

6.3 BULKHEADS POSITION

The positioning of bulkheads in the AUTOFLEX CEMT II vessel follows the structural regulations outlined in Bureau Veritas Inland Navigation Rules, [6], Pt B, Ch 2, Sec 1 and ES-TRIN 2025 [7], Article 3.03.

According to BV rules, all vessels must have at least the following transverse watertight bulkheads:

- A collision bulkhead, positioned in the forward section of the vessel
- An aft-peak bulkhead, located towards the stern to prevent water ingress from the aft compartment
- If the machinery is located aft, only one bulkhead forward of the machinery space is required
- For vessels with an electrical propulsion plant, the engine room must be enclosed by watertight bulkheads

6.3.1. COLLISION BULKHEAD

The collision bulkhead is to be positioned aft of the fore perpendicular at a distance d_C, in m ([6] Pt B, Ch 2, Sec 1, p. 41), such that:

$$0.04\, L_{WL} \le dc \le 0.04\, L_{WL} + 2$$

with a waterline length (L_{WL}) of 52.9 m, the position of the collision bulkhead:

- $d_c(min) = 0.04 \times L_{WL} = 0.04 \cdot 52.9m = 2.12m$
- $d_c(max) = 0.04 \times L_{WL} + 2 = 4.12\ m$

Therefore, the collision bulkhead should be positioned between 2.12 m and 4.12 m aft of the forward perpendicular.

Chosen location of collision bulkhead:

on frame Nr. 89, 2.6 m from forepeak, which corresponds to the minimum distance $d_C(\text{min})$ from the forward perpendicular.

The collision bulkhead is to extend up to the bulkhead deck [5], Pt B, Ch2, Sec1, p. 41.

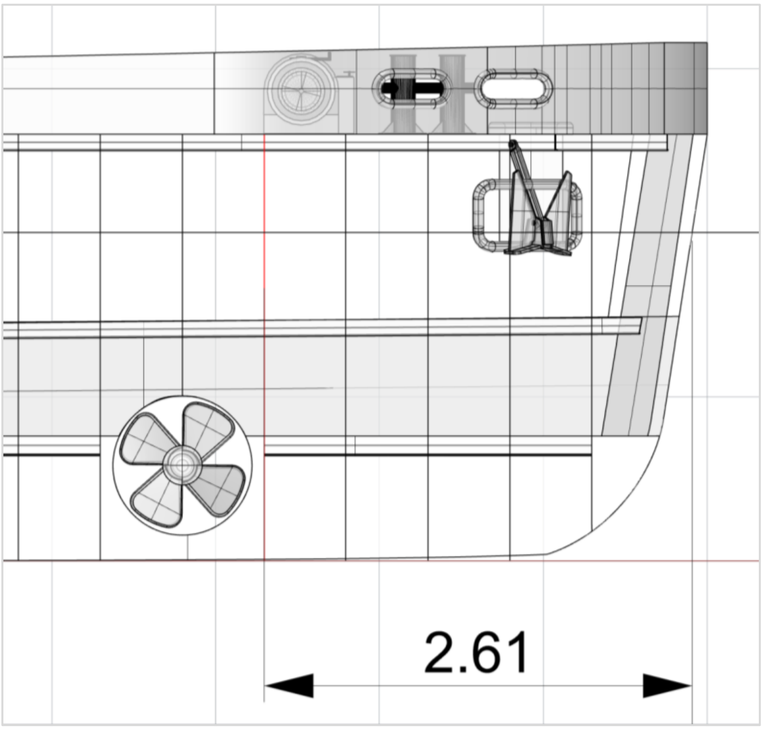

Figure 6-11: Positioning of collision bulkhead

6.3.2. AFT-PEAK BULKHEAD

For vessels exceeding 25 meters in length, an aft-peak bulkhead is mandatory for stability in case of flooding. It must be positioned at 1.4m to $0.04 \cdot L + 2m$ from the aft intersection of the hull with the maximum draught line [7], p. 15.

Calculate the maximum distance:

$$0.04L + 2 = 0.04 \times 53.00m + 2 = 2.12 + 2 = 4.12\ m$$

So, the aft peak bulkhead should be placed between 1.4 meters and 4.12 meters from the aft point of the intersection of the hull with the maximum draught line.

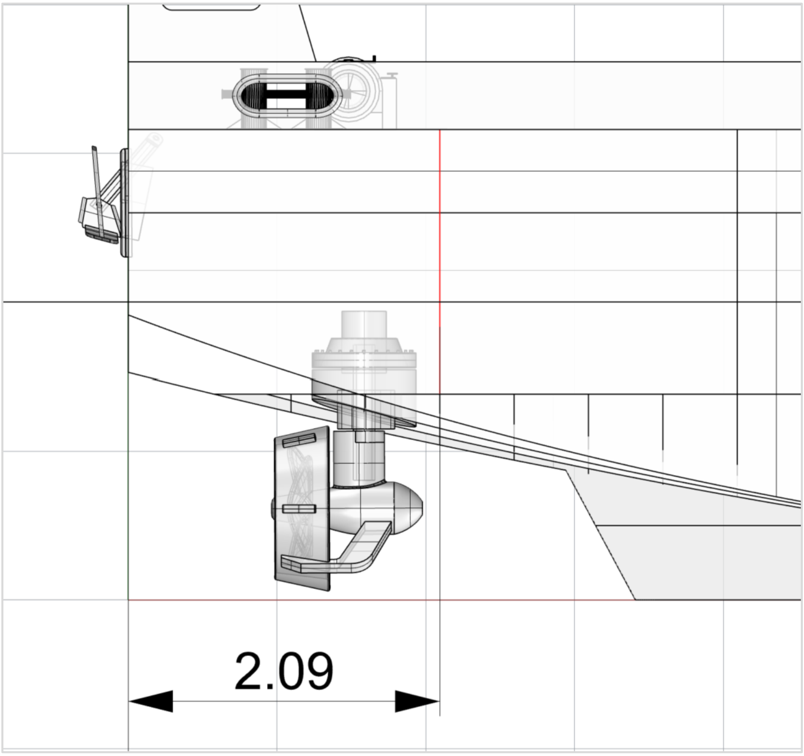

Figure 6-12: Position of aft-peak bulkhead

To align with the regulations the aft peak bulkhead has been positioned at 2.09 m at frame Nr. 4.

Table 6-1: Longitudinal dimensional chain of the vessel

	Aft ship	Machinery space	Cargo hold	Foreship
Number of frames	4	14	62	13
Frame spacing, [mm]	500	500	600	500
Room length, [mm]	2000	7000	37200	6500
Sum, [mm]	**2000**	**9000**	**46200**	**52700**

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6.3.3. DIMENSIONS OF DOUBLE BOTTOM AND DOUBLE SIDES

The following report presents the design considerations for the double bottom and double sides of the AUTOFLEX vessel, based on relevant classification society regulations. The guidelines have been thoroughly assessed and integrated into the vessel's structural design, ensuring compliance with BV rules [6] and incorporating the DST recommendations, including a 500 mm double bottom height.

The primary reference for these design principles is references: Pt B, Ch 2 & Pt B, Ch 5 & Pt D, Ch 2 from BV rules [6]. This report details the specific regulations, their direct application, and how they have been adapted within the AUTOFLEX vessel concept.

Floor spacing

Extract from [6], Pt B, Ch 5, Sec 2, p. 143:
Floors are to be fitted at every frame. Watertight floors are to be fitted:

- *in way of transverse watertight bulkheads*
- *in way of double bottom steps*
- *in general, floors are to be continuous*

Application in AUTOFLEX vessel:

- Floors are installed at every frame, ensuring structural continuity
- Watertight floors are placed strategically in areas such as transverse bulkheads and double bottom steps

Floor and girder spacing

Extract from [6], Pt D, Ch 2, Sec 3, p. 105:
As a recommendation, the floor spacing is to be such that floors are located in way of the container corners. Floors are also to be fitted in way of watertight bulkheads. Girders are generally to be fitted in way of the container corners

Application in AUTOFLEX vessel:

- Floors are aligned with container corners to optimize load distribution
- Additional floors are fitted at watertight bulkheads, reinforcing overall vessel stability
- Girders are placed beneath container corners, preventing localized stress concentrations and improving structural integrity

Centre girder

Extract from [2], Pt B, Ch 5, Sec 2, p. 143:
A centre girder is to be fitted on all vessels exceeding 6 m in breadth. This centre girder is to be formed by a vertical intercostal plate connected to the bottom plating and to double bottom top

Application in AUTOFLEX vessel:

- A continuous centre girder is installed

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- The vertical intercostal plate is welded to both the bottom plating and the double bottom top, ensuring high structural stability

Floor and girder manholes

Extract from [6], Pt B, Ch 2, Sec 1, p. 43:
Manholes are to be provided in floors and girders so as to provide convenient access to all parts of the double bottom. The size of manholes and lightening holes in floors and girders is, in general, to be less than 50 per cent of the local height of the double bottom. Where manholes of greater sizes are needed, edge reinforcement by means of flat bar rings or other suitable stiffeners may be required. Manholes may not be cut into the continuous centreline girder or floors and girders below pillars, except were allowed by the Society on a case-by-case basis

Application in AUTOFLEX vessel:

- Manholes provide accessibility for maintenance within the double bottom compartments
- Openings comply with the 50% height limit to maintain structural integrity
- Reinforcement is applied to manholes exceeding the recommended size
- No manholes are positioned within the centreline girder or beneath structural pillars

Side and inner side web frames

Extract from [6], Pt B, Ch 5, Sec 3, p. 149:
It is recommended to provide web frames, fitted every 3 m and in general not more than 6 frame spacings apart. In any case, web frames are to be fitted in way of strong deck beams

Application in AUTOFLEX vessel:

- Web frames are installed every 3 meters, ensuring maximum spacing of 6 frame intervals

Stringer Plate

Extract from [6], Pt B, Ch 5, Sec 4, p. 152:
The stringer plate is to extend between the side shell plating and the hatch coaming. In principle its width, in m, is to be not less than:

- *b = 0.1 B for single hull vessels*
- *b = 0.6 m for double hull vessels unless otherwise specified*
- *The stringer plate width and arrangements are to be so that safe circulation of people is possible*

Application in AUTOFLEX vessel:

- The stringer plate width is 0.6 meters for double hull vessels, ensuring compliance
- The layout guarantees safe crew movement and accessibility along the deck perimeter

Conclusion

The double bottom, girders, floors, and side structures in AUTOFLEX have been meticulously designed to comply with BV classification rules [6]. These modifications uphold classification standards and enhance the safety and functionality of the AUTOFLEX vessel design.

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7 SCANTLING CALCULATIONS

This chapter presents the scantling calculation for the AUTOFLEX vessel. The calculation follows the classification society rules, including Bureau Veritas [6] and ES-TRIN 2025 [7] regulations, ensuring compliance with structural integrity, safety, and operational efficiency.

7.1 MIN. PLATE THICKNESSES ACCORDING TO ES-TRIN, ARTICLE 3.02

Given Data:

Vessel length: $L_{OA} = 53.0$ m

Vessel beam: $B_{OA} = 6.6$ m

Vessel draught: $T = 2.0$ m

Frame spacing (a):

- Aft & Fore ship areas: 500 mm
- Cargo hold area: 600 mm

Structure type: double bottom and double sides

- Factors:
  - $b = 1.0$ for bottom and side plates
  - $b = 1.25$ for bilge plates
  - $c = 0.95$ for double bottom & double side construction

Minimum Thickness Calculation using ES-TRIN formula [7], Part II, Ch 3, Article 3.02, p. 13:

For vessels longer than 40 m:

$t_{min} = f \cdot b \cdot c \cdot (2.3 + 0.04L)\ [mm]$, where:

$f = 1 + 0.0013 \cdot (a - 500), for\ a > 500mm;$

$f = 1, for\ a \ \leq 500mm;$

Aft and fore ship areas ($a = 500$ mm):

- Frame spacing factor: $f = 1$
- Bottom & side plates:

$t_{min} = 1.0 \cdot 1.0 \cdot 0.95 \cdot (2.3 + 0.04 \times 53.0) = 4.2\ mm$

- Bilge plates:

$t_{min} = 1.0 \cdot 1.25 \cdot 0.95 \cdot (2.3 + 2.12) = 5.25\ mm$

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Cargo hold area ($a = 600$ mm):

- Frame spacing factor:

$f = 1 + 0.0013 \times (600 - 500) = 1.13$

- Bottom & side plates:

$t_{min} = 1.13 \cdot 1.0 \cdot 0.95 \cdot (2.3 + 2.12) = 4.75\ mm$

- Bilge plates:

$t_{min} = 1.13 \cdot 1.25 \cdot 0.95 \cdot (2.3 + 2.12) = 5.94\ mm$

Table 7-1: Minimum thicknesses of the bottom, bilge and side plates of vessel according to ES-TRIN 25

Area	Frame Spacing (mm)	Bottom & Side Plates (mm)	Bilge Plates (mm)
Aft & Fore Ship	500	4.2	5.25
Cargo Hold	600	4.75	5.94

7.2 HULL SCANTLINGS ACCORDING TO BV RULES - NORMAL STEEL FOR TRANSVERSAL FRAMING SYSTEM

7.2.1. BULKHEAD PLATING

acc. to [6], Pt B, Ch2, Sec 3, p.51:

The minimum net thicknesses of bulkheads:

Collision bulkhead:

$t_{col.\ bulkhead} = 0.026 \cdot L \cdot k^{0.5} + 3.6 \cdot s$

$t_{col.\ bulkhead} = 0.026 \cdot 53 \cdot 1^{0.5} + 3.6 \cdot 0.6 = 3.38\ \text{mm}$

Watertight bulkhead and hold bulkhead:

$t_{watertight\ bulkhead} = 0.026 \cdot 53 \cdot 1^{0.5} + 3.6 \cdot 0.6 = 3.38\ \text{mm}$

Tank bulkhead:

$t_{tank} = 2 + 0.003 \cdot L \cdot k^{0.5} + 3.6 \cdot s$

$t_{tank} = 2 + 0.003 \cdot 53 \cdot 1^{0.5} + 3.6 \cdot 0.6 = 4.33\ \text{mm}$

Summary of bulkheads thicknesses:

Collision bulkhead: 4.0 mm

Watertight bulkhead and hold bulkhead: 4.0 mm

Tank bulkhead: 5.0 mm

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7.2.2. BOTTOM PLATING

acc. to [6], Pt B, Ch 5, Sec 2, p.142,:

Bottom plating:

$t_1 = 1.85 + 0.03 \cdot L \cdot k^{0.5} + 3.6 \cdot s$

$t_1 = 1.85 + 0.03 \cdot 53 \cdot (1)^{0.5} + 3.6 \cdot 0.6 = 5.60\ mm$

Inner bottom plating:

$t_1 = 1.5 + 0.016 \cdot L \cdot k^{0.5} + 3.6 \cdot s$

$t_1 = 1.5 + 0.016 \cdot 53 \cdot (1)^{0.5} + 3.6 \cdot 0.6 = 4.51\ mm$

Ordinary stiffeners acc. to [6], Pt B, Ch 5, Sec 2, p.140:

For ($L < 120$) meters:

$t = 1.63 + 0.004 \cdot L \cdot k^{0.5} + 4.5 \cdot s$

$t = 1.63 + 0.004 \cdot 53 \cdot (1)^{0.5} + 4.5 \cdot 0.6 = 4.54\ mm$

Primary supporting members acc. to [6], Pt B, Ch 5, Sec 2, p.140:

$t = 3.8 + 0.016 \cdot L \cdot k^{0.5}$

Calculation:

$t = 3.8 + 0.016 \cdot 53 \cdot (1)^{0.5} = 4.65\ mm$

Summary of bottom plating thicknesses:

Ordinary stiffeners: 5.0 mm

Primary supporting members: 5.0 mm

Bottom plating (Transverse framing): 6.0 mm

Inner bottom plating (Transverse framing): 5.0 mm

7.2.3. SIDE PLATING

acc. to [6], Pt B, Ch 5, Sec 3, p. 146:

Ordinary stiffeners:

For L < 120 meters:

$t = 1.63 + 0.004 \cdot 53 \cdot (1)^{0.5} + 4.5 \cdot 0.6 = 4.54\ mm$

Primary supporting members:

$t = 3.8 + 0.016 \cdot 53 \cdot (1)^{0.5} = 4.65\ mm$

Side Plating (Transverse Framing):

$t_1 = 1.68 + 0.025 \cdot 53 \cdot (1)^{0.5} + 3.6 \cdot 0.5 = 4.81\ mm$

Inner Side Plating (Transverse Framing):

$t_1 = 2 + 0.003 \cdot 53 \cdot (1)^{0.5} + 3.6 \cdot 0.5 = 3.96\ m$

Summary of side plating thicknesses:

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Ordinary Stiffeners: 5.0 mm

Primary Supporting Members: 5.0 mm

Side Plating Net Thickness (Transverse Framing): 5.0 mm

Inner Side plating net thickness (Transverse Framing): 4.0 mm

7.2.4. STRINGER PLATING

Stringer Plate (Transverse Framing):

$t_1 = 2 + 0.02 \cdot 53 \cdot (1)^{0.5} + 3.6 \cdot 0.6 = 5.22\ mm$

Stringer plate thickness (Transverse Framing): 6.0 mm

7.2.5. DECK PLATING

Deck Plating (Transverse Framing):

$t_1 = 0.9 + 0.034 \cdot 53 \cdot (1)^{0.5} + 3.6 \cdot 0.7 = 5.22\ mm$

Summary of deck plating thicknesses:

Deck plating thickness (Transverse Framing): 6.0 mm

Table 7-2: Summary of plate thicknesses for S235 steel

Component	Net thickness [mm]
Collision bulkhead (Transverse)	4.0
Watertight bulkhead and hold bulkhead (Transverse)	4.0
Tank bulkhead (Transverse)	5.0
Ordinary stiffeners (Bottom Plating)	5.0
Primary supporting members (Bottom Plating)	5.0
Bottom plating (Transverse framing)	6.0
Inner bottom plating (Transverse framing)	5.0
Ordinary stiffeners (Side Plating)	5.0
Primary supporting members (Side Plating)	5.0
Side Plating (Transverse Framing)	5.0
Inner Side Plating (Transverse Framing)	4.0
Stringer Plate (Transverse Framing)	6.0
Deck Plating (Transverse Framing)	6.0

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7.3 HULL SCANTLINGS ACCORDING TO BV RULES - HIGH TENSILE STEEL FOR TRANSVERSAL FRAMING SYSTEM

Analogous to the calculations for normal steel (S235) in Chapter 7.2 , the plate thicknesses for high tensile steel (S355) were determined according to Bureau Veritas (BV) rules. The same calculation method was applied but using the material properties of S355 steel.

The results of the calculations are presented in the following Table 7-3:

Table 7-3: Summary of plate thicknesses for high tensile steel S355

Component	Net thickness [mm]
Collision bulkhead (Transverse)	4.0
Watertight bulkhead and hold bulkhead (Transverse)	4.0
Tank bulkhead (Transverse)	5.0
Ordinary stiffeners (Bottom Plating)	5.0
Primary supporting members (Bottom Plating)	5.0
Bottom plating (Transverse framing)	6.0
Inner bottom plating (Transverse framing)	5.0
Ordinary stiffeners (Side Plating)	5.0
Primary supporting members (Side Plating)	5.0
Side Plating (Transverse Framing)	5.0
Inner Side Plating (Transverse Framing)	4.0
Stringer Plate (Transverse Framing)	5.0
Deck Plating and Stringer Plate (Transverse Framing)	5.0

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8 WEIGHT REDUCTION

8.1 INTERPRETATION OF STRUCTURAL WEIGHT REDUCTION USING HIGH TENSILE STEEL

A comparative analysis was carried out to evaluate the potential for structural weight reduction of the AUTOFLEX vessel when switching from conventional mild steel (e.g. S235) to high tensile steel (e.g. S355) in the context of the AUTOFLEX CEMT II vessel design.

Theoretical Potential – based on exact calculated thicknesses:

When using the exact minimum required plate thicknesses as derived from the BV Rules (applying k = 1.0 for mild steel and k = 0.72 for high tensile steel) [6], Pt B, Sec 2, Sec 3, p. 50, a clear potential for structural weight savings becomes evident. Reductions in plate thicknesses range between $7\text{–}10\%$ for most structural areas, with some elements (e.g. bulkheads, stringer and deck plating) showing theoretical thickness reductions up to $\sim 9\%$, see Table 8-1 .

This theoretical gain translates to a calculated weight saving of up to $\sim 8 - 10\%$ in affected steel components, which in turn could improve lightship weight and energy performance.

Table 8-1: Thickness comparison – exact calculated values

Structural Element	Normal Steel (k = 1.0) [mm]	High Tensile Steel (k = 0.72) [mm]	Reduction [mm]	Reduction [%]
Collision bulkhead	3.38	3.05	0.33	9.8 %
Watertight bulkhead and hold bulkhead	3.38	3.05	0.33	9.8 %
Tank bulkhead	4.33	4.00	0.33	7.6 %
Ordinary stiffeners (bottom)	4.54	4.23	0.31	6.8 %
Primary supporting members (bottom)	4.65	4.35	0.30	6.5 %
Bottom plating	5.60	5.20	0.40	7.1 %
Inner bottom plating	4.51	4.12	0.39	8.6 %
Ordinary stiffeners (side)	4.54	4.23	0.31	6.8 %
Primary supporting members (side)	4.65	4.35	0.30	6.5 %
Side plating	4.81	4.43	0.38	7.9 %
Inner side plating	3.96	3.62	0.34	8.6 %

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Stringer plate	5.22	4.77	0.45	8.6 %
Deck plating	5.22	4.81	0.41	7.9 %

Limitations due to available Steel Plate Thicknesses:

However, in practice, shipyards and steel suppliers do not typically provide custom-manufactured plate thicknesses that match exact calculation outputs. Instead, standard commercially available plate dimensions (typically in full 1 mm increments) are used.

To reflect this, the calculated thicknesses were rounded upwards to the next standard millimetre as per classification and procurement practice, see Table 8-2. When recalculated using these rounded values, it became evident that most high tensile steel sections had to be rounded up to the same nominal thickness as their mild steel counterparts. For example, a calculated thickness of 4.23 mm for stiffeners must be rounded up to 5.0 mm identical to that of mild steel.

Table 8-2: Rounded thickness comparison

Structural Element	Rounded t, k = 1.0 [mm]	Rounded t, k = 0.72 [mm]	Δt [mm]	Reduction [%]
Collision bulkhead	4.00	4.00	0.00	0.0 %
Watertight bulkhead and hold bulkhead	4.00	4.00	0.00	0.0 %
Tank bulkhead	5.00	5.00	0.00	0.0 %
Ordinary stiffeners (bottom)	5.00	5.00	0.00	0.0 %
Primary supporting members (bottom)	5.00	5.00	0.00	0.0 %
Bottom plating	6.00	6.00	0.00	0.0 %
Inner bottom plating	5.00	5.00	0.00	0.0 %
Ordinary stiffeners (side)	5.00	5.00	0.00	0.0 %
Primary supporting members (side)	5.00	5.00	0.00	0.0 %
Side plating	5.00	5.00	0.00	0.0 %
Inner side plating	4.00	4.00	0.00	0.0 %
Stringer plate	6.00	5.00	1.00	16.7 %
Deck plating	6.00	5.00	1.00	16.7 %

As a result, the practical weight-saving effect becomes negligible, with only a few structural elements (e.g. stringer and deck plating) still showing slight reductions. The total estimated weight saving for the hull structure under these real-world conditions amounts to around 1 tonne, which is not significant in the context of total lightship weight for a vessel of CEMT II dimensions. The comparative analysis between conventional mild steel and high tensile steel shows that while theoretically significant reductions in plate thickness can be achieved, in practice, these are constrained by market availability. Plate thicknesses are standardized and typically available in full millimetre steps. Therefore, even if a calculated minimum thickness for high tensile steel is lower, the use of standardized plate dimensions often eliminates the potential reduction when rounding up is applied.

This result indicates that, for small inland vessels such as the AUTOFLEX CEMT II vessel, the use of high tensile steel offers limited benefit in terms of lightship weight reduction under realistic construction and procurement conditions.

8.2 ALTERNATIVE LIGHTWEIGHT MATERIALS

In conventional inland cargo vessels, the accommodation and wheelhouse structures - typically located on deck and built from lightweight materials such as aluminium, composite panels, or sandwich constructions - constitute a significant portion of the non-cargo superstructure. These components often require the use of high-cost materials to keep the vertical centre of gravity low, reduce propulsion power demand, and increase cargo capacity by minimizing structural mass. As discussed in PLATINA3-Project [35] , Section 3.4, p. 43, such lightweight materials are especially relevant for elevated structures like the bridge deck or crew accommodation, where steel use would otherwise introduce excessive top weight.

However, AUTOFLEX differs fundamentally in this respect. The autonomous vessel design eliminates the need for onboard crew and therefore does not require any wheelhouse or crew accommodation modules. This architectural simplification not only removes associated systems (HVAC, sanitation, furniture, insulation) but also makes the application of high-performance lightweight materials redundant in this context.

According to chapter 9.2.2 (Steel Weight), the accommodation superstructure in comparable manned CEMT II vessel accounts for approximately 43.25 tonnes of structural weight. Since the AUTOFLEX platform does not include these features, this entire mass has already been excluded from the vessel's lightship weight by design.

This results in conclusions:

- The effective mass saving from eliminating the accommodation block exceeds what could reasonably be achieved through material substitution across the entire hull structure
- Investing in expensive lightweight materials for components such as a wheelhouse or upper deck superstructure would provide no benefit in this context, as these elements no longer exist on board

Therefore, from both a cost-efficiency and engineering standpoint, the use of aluminium, composite, or sandwich structures is not justified in the AUTOFLEX application. The structural weight savings have already been realised more substantially through design innovation rather than through material selection.

It should also be noted that additional lightship weight reductions may potentially be achieved through structural optimization of the hull itself, for example by refining the framing system or through advanced stress path analysis. Such measures may allow for further localized plate thickness reductions or more efficient structural arrangements. However, this would require detailed strength analyses such as finite element modelling and classification society approval based on a finalized design.

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Since the AUTOFLEX vessel is currently in the concept design phase, and a final variant has not yet been defined, such structural fine-tuning lies outside the present scope. For this reason, optimization via complex structural analysis is acknowledged as a future opportunity but not considered actionable at this stage of development.

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9 APPLICATION AND VALIDATION OF CALCULATION MODELS

9.1 3D MODEL AND GAP OF THE AUTOFLEX VESSEL

This section presents the 3D model and General Arrangement Plan (GAP) developed for the AUTOFLEX CEMT II vessel. The GAP and digital model illustrate the spatial layout, structural arrangement, and primary vessel dimensions based on the improved hull form and the adopted design configuration as defined in Chapter 5.3 These graphical and three-dimensional representations serve not only as design documentation but also as essential validation and coordination tools during the entire concept development phase. By visualizing the interaction of structural elements, internal volumes, and deck arrangements, the model supports technical decisions regarding space utilization, machinery integration, safety zoning, and regulatory compliance. Moreover, the GAP provides a fixed reference for classification assessments, production planning, and refinement of subsystem layouts, especially related to container arrangement, ballast tanks, and machinery compartments. Together, the GAP and 3D model ensure that all design objectives - functionality, feasibility, and modularity are aligned and transparently communicated.

The GAP (Figure 9-1) shows the vessel's profile, upper deck, tank top views, main particulars, and cross-section arrangement. These drawings provide a clear overview of cargo hold dimensions, compartment distribution, bulkhead positions, ballast tanks layout, and overall vessel proportions.

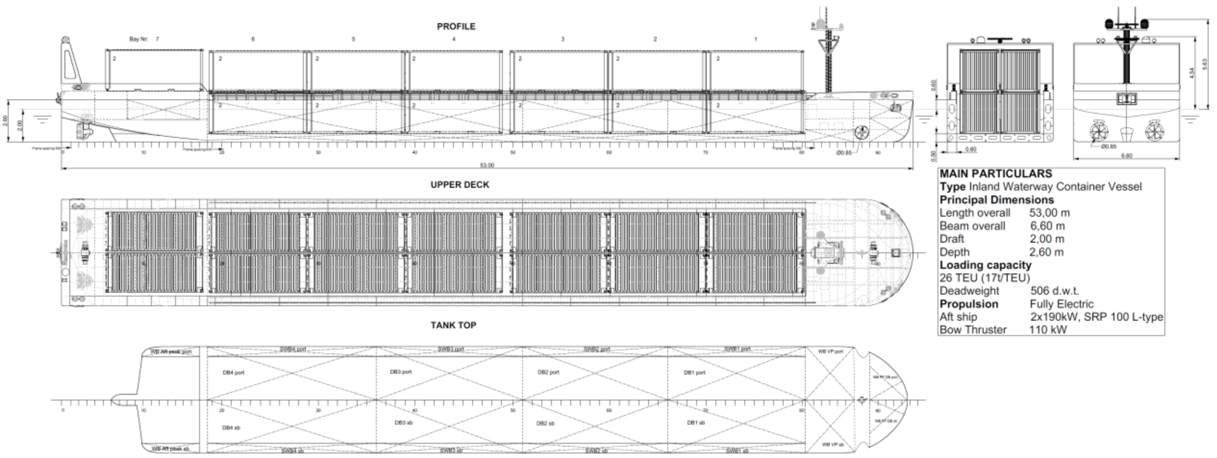

Figure 9-1: GAP of AUTOFLEX CEMT II vessel

The 3D model (Figure 9-2) complements the GAP by providing a visual representation of the final design. It includes container stacks, navigation mast, propulsion units, and deck structure. This model was developed using Rhino 3D software and serves multiple purposes:

- Verifying component fit and internal arrangements
- Supporting stability and hydrostatics assessments
- Facilitating visualization for stakeholder communication and design review

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- Providing a geometric foundation for estimating the lightship weight using Orca 3D analysis tools

The digital model was used throughout the development process to iteratively test design assumptions and incorporate feedback from partners, ensuring technical feasibility and regulatory compliance. It also formed the basis for hydrostatic and weight estimation simulations that contributed to structural and performance validation.

Figure 9-2: 3D-model of AUTOFLEX CEMT II vessel

9.2 LIGHTSHIP WEIGHT ESTIMATION

The estimation of the lightship weight is a fundamental step in the design process of inland waterway vessels, particularly for innovative concepts such as the uncrewed, zero-emission CEMT II vessel. Accurate weight prediction is essential not only for verifying compliance with stability criteria and structural requirements, but also for evaluating energy demand, propulsion efficiency, and overall vessel performance.

The structural thicknesses of the primary hull elements, previously calculated according to Bureau Veritas rules for inland vessels [6], are used here as the basis for determining the steel structure's contribution to the lightship weight. These rule-based values establish the required plate thicknesses and serve to define the hull geometry relevant for the weight model.

To refine the weight estimation, the SO team provided detailed data on the types, dimensions, and individual weights of critical propulsion-related equipment. This included components such as propulsion units (ducted azimuth thrusters and bow thruster), converters, inverters, electric switchboards, electric motors, and auxiliary power electronics, all of which are essential to the vessel's fully electric propulsion architecture, see Figure 9-3.

Cargo-related masses, such as swappable ZES battery containers, were explicitly excluded from the lightship weight calculation, in line with standard ship architecture definitions.

Using a detailed 3D model developed in Rhinoceros 3D [12] and further processed with the Orca3D plugin [13], a comprehensive parametric weight analysis was conducted. All major structural and outfitting components, as well as onboard equipment relevant to the ship's light condition, were parameterized and assigned material properties. This enabled accurate computation of mass, centres of gravity, and distribution across the vessel. Advanced computer-aided design methods allow determination of the areas of plates on the hull and bulkheads quickly and accurately. Also specific weights, per area of stiffened plates can be quickly determined using the dimensioning tools of classification societies which consider the distance between stiffeners, loads and material [36].

The resulting CAD-analysis determined the lightship weight to be **118 tons**. The longitudinal centre of gravity (LCG) is located at 25.75 meters from the defined reference point, and the vertical centre of gravity (VCG) is positioned at 1.16 meters above the baseline. These values serve as key inputs for further stability calculations and hydrostatic assessments. Extended data and detailed weight breakdowns can be found in the appendix in Table A 1.

This method ensures a realistic and precise lightship weight assessment at the concept design stage, which is critical for downstream analyses such as stability, hydrostatics, and energy performance. The resulting dataset serves as the basis for further development of the AUTOFLEX vessel design.

9.2.1. EMPIRICAL PREDICTION METHOD FOR STEEL WEIGHT ESTIMATIONS

For comparative analysis of the steel weight of the CEMT II autonomous cargo vessel, with transversal framing an empirical prediction method has been employed. Specifically, the Hekkenberg approach [37] is used to estimate the portion of the steel weight. This method leverages the vessel's principal dimensions and applies a correction for accommodation structure, aligning closely with the results of a 3D CAD model.

9.2.2. STEEL WEIGHT

Determining the steel weight is a key step in inland ship design, as it directly influences structural rigidity, overall displacement, and vessel stability. Employing an empirical formula tailored to inland waterway vessels streamlines early-stage design decisions and helps avoid expensive redesigns later.

This section outlines Hekkenberg's method (HM) for a more precise estimate of the steel weight. Next, a dedicated local mass formula refines the calculation for autonomous vessels with reduced accommodation areas. Finally, there is a brief comparison with a 3D CAD model assessment.

Hekkenberg's Method:

Hekkenberg's approach is derived from extensive research on inland vessels, making it particularly suitable for the CEMT II class. The general expression is, [37], p. 234:

$$W_{steel,\,HM} = c_1(L \cdot B \cdot T)^2 + c_2(L \cdot B \cdot T)$$

where:

$L = 53.0\ m$

$B = 6.6\ m$

$T = 2.0\ m$

$c_1 = 1.36 \times 10^{-5}$

$c_2 = 1.95 \times 10^{-1}$

$$\rightarrow \boldsymbol{W}_{steel,\,HM} = 1.36 \times 10^{-5} \cdot (699.6)^2 + 0.195 \cdot 699.6 = \boldsymbol{143.1\ tones}$$

Explicit formula for accommodation weight:
Because the vessel is autonomous without superstructure, mass for a typical deckhouse or

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living quarters can be removed. Hekkenberg's local mass formula for accommodation is applied, [37], p. 97:

$$W_{accomodation,\ HM} = 0.173 \cdot 2.5 \cdot max\left(\frac{L}{4}(B-2); 100\right)$$

$$\frac{L}{4}(B-2) = 60.95;\ \ max(60.95; 100) = 100$$

$$\boldsymbol{W_{accomodation,\ HM}} = 0.173 \cdot 2.5 \cdot 100 = \boldsymbol{43.25\ tonnes}$$

Adjust the steel weight:

$$\boldsymbol{W_{steel,\ adjusted,\ HM}} = W_{steel,\ HM} - W_{(accomodation,HM)} = 143.1 - 43.25 = 99.9 \approx \boldsymbol{100\ tonnes}$$

Hence, the effective hull steel weight after subtracting accommodation mass is ≈ 100 tonnes.

Comparison with 3D CAD Model

A 3D CAD model returned a steel weight of approximately **102 tonnes**, only about 2 tonnes higher than Hekkenberg's 100 tonnes. Given the potential for minor local differences or simplifications, this close agreement is considered excellent for a vessel of this size.

Designers often use both approaches. Hekkenberg's formula provides rapid estimates in early design phases, while a detailed CAD model yields a more exact breakdown later, once the hull form and structural layout are finalized.

Conclusion

After applying the accommodation correction, Hekkenberg's formula predicts a steel weight of about **100 tonnes** for the CEMT II autonomous inland dry cargo vessel. This figure aligns with the **102 tonnes** from the CAD analysis, confirming the suitability of Hekkenberg's method for such an inland design.

9.2.3. LIGHTSHIP WEIGHT

To calculate the lightship weight of the AUTOFLEX vessel, additional equipment data were considered. These items are grouped into two categories:

Propulsion-related equipment, based on data provided by the SO team for the electric propulsion system:

- Two azimuth thrusters (ducted), each weighing 3.5 tonnes
- Bow thruster: 1.2 tonnes
- Auxiliary machinery room equipment, totalling 0.855 tonnes

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CEMT Class	Converter –Type (2 Converters)	Power Range [kW]	Inverter Type	Power Range [kW]	Cooling unit	Total Weight [kg]	Volume [m3]
I	2xACS880-1604-LC0600A	527	2xACS880-104-LC0190A ACS880-1604-LC0100A	160 90	ACS880-1007LC 70 [kW]	855	1.04
II	2xACS880-1604-LC0700A	615	2xACS880-1604-LC0290A ACS880-1604-LC0140A	250 132	ACS880-1007LC 70 [kW]	855	1.04
III	2xACS880-1604-LC1200A	1050	2xACS880-1604-LC0389A ACS880-1604-LC0220A	355 200	ACS880-1007LC 70 [kW]	1343	1.44
IV	2xACS880-1604-LC1800A	1581	2xACS880-1604-LC0560A ACS880-1604-LC0340A	500 315	ACS880-1007LC 190 [kW]	1579	1.62

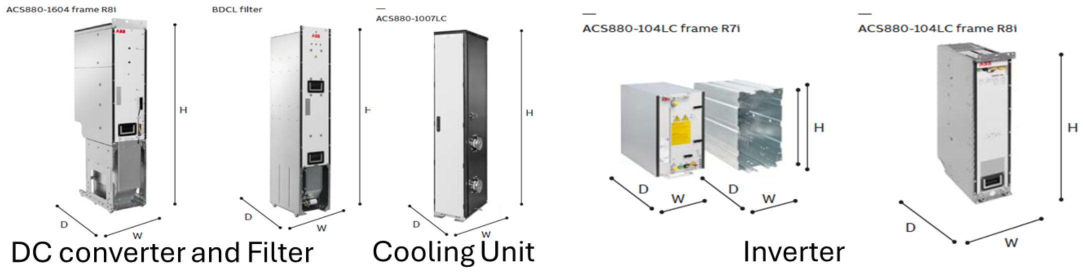

Figure 9-3: Machinery room equipment for CEMT II vessel

and outfitting components, like anchoring and mooring arrangement, navigation masts etc.:

- Anchor chain: 1.5 tonnes
- Bow anchors: 0.7 tonnes each
- Anchor (stern): 0.7 tonnes
- Bow winch: 0.8 tonnes
- Stern winch: 0.8 tonnes
- Mast (bow): 0.8 tonnes
- Emergency batteries: 1.6 tonnes

$$\boldsymbol{Light\ ship\ weight} = 102.0 + 7.0 + 1.2 + 0.86 + 1.5 + 0.7 + 0.7 + 0.8 + 0.8 + 0.8 + 1.6 = 117.96 \approx \boldsymbol{118\ tonnes}$$

9.3 DEADWEIGHT

To calculate the deadweight (DWT) of the AUTOFLEX vessel, the standard definition is applied:

$$\boldsymbol{Deadweight} = \boldsymbol{Displacement\ (at\ loading\ condition)} - \boldsymbol{Lightship\ weight}$$

Given:

$Lightship\ weight = 118\ tonnes$, see Chapter 9.2.3

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$Displacement\ at\ reference\ condition\ LC2\ =\ 624.2\ tonnes$, see Table 10-1.

$\boldsymbol{Deadweight = 624.20\ t\ - 117.96\ t = 506.24\ tonnes}$

This deadweight is consistent with vessels classified under CEMT Class II, which typically range between 400 and 650 tonnes according to the relevant classification standards.

This means the vessel is designed to carry up to 506.24 tonnes in its given loading condition, including:

- Cargo (Payload)
- ZESpacks
- Ballast water (if any)
- Other operational supplies

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10 STABILITY ASSESSMENT

This section provides an overview of the stability assessment for the AUTOFLEX vessel. The assessment focuses on compliance with relevant regulations and identifies potential challenges arising from the vessel's innovative design.

10.1 APPLICABLE REGULATIONS

Intact stability of inland container vessels operating in Western Europe is required to comply with the criteria outlined in the European Standard Laying Down Technical Requirements for Inland Navigation Vessels (ES-TRIN), Chapter 27 [7], p. 193. The stability standards differ depending on whether the ship transports secured or non-secured containers. The minimum metacentric height (GM_{min}) must not be less than 1 m for vessels transporting non-secured containers and 0.5 m for vessels carrying secured containers. Additionally, the static angle of heel should not exceed the angle at which the deck edge enters the water (φ_{deck}) or 5°, whichever is less, when the ship is exposed to simultaneous action of heeling moments due to turn (M_{dr}) and beam wind (M_w). These criteria are presented in Figure 10-1. Since inland container vessels have a large open cargo hold, intact stability calculations should be conducted assuming the presence of rainwater and residual water in the cargo hold. Additionally, all intact stability calculations should be carried out with 50% of supplies (in practice, mainly fuel and fresh water). However, considering that the AUTOFLEX vessel would be unmanned and would operate with a zero-emission propulsion system, it would not rely on conventional fuel or freshwater supplies. Hence, this aspect is irrelevant and is therefore omitted.

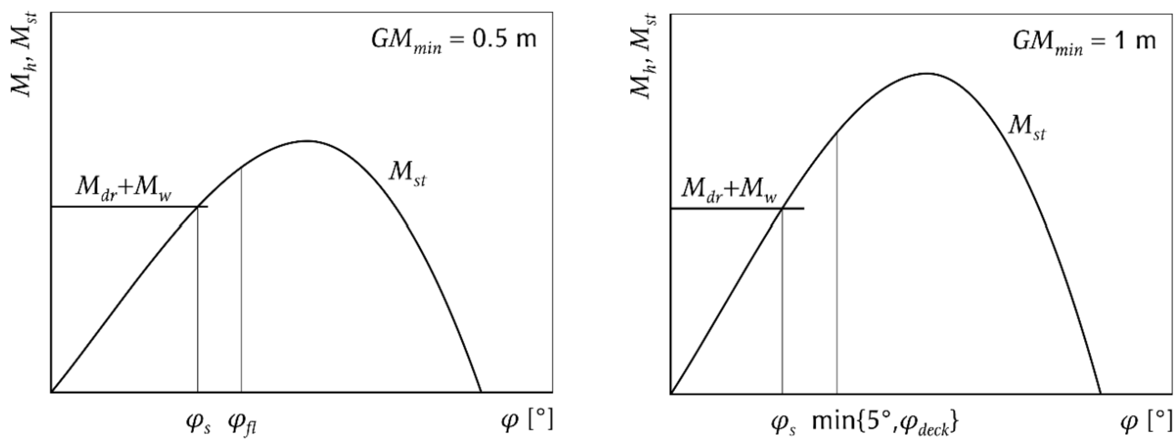

Figure 10-1: Stability criteria diagrams illustrating the righting and heeling moments for the case when containers are secured (left) and non-secured containers (right), based on [38]

While ES-TRIN provides the primary regulatory framework for vessels navigating inland waterways within the European Union, strictly speaking, its rules apply to the navigation Zone 3 (e.g. the Rhine), whereas the AUTOFLEX vessel should partly sail in Zone 2 as well. As a result, additional stability criteria need to be considered. In this context, stability

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assessment is also subject to the classification rules of Bureau Veritas [6]. While largely aligned with ES-TRIN, Bureau Veritas requirements introduce certain adjustments for different operational zones, particularly in relation to wind pressure.

For inland container vessels, damage stability assessment is not required unless:

- The vessel carries dangerous cargo, in which case it would be subject to the ADN (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways) rules, Chapter 9 [39]
- The vessel's length exceeds 110 m, in which case it would be subject to ES-TRIN, Chapter 28 [7]

Accordingly, the vessels such as the AUTOFLEX design are not obliged to comply. However, the situation is not entirely straightforward. One of the business cases foresees "energy as cargo", that is the transport of battery packs (instead of cargo containers or even mixed with the regular cargo containers). Depending on whether these energy storage units are considered as dangerous goods or not, additional regulatory considerations may be needed.

At this stage of the design process, the damage stability assessment has not been performed. Nonetheless, as outlined in Deliverable D4.1 [40], preliminary evaluations have indicated that achieving compliance with the applicable damage stability criteria could present a significant challenge for this vessel class.

10.2 HYDROSTATICS AND STABILITY ASSESSMENT

The stability assessment has been carried out in compliance with the standards applicable to transport of non-secured containers, as it is predominantly done in inland navigation in Western Europe. To achieve the required *GM* of 1 m, the cargo had to be unequally distributed in two tiers (i.e., heavier containers in the lower tier). The vertical centre of gravity of all containers, including ZES battery packs, has been assumed at 40% of their height. The weight of each ZES battery pack is taken as 29 t, as previously specified. The vessel's lightweight has been estimated at 117.9 t, with further details provided in Chapter 9.2.3 of this deliverable report.

The hydrostatics and stability assessment has been performed for a range of loading conditions (LC). The first set of the loading conditions is characterized by variation of the swappable battery packs (ZESpacks) position. If ZESpacks are placed in the cargo hold, TEU containers are not stowed on top of them, in line with the [7] CESNI Guideline. The following loading conditions were examined (see also Figure 10-2):

- LC1: ZESpacks located on the aft deck
- LC2: ZESpacks placed in the first row of the cargo hold
- LC3: ZESpacks placed in the second row of the cargo hold
- LC4: ZESpacks placed in the third row of the cargo hold
- LC5: ZESpacks placed in the fourth row of the cargo hold
- LC6: ZESpacks placed in the fifth row of the cargo hold
- LC7: ZESpacks placed in the sixth row of the cargo hold

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- LC8: ZESpacks carried as cargo

Since the battery packs have considerable mass, the first set of calculations was carried out with a goal of finding the most suitable position of the battery packs from the flotation point of view, i.e., the position of the battery packs which would result in the smallest trim.

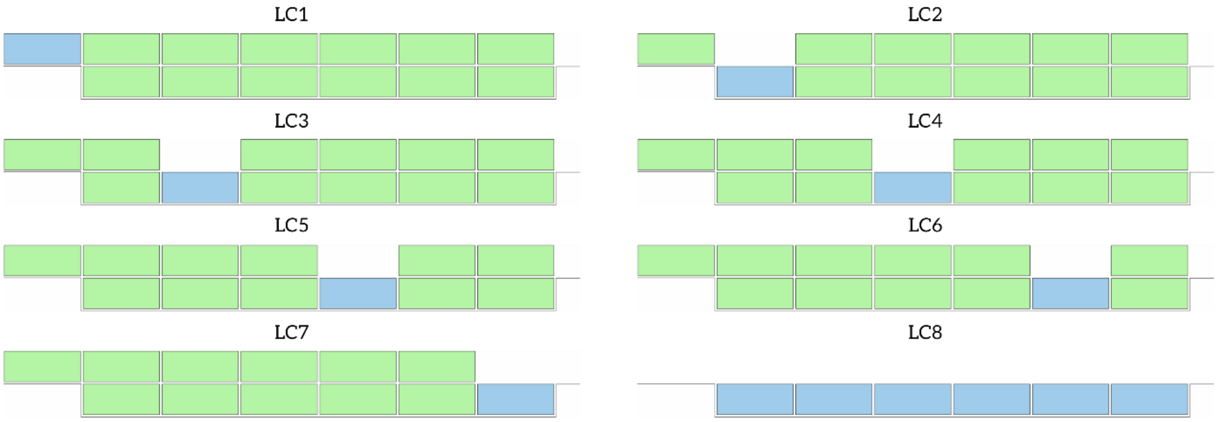

Figure 10-2: Main loading conditions considered for the stability assessment, showing different configurations of cargo containers (green) and swappable battery packs (blue)

The main outcomes of the first set of calculations are given in Figure 10-3 and Table 10-1. It may be noticed that the most suitable position of the battery packs would be in the lower tier in the first row in the cargo hold (LC2). This qualifies LC2 to be the reference loading condition for which the vessel has been designed.

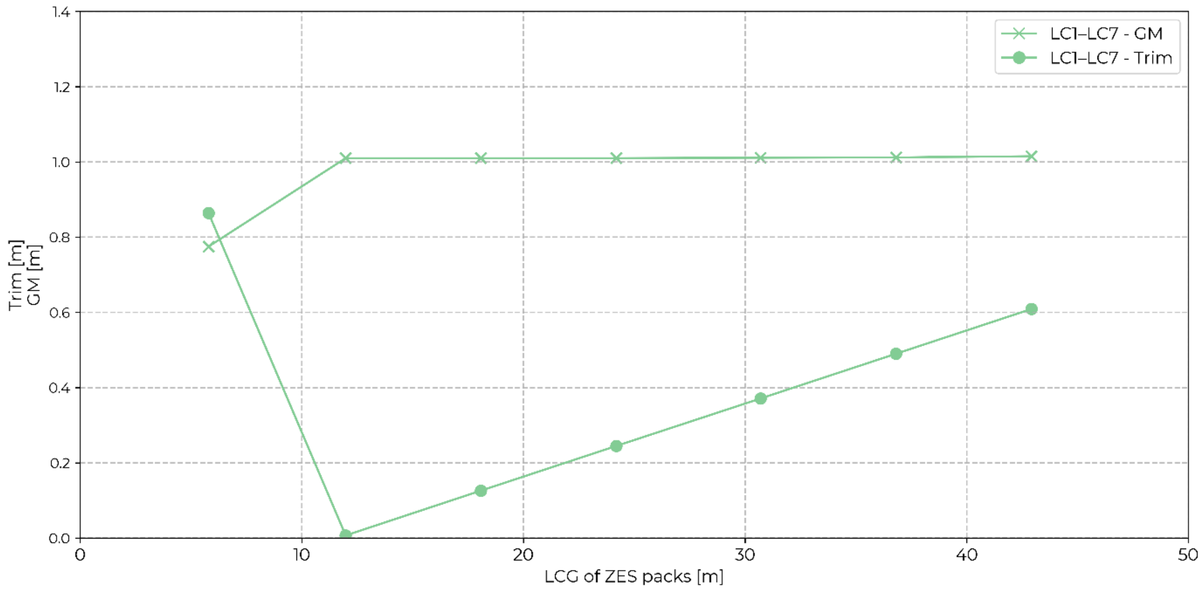

Figure 10-3: Influence of longitudinal position (LCG) of ZES battery packs on vessel trim and metacentric height (GM) for loading conditions LC1 to LC7

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Table 10-1: Main results for loading conditions LC1 to LC8. LC2 represents the reference loading condition

	LC1	LC2	LC3	LC4	LC5	LC6	LC7	LC8
d [m]	1.924	1.932	1.930	1.929	1.928	1.927	1.926	1.470
Δ [t]	624.2	624.2	624.2	624.2	624.2	624.2	624.2	465.9
L_{WL} [m]	52.784	52.850	52.841	52.832	52.822	52.813	52.803	52.763
VCG [m]	2.227	1.981	1.981	1.981	1.981	1.981	1.981	1.536
LCG [m]	25.262	27.257	26.981	26.703	26.408	26.130	25.853	27.016
Trim (aft) [m]	0.864	0.007	0.126	0.245	0.371	0.490	0.609	0.216
GM [m]	0.775	1.010	1.010	1.010	1.011	1.012	1.015	1.861
φ [°]	4.085	3.146	3.145	3.146	3.149	3.132	3.105	2.279

For conditions LC2 (22 TEU) through LC7, a metacentric height of 1 m was achieved with vertical distribution of deadweight, with approximately 78% of the weight allocated to the first tier and 22% to the second tier. Consequently, the average mass of a TEU container in the first tier is 32.25 t, while the average mass of a TEU container in the second tier is 10.46 t (including two TEU containers located on the aft deck).

In addition, several loading conditions were examined to assess stability in various scenarios:

- LC2-1: 50% of cargo
- LC2-2: 50% of cargo with ballast
- LC2-3: 100% of cargo in Zone 2
- LC8-1: ZESpacks carried as cargo with ballast
- LC9: Empty ship (no cargo containers)
- LC9-1: Empty ship (no cargo containers) with ballast

Main results of the calculations for these additional loading conditions are given in Table 10-2. Ballast water has been added in the following amounts: 44.1 t in LC2-2 (around +7% of displacement in LC2), 17.2 t in LC8-1 (around +3.7% of displacement in LC8), and 96.7 t in LC9-1 (around +55% of displacement in LC9). Nevertheless, ballasting is practically not required in the examined cases, considering that both the main propulsors and the bow thruster would be submerged even without the ballast water. The righting lever curves (*GZ*-curves) for the relevant loading conditions are given in Figure 10-4.

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Table 10-2: Main results for additional conditions LC2-1, LC2-2, LC2-3, LC8-1, LC9, and LC9-1

	LC2-1	LC2-2	LC2-3	LC8-1	LC9	LC9-1
d [m]	1.274	1.407	1.931	1.522	0.605	0.894
Δ [t]	399.9	443.9	624.200	483.2	176	272.5
L_{WL} [m]	52.706	52.769	52.850	52.788	51.342	50.712
VCG [m]	1.836	1.752	1.981	1.499	1.326	1.144
LCG [m]	25.927	27.734	27.257	27.611	21.207	28.336
Trim (aft) [m]	0.565	0.006	0.008	0.005	1.149	0.042
GM [m]	1.895	1.649	1.010	1.739	5.624	3.567
φ [°]	2.605	2.708	3.490	2.383	1.978	2.023

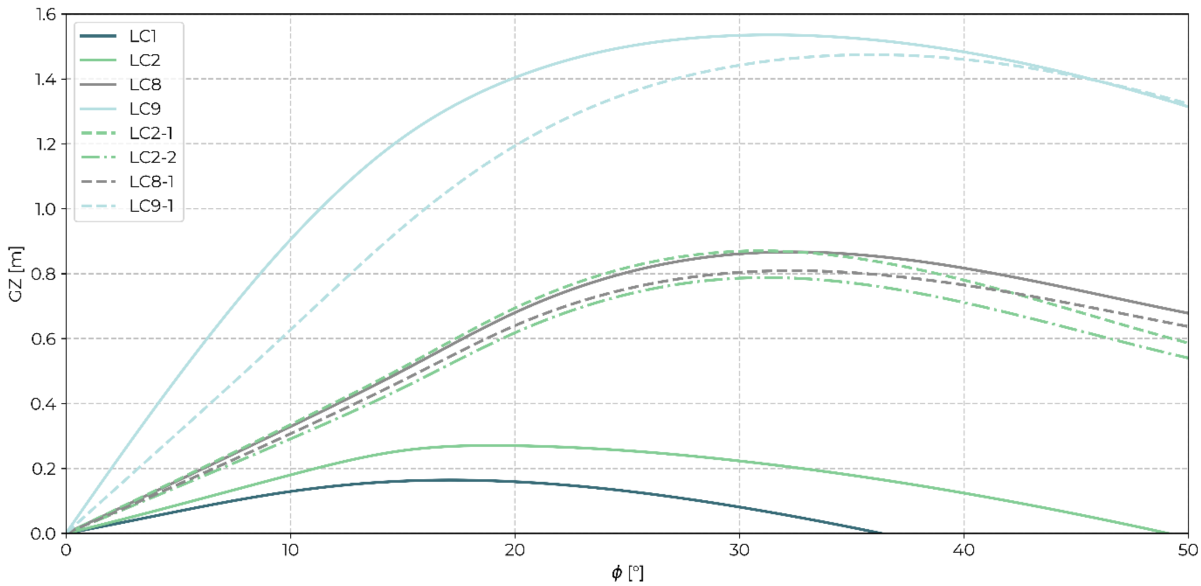

Figure 10-4: Righting lever (GZ) curves for key loading conditions (LC1, LC2, LC8, LC9) and (LC2-1, LC2-2, LC8-1, and LC9-1)

10.3 CONCLUSION

The stability assessment confirms that all examined loading conditions comply with the relevant intact stability criteria given by ES-TRIN and Bureau Veritas (with the exception of LC1, which does not meet the required minimum *GM* value of 1 m). The loading condition LC2 has been selected as the design reference scenario since the heavy ZES battery packs are placed in the first row of the lower tier in the cargo hold causing the smallest trim when the ship carries 100% cargo.

Additional loading conditions, including partial loading, ballast, and additional wind load scenarios, have been analysed to verify the vessel's hydrostatics and stability in different

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operational circumstances. The results demonstrate that stability remains within acceptable limits, with ballast serving as an effective corrective measure in conditions with reduced loading or unfavourable weight distribution.

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11 PROPULSION CONCEPT DEVELOPMENT AND ASSESSMENT

11.1 POSITION OF AZIMUTH PROPULSORS AND TUNNEL THRUSTERS

The propulsion concept of the developed vessel comprises two azimuth thrusters with pushing ducted propellers. The rationale behind choosing this type of propulsion system is presented in the AUTOFLEX Deliverable D4.1, Section 4 “Implementation of Zero-Emission Propulsion” [40], and it is also addressed in [45]. The pushing ducted azimuth thrusters are commonly installed on offshore supply vessels, wind turbine installation vessels, harbour service / tugboats, tug barges, etc., but are also common on oceanographic research vessels, bunkering vessels, aquaculture support vessels and dry cargo vessels. Typical examples are given by Schottel Rudder Propeller (SRP) and Brunvoll Azimuth Thruster with Push Ducted Propeller. Figure 11-1 shows a summary of technical data for standard SRP units delivered for different ranges of required power. Except for wind turbine installation vessels, which may have up to 6 thrusters, the typical vessel propulsion concepts based on azimuth thrusters are usually twin-screw vessels, where the thrusters are installed symmetrically on the port side and starboard side of the ship. Installation of azimuth thrusters on inland navigation vessels is less common. However, recently, this solution received close attention due to superior manoeuvring performance at low speeds [43], [44]. The detailed hydrodynamic design of a wake-adapted azimuth thruster, including the optimization of propeller diameter and RPM, for the vessel design developed in AUTOFLEX will be performed in the project Task 4.3. In the scope of the present Task 4.2, the focus was on preliminary assessment of the longitudinal and transverse positions of the thruster on ship hull, since these parameters have direct influence on the hydrostatics and stability analyses (Chapter 10) as well as the weight distribution calculations (Chapter 9). In this assessment, the propeller diameter D=0.85 (m) was assumed based on the recommendations given in the AUTOFLEX Deliverable D4.1 [40] as adopted in the present design concept.

The choice of the longitudinal and transverse positions of azimuth thrusters installed on twin-screw vessels is a trade-off between propulsive efficiency, manoeuvrability, directional stability and mitigation of cavitation, pressure pulses and vibrations. Considering interaction effects between the thruster and hull and between the thrusters is important for finding an optimum solution for each specific case. The mentioned interaction effects depend on the developed hull design and on the configuration of the chosen thruster.

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Type	Input power [kW]				Input speed Z-Drive [min -1]	Input Speed L-Drive [min-1]	Propeller [m]		Azimuth standard module			Azimuth compact module			SRP-D
	A ⓘ	B ⓘ	C ⓘ	D ⓘ			Ø	CP	Z	ZY	L	Z	ZY	L	
< SRP 100					auf Anfrage / on request										
SRP 100		190	200	225	1800 / 2300		0.85		S		O				
SRP 130		260	280	315	1800 / 2000		1.00		S						
SRP 150		330	360	400	1800 / 2100	1300	1.20		S		O			O	
SRP 180	400	420	450	500	1600 / 1800 / 2100	1200	1.30		S	O	O	O	O	O	
SRP 210	500	530	560	640	1600 / 1800 / 2100	1200	1.45		S	O	O	O	O	O	
SRP 240	660	700	750	850	1600 / 1800 / 2100	1200	1.70		S	O	O	O	O	O	
SRP 270	780	840	900	1000	1600 / 1800 / 2100	1200	1.85		S	O	O	O	O	O	
SRP 340	1090	1170	1250	1400	750 / 900 / 1000 / 1200 / 1600 / 1800	780	2.10		S	O	O				

Figure 11-1: Image and technical data of Schottel Rudder Propellers (SRP) [41]

The vessels that are to be developed within the AUTOFLEX project are autonomous inland cargo vessels, which are designed to operate in confined waterways. Therefore, these vessels require enhanced manoeuvrability at low-speed operation, which makes the placement of the thrusters further aft (closer to the stern) advantageous. As shown in Figure 11-2, this measure increases the arm of the transverse thrust component, resulting in an increase of the moment produced by this thrust component, which turns the ship about the pivot axis. In operation, this allows for the application of smaller heading angles to the thrusters, thus reducing the risk of unsteady cavitation and ventilation on propeller in oblique flow conditions. The moments about the same axis, which are produced by the axial thrust component of the two thrusters compensate each other, to a significant degree. The transverse force developed on the pod housing and duct because of lift is relatively small at low-speed operation.

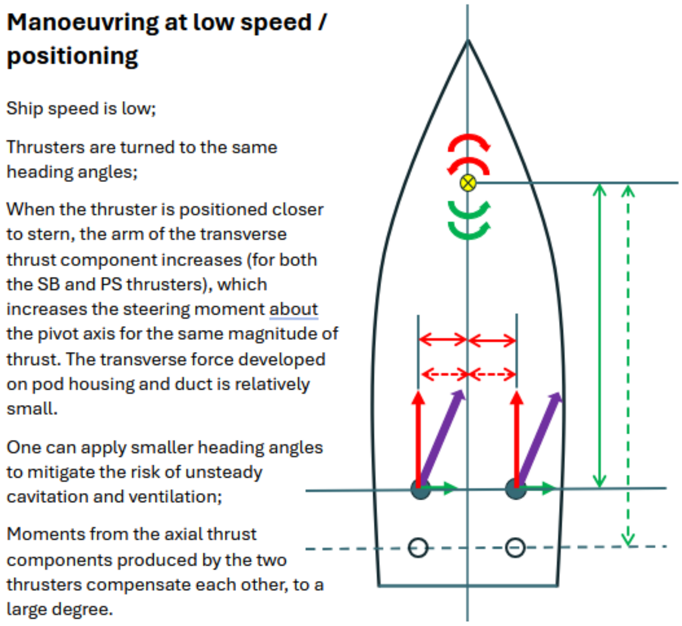

Figure 11-2: Schematic illustration of the influence of the thruster positioning at low speed

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The impact of longitudinal position of thrusters on vessel course stability (directional stability) at sailing speed is less straightforward. On the one hand, moving thruster further aft improves course stability because:

- the control surface area shifts downstream (the thruster itself, when not actively steered, acts as a stabilizing control surface)
- the moment produced by the transverse thrust component + transverse force developed on the pod housing and duct about the pivot axis, which returns the ship to the straight course, increases due to a greater force arm (see Figure 11-2)
- placing thrusters further aft permits using a longer central skeg (larger skeg area)

On the other hand, when thrusters are moved aft, the force arm of the axial thrust component increases for the thruster located on the side of the ship in the direction of stern motion. This moment tends to increase the yaw angle and deviate the ship further from the straight course. The force arm of the axial thrust component for the thruster on the opposite side of the ship whose moment counteracts ship's yaw, on the contrary, decreases, and at larger yaw angles the moment may change sign and start acting in the direction of increasing yaw. A schematic illustration of the discussed hydrodynamic mechanisms is shown in the following Figure 11-3.

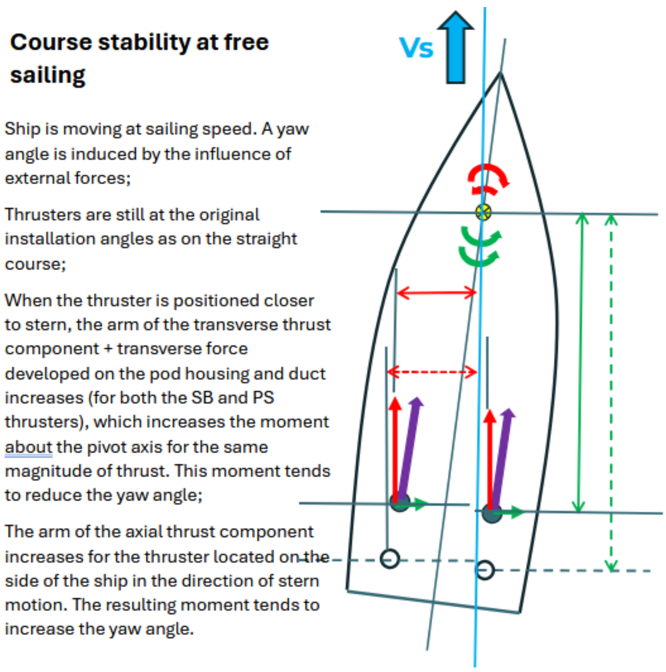

Figure 11-3: Schematic illustration of course stability at free sailing

In order to improve propulsive efficiency, it is important to ensure sufficient wake (in average sense, expressed by the wake fraction (WT)) on the propulsor. The wake fraction normally increases when the thruster is moved upstream, closer to the hull. At the same time, when the thruster is moved closer to the hull, thrust deduction (t), also increases, which reduces the gain of efficiency due to a higher value of WT. Relative rotative efficiency (η_R), depends on the non-homogeneity of the wake field at the location of the thrusters. For twin-screw ship equipped with pods, it does not change significantly with the longitudinal

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position. For ducted pushing thrusters, most of the flow inhomogeneity on the propeller is caused by the influence of pod strut and brackets supporting the duct, and it is thus related to the configuration of the propulsor itself, rather than propulsor interaction with ship hull. The resulting effect of propulsor/hull interaction on propulsive efficiency is expressed by the hull efficiency coefficient η_H, which can be calculated according to the following equation [46]:

$$\eta_H = \frac{(1-t)}{(1-WT)}$$

The propulsive efficiency (η_D) is obtained by multiplication of the propulsor efficiency in open water (η_O), hull efficiency (η_H) and relative rotative efficiency (η_R), as follows [46]:

$$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$$

For the offshore and harbour service vessels equipped by azimuth pushing ducted thrusters, propulsive efficiency is lower compared to the ships equipped with other types of azimuth propulsors, and η_D is normally found in the range of 0.52-0.55. For the same ship equipped with pulling azimuth thrusters featuring open propellers, the efficiency in free sailing can be 3-4 % higher. However, at low speed, heavy loading operation, the ducted thrusters are considerably more efficient (20 – 30 %) than thrusters with open propellers.

Based on the design practices for offshore vessels and tugs, the longitudinal position of azimuth thrusters about $\frac{x}{L_{pp}} = -(0.44 \div 0.45)$ from midship is recommended. For the developed inland vessel design, it can further be increased to $\frac{x}{L_{pp}} = -(0.46 \div 0.47)$ from midship.

In general, in absence of interaction between the thrusters, the influence of their transverse position on vessel manoeuvrability is less pronounced than the influence of their longitudinal position. Interaction between both thrusters leads to the loss of effective thrust, more unsteady flow pattern around the thrusters, and hence compromises the steering and positioning capabilities during low-speed operation. In this regard, it is advantageous to increase transverse separation by placing the thruster further away from the central plane (CP).

Considering vessel course stability (directional stability) at sailing speed it is better to move the thrusters closer to the CP. This enables an improvement of the overall flow pattern over the aft ship as well as a smaller arm of the axial thrust component about the pivot axis. Thus, the moment which tends to increase the yaw angle is reduced for the thruster located on the side of the ship in the direction of stern motion, see Figure 11-3.

For ships featuring a central skeg, placing thrusters closer to the CP means that propeller blades will be facing more non-homogenous inflow and experience larger pressure gradients when passing through the hull boundary layer. This leads to the increased risk of unsteady cavitation under heavy-loading operating conditions and elevates pressure pulses levels.

When placing the thruster in transverse direction, one should also consider the slopes of hull lines and avoid applying too large thruster installation angles. In general, having installation angles larger than 5° is not advisable. The application of a headbox above the thruster allows in principle to deal with larger hull slopes. However, one also needs to take the following aspects into consideration:

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- installation of a headbox results in additional hull resistance (headbox acts as an appendage)
- for inland vessels, where the base clearance is small, there may be too little space to accommodate a headbox, so mounting the thruster directly under hull is necessary

On offshore and harbour service vessels, the ducted azimuth pushing thrusters are usually positioned around $\frac{Y_{pc}}{\frac{B}{2}} = \pm(0.50 \div 0.55)$. For the developed inland vessel design, the transverse position about $\frac{Y_{pc}}{\frac{B}{2}} = \pm(0.50 \div 0.53)$ from CP can be recommended, but in further design exploration studies more inward positions, starting from $\frac{Y_{pc}}{\frac{B}{2}} = 0.45$ will also be evaluated.

The following Table 11-1 shows the recommended positions of the ducted pushing thrusters for the developed AUTOFLEX vessel concept. These recommendations were derived using the data on several reference vessels, and they reflect the considerations of manoeuvrability, course keeping and propulsive efficiency discussed above. Since there is no available reference data on inland vessels propelled by azimuth thrusters the offshore supply vessels (OSV) equipped with ducted and open pushing thrusters were used as reference ships in this case.

Table 11-1: Thruster positioning for the AUTOFLEX Vessel concept and for reference offshore supply vessels

AUTOFLEX Vessel Concept		
DST CEMT_II		
Ducted pushing thrusters		
D (m)	0.85	
Loa	53	
B	6.6	
L/B	8.03030303	
CB	0.916	
Present position of thrusters		
Longitudinal		
from stern		
Xpc	**1.84**	
from midship		
X	-24.66	
X/Lpp	-0.465	
Transverse		
from CP		
Ypc	**1.725**	
Ypc/B	0.261	
Ypc/(B/2)	0.523	

(!) Recommended values of the longitudinal, Xpc, and transverse, Ypc, positions of the azimuth thruster are shown by red colour. They refer to the "pod centre", the point where the steering axis of the azimuth unit (strut axis) intersect propeller shaft.

Reference OSV-1			Reference OSV-2			Reference OSV-3		
Ducted pushing thrusters			Ducted pushing thrusters			Open pushing CRP thrusters		
D (m)	2.4		D (m)	2.3		D (m)	2.3	
Loa	79.412		Loa	76.299		Loa	110.7	
B	17.6		B	17		B	22	
L/B	4.51205		L/B	4.48818		L/B	5.03182	
CB	0.724		CB	0.764		CB	0.736	
Position of thrusters			Position of thrusters			Position of thrusters		
Longitudinal			**Longitudinal**			**Longitudinal**		
from stern			from stern			from stern		
Xpc	4.57		Xpc	3.82		Xpc	6	
from midship			from midship			from midship		
X	-35.136		X	-34.33		X	-49.35	
X/Lpp	-0.442		X/Lpp	-0.450		X/Lpp	-0.446	
Y			Y			Y		
Transverse			**Transverse**			**Transverse**		
from CP			from CP			from CP		
Ypc	4.2		Ypc	4.781		Ypc	5.88	
Ypc/B	0.239		Ypc/B	0.281		Ypc/B	0.267	
Ypc/(B/2)	0.477		Ypc/(B/2)	0.562		Ypc/(B/2)	0.535	
Installation angles			**Installation angles**			**Installation angles**		
YOZ	5	out	YOZ	7.8	out	YOZ	4	out
XOZ	5	down	XOZ	6	down	XOZ	3	down
XOY	5	out	XOY	2	out	XOY	0	

Further investigations in Task T4.3 will focus on the optimization of the developed vessel design, more specifically, considering possible increase of propeller diameter (d > 0.85 m), reduction of the block coefficient of the ship hull, and a slenderer bow outline. In these optimization studies, CFD methods will be employed for the prediction of ship's resistance and self-propulsion performance, while manoeuvring simulation codes extended with CFD corrections will be used to examine the impact of design modifications on the ship's manoeuvring characteristics. In the later phase of the project, the final design will be verified

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through dedicated model tests. The detailed design exploration studies may lead to minor changes in the recommended longitudinal and transverse positions of the azimuth thrusters.

From the general operational experience with vessels equipped with twin azimuth thrusters one can infer that, while such vessels demonstrate superior manoeuvring performance at low speeds, achieving desired course stability in free sailing may require additional measures. This observation is particularly relevant for ships having relatively small propellers compared to ship length, and full overall hull shape. Therefore, having a central skeg may be mandatory for course stability in narrow waterways with heavy density of traffic. Placing the azimuth thrusters further downstream, closer to stern, would allow to have a longer skeg. The skeg, however, should not extend to the location of the thrusters. The downstream end of the skeg should not come closer than 0.6D upstream to the thruster steering axis. The common criterion to check is that propeller slipstream can pass behind skeg with some margin, when the thruster is working at 90° heading angle, as shown in the schematic illustration in the following Figure 11-4.

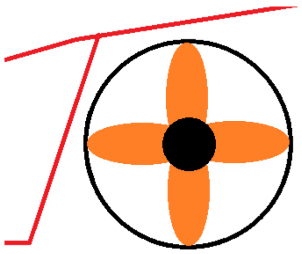

Figure 11-4: Schematic illustration of the positioning of the azimuth thruster behind the central skeg

The slipstream of a ducted propeller is wider than that of an open propeller. Hence, the distance of 0.6D is recommended. The shape of the skeg should be further optimized using CFD analyses during the hull design process, to avoid significant flow separation on the skeg itself and in the area of integration between the skeg and hull.

In the process of hydrodynamic design optimization (T4.3), it is also relevant to consider the influence of the direction of propeller rotation with respect to ship hull, i.e. inward vs. outward. Inward rotation is generally more favourable for course stability and for directional control during low-speed manoeuvres. Some studies indicate that higher propulsive efficiency may be achieved with outward rotating propellers. However, the latter observation is not conclusive, since in each case, the alignment of thrusters with the inflow must be considered.

Thrusters installed on the ship should generally be aligned with the flow at the design condition (draught/ speed) by applying thruster installation angles (tilt, head and heel). These angles are most accurately derived from full-scale CFD simulations of the flow past ship, considering the effect of working propellers – it is the effective flow (including velocity field induced by the thruster) that needs to be considered.

Operations near cargo terminals and when entering or leaving locks require precise positioning of the vessel, which necessitates the use – alongside with azimuth propulsion units – of auxiliary steering devices installed at the bow of the ship. Based on the investigations conducted in Task 4.1 and reported in [40], one transverse tunnel thruster

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with the power around 115 (kW) is recommended as an active steering device for the present conceptual design. The Brunvoll Standard and LowNoise Tunnel Thrusters FU 37 [47] provide flexible options regarding the size/power of the units to fit on different classes of vessels studies in AUTOFLEX. The FU 37 thrusters with propeller diameter of 0.85 (m) are used in the power range of 75 to 200 (kW). The standard tunnel thrusters are available in Z- and L-drive configurations. Electric motor can be installed either on the bed frame in vertical or tilted position, or on a separate foundation with vertical intermediate shaft. To best fit the hull lines, custom tunnel extensions may be applied. To ease the maintenance and reduce associated costs, the suppliers offer replaceable propeller blades bearing liners and possibility to remove the thruster gear housing from the tunnel with propeller blades in place. In the trunk-mounted solution, the entire thruster is arranged in a special trunk (case) with a bolt in the tank top plate. This significantly reduces the installation effort by the shipyard and allows to remove the thruster for service and repair without dry-docking of the vessel. For the vessels with strict noise requirements, special low-noise designs of tunnel thrusters are available which permit the reduction of noise levels by about 11÷15 (dB) compared to standard bow thrusters. Noise reduction is achieved through combination of different measures such as full-length double-wall tunnel, resilient mounting, tailoring of tunnel entrances to fit hull line, profiling of protective grids, and not least important, low-noise propeller design. In some cases, an elastic well installation is applied for further damping of vibration levels in the systems [48]. Noise levels of 75-85 (dB) are not uncommon in the ship compartments next to and above the standard tunnel thruster. Considering that tunnel thruster is not the only noise source onboard vessel, this is a fairly high level. The European Standard laying down Technical Requirements for Inland Navigation Vessels [49] specifies that:

(1) "The noise generated by a vessel under way shall not exceed 75 dB(A) at a lateral distance of 25 m from the ship's side."

(2) "Apart from transhipment operations the noise generated by a stationary vessel shall not exceed 65 dB(A) at a lateral distance of 25 m from the ship's side."

For the vessels designed in AUTOFLEX for operation in smaller rivers and canals, some of which are found in the residential and recreational areas, reduction of noise emitted by main propulsors and auxiliary thrusters becomes relevant. Therefore, low-noise variants of tunnel thrusters are recommended. Different customized solutions of tunnel thrusters offered by Brunvoll are illustrated in Figure 11-5.

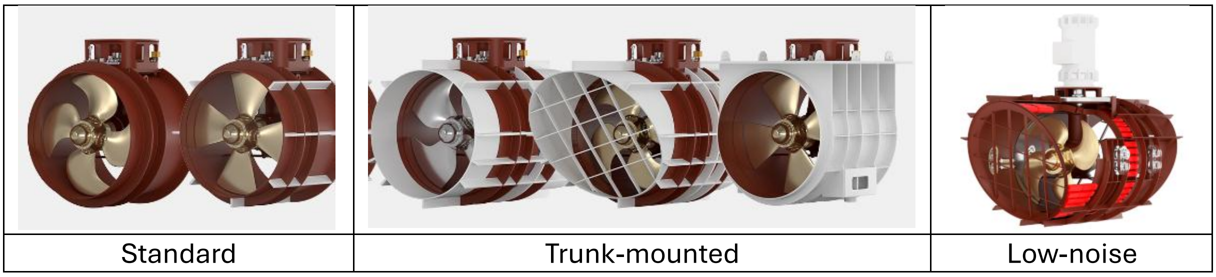

Figure 11-5: Different customized solutions of tunnel thrusters offered by Brunvoll [44]

Mitigation of the risk of ventilation on a tunnel thruster in shallow draught conditions is an important aspect to consider in the design process. While there exist different empirical

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formulas to estimate the submergence of a tunnel thrusted under the free surface, both in calm water and in waves, the common rule of thumb states that the relative submergence to avoid developed ventilation should be $h_0/D \geq 1.0 \div 1.25$. At the same time, the tunnel should not be placed too close to the base to avoid re-circulation of the flow under the bottom of the vessel which may occur, especially if the thruster is operated under heavy loading and the hull is narrow at the location of the tunnel. Some estimations of the tunnel submergence at different draughts are presented inTable 11-2 Table 11-2, while Figure 11-6 explains the definition of quantities used in the table. It can be concluded that, for the draught of 2.5 (m), both the D=0.85 (m) and D=1.0 (m) tunnels can be used without immediate risk of ventilation. For the draught of 2.0 (m), which is close to the present conceptual design case, the choice should be with D=0.85 (m) or D=0.8 (m) thrusters. For the draught of 1.5 (m), only the smallest thrusters with D=0.62 (m) would meet the nominal criterion of ventilation absence.

Table 11-2: Assessment of tunnel thruster submergence and position relative to base

Draught, d (m)	**1.5**			**2**			**2.5**		
Tunnel, D (m)	0.8	0.740	0.62	1	0.850	0.8	1	0.850	0.8
Elevation from base, zb (m)	0.6	0.550	0.5	0.75	0.700	0.7	0.75	0.700	0.7
Submergence, h0 (m)	0.5	0.580	0.69	0.75	0.875	0.9	1.25	1.375	1.4
h0/D	**0.625**	**0.784**	**1.113**	**0.75**	**1.029**	**1.125**	**1.25**	**1.618**	**1.75**

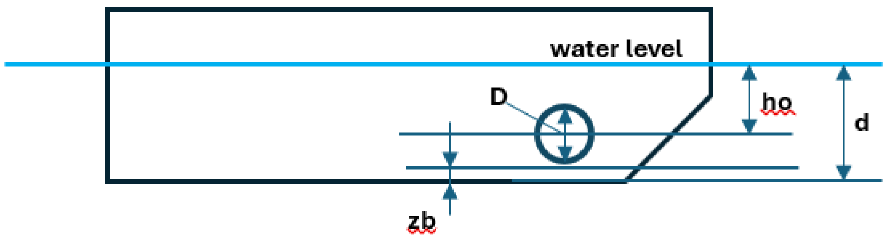

Figure 11-6: To the definition of tunnel thruster submergence

For what concerns the longitudinal position of the tunnel thruster, it is advantageous to place the thruster closer to the ship's bow to provide the largest possible arm for the steering moment. Such a consideration is however rather simplified, since in the reality the tunnel thruster and ship hull act as one hydrodynamic system [46]. The flow characteristics around the location of the tunnel are equally important for the effectiveness of the tunnel thruster during the manoeuvres, and for tunnel's contribution to hull resistance during free sailing. The quality of the inflow on the propeller inside the tunnel and propeller design are also important for the propeller cavitation characteristics. Hydraulic losses during the operation of a tunnel thruster are associated with flow separation at the inlet and outlet tunnel entrances (these in turn depend on the waterline and frame angles of hull lines at the location of the tunnel, constructive features of the tunnel entrance edges and vessel speed

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through water), friction in the boundary layer on the tunnel walls, resistance and flow blockage by the gear housing in presence of operating propeller, and resistance of protective grids installed at the tunnel entrances. Therefore, final position of the tunnel thruster on the ship will be elaborated during the detailed ship design in Task 4.3. For this purpose, CFD simulations will be conducted to support the decisions following common design practices.

11.2 CFD VALIDATION ACTIVITIES

To validate the developed conceptual hull design and the corresponding developed propulsion system preliminary CFD simulations were performed. Therefore, a numerical model of the developed vessel was created, see Figure 11-7.

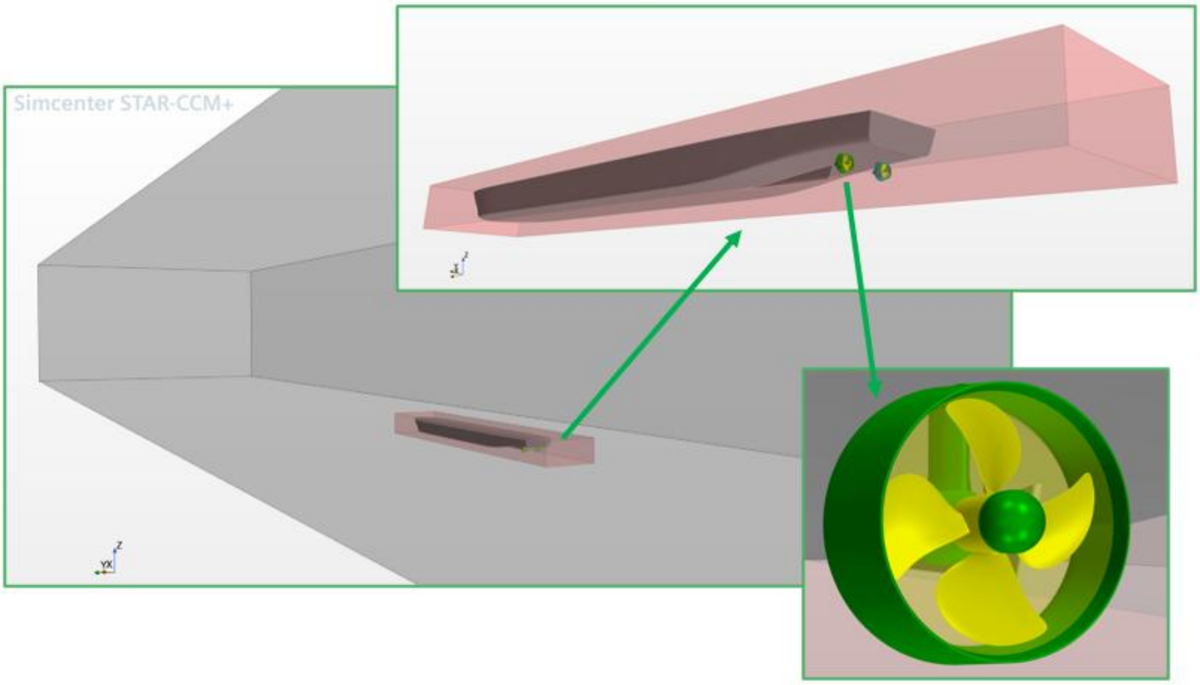

Figure 11-7: CFD Model Setup for the developed AUTOFLEX conceptual vessel design and the corresponding propulsion system

To model the ship motions with respect to the waterway, the Overset Mesh (OM) approach was applied. A "tight" OM region was constructed around the ship with propulsors. This region can be a subject to DFBI solution to find the dynamic squat of the ship, or to a prescribed motion (e.g., in manoeuvring calculations), or it can be fixed at a given position of the ship.

The propulsors are fully resolved and geometrically accurate models of the rudder/pod gear-housing, duct, propeller blades and hub were created. The rotation of propellers is addressed using the Sliding Mesh (SM) technique, see Figure 11-8. The SM regions constructed around each propeller participate in a superposed rotation motions about propeller axis that follow the OM region and, therefore, the dynamic position of the ship.

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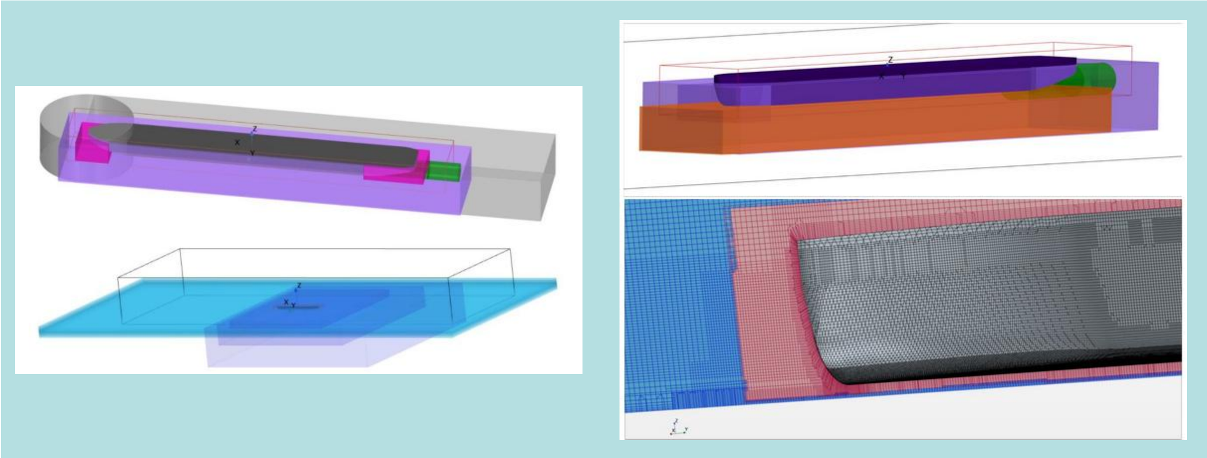

Figure 11-8: CFD Setup illustrating the standard volume refinement controls (left) and the bottom refinement control specific to extreme shallow water conditions

Based on the developed model preliminary CFD calculations were performed and compared to the experimental data of a reference validation case (model scale 1:16). The following figures show that a sufficient correlation between the CFD calculations and the experimental data could be achieved for the towing resistance, Figure 11-9, as well as for the dynamic position see Figure 11-10.

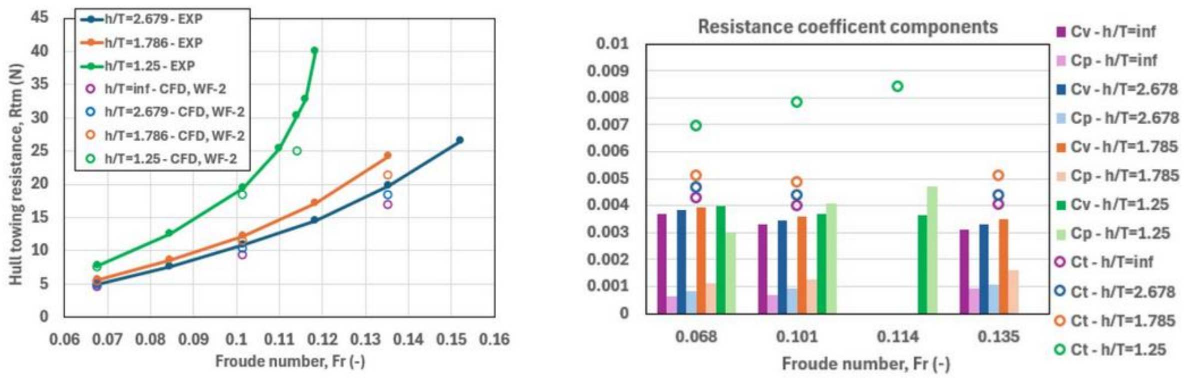

Figure 11-9: Direct comparison of the towing resistance between the CFD results and experimental measurements

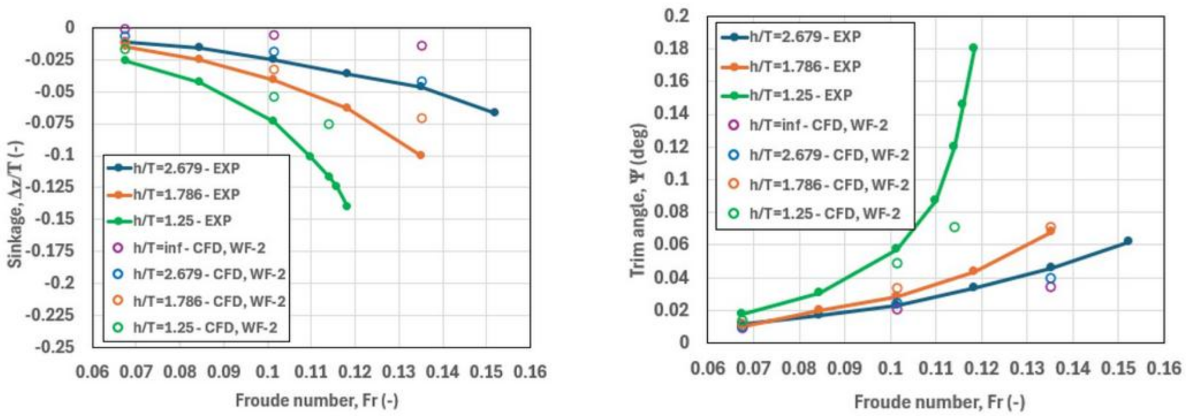

Figure 11-10: Direct comparison of the dynamic position between the CFD results and experimental measurements

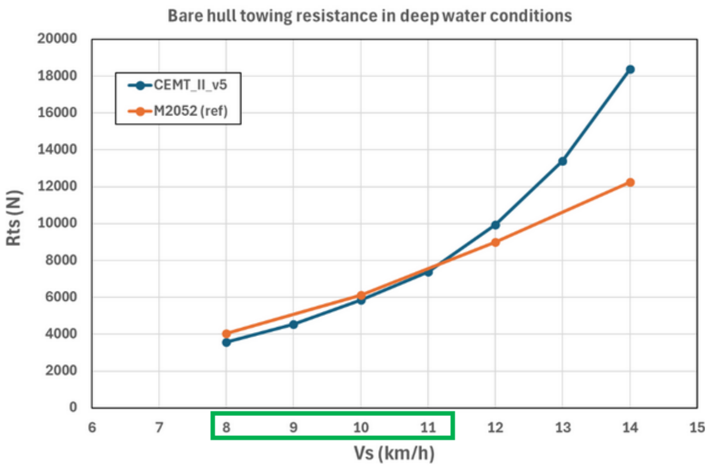

Figure 11-11: CFD bare hull towing resistance calculations in deep water conditions for the developed AUTUFLEX vessel concept (CEMT_II_v5) in comparison to a reverence vessel (M2052 ref)

Also, the developed conceptual design was evaluated regarding its hull towing resistance. Figure 11-11 shows the results for the towing resistance of the bare hull with a central skeg in deep water conditions without appendages and aerodynamic resistance of on-deck structures based on a standard hull roughness. For the simulation the loading condition LC6 (T = 1.932 m, GM = 1, Trim = 0) was selected. Figure 11-11 also shows the comparison to a reference vessel, based on another hull, which was converted to a comparable ship size. The comparison shows that an acceptable hull performance in the speed range from 8 to 11 km/h could be accomplished. However, higher service speeds lead to a rapid increase of hull towing resistance due to wave making and an increase of dynamic sinkage and trim by bow . In conclusion the developed conceptual AUTOFLEX vessel design suits the targeted lower service speed range from 6 to 12 km/h very well. The following Figure 11-12 illustrates the influence of different service speeds on the formation of free surface waves and the corresponding wake fields.

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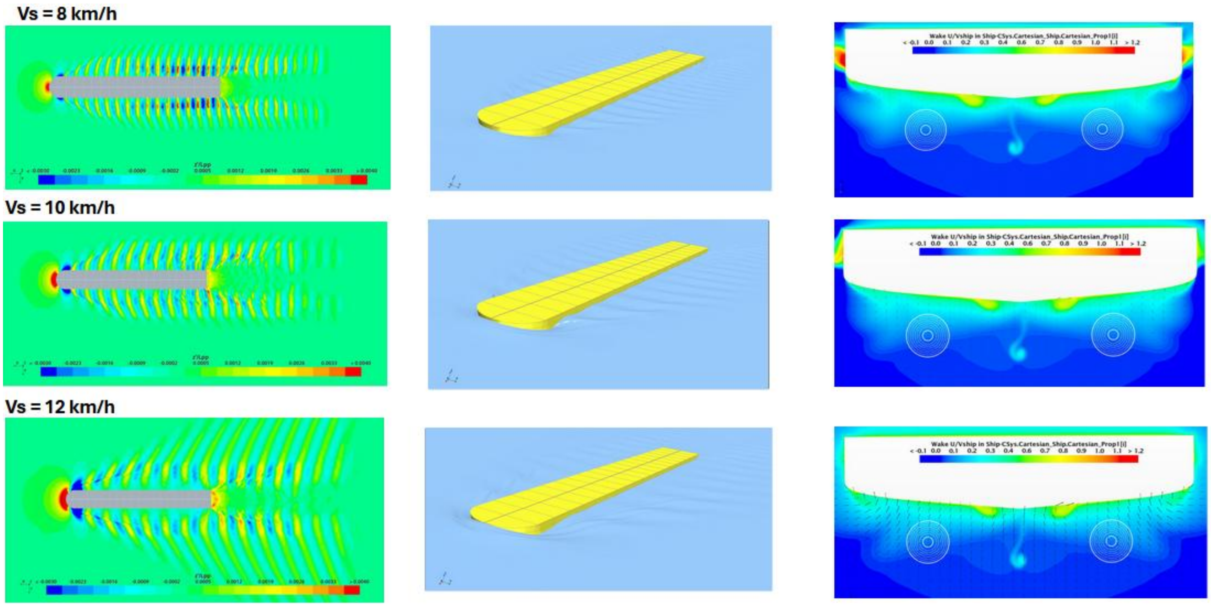

Figure 11-12: CFD simulation results of free surface waves and nominal wake fields for different service speed levels

Since the AUTOFLEX vessel is supposed to operate in underutilized small and shallow waterways CFD simulations were performed in order to assess the power demand according to different waterway conditions, see Figure 11-13.

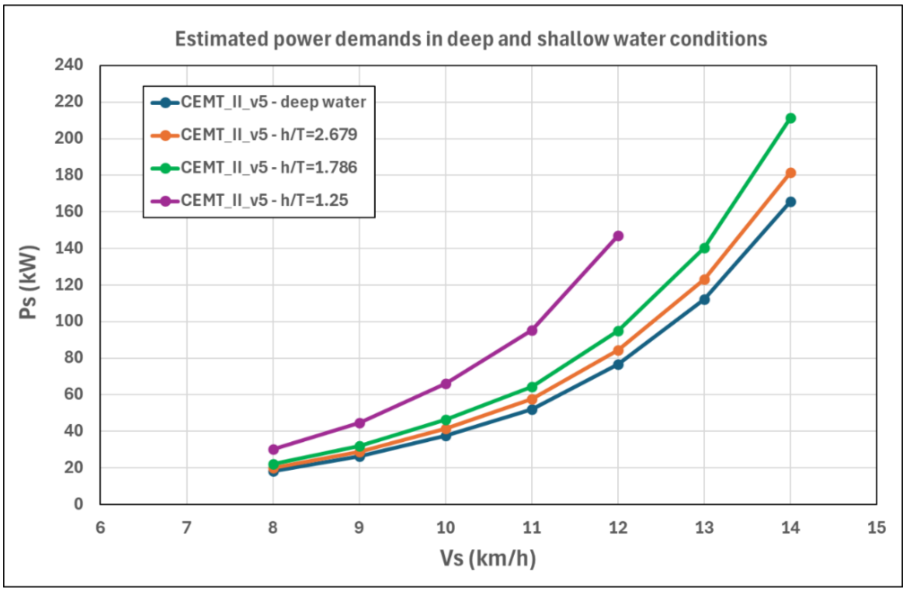

Figure 11-13: CFD simulation of estimated power demands in deep and shallow water conditions

The simulations were based on a propulsive efficiency of η_d = 0.50 and a mechanical efficiency of the azimuth thrusters of η_M = 0.95. The shallow water assumptions were based according to a reference case provide by DST. No canal width restrictions were included. The results show an increase of the estimated power demand for increasing service speeds

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as well as for decreasing water depth. However, the estimated power demand for the targeted lower service speeds suits the selected azimuth thrusters very well.

11.3 CONCLUSIONS

The conducted CFD towing resistance calculations on the developed conceptual ship hull design indicate an acceptable hull performance in the targeted service speed range from 8 to 11 km/h. For higher service speeds ($v_s \geq 12$ km/h) a rapid increase of resistance due to wave building and increase of dynamic sinkage and trim by the bow is observed.

Preliminary estimations of the requested propulsion power demand in shallow water conditions indicate that, for the targeted service speed range from 8 to 11 km/h, the developed conceptual design may have an excess of power onboard. That is due to the fact, that the earlier power demand estimation done in Task 4.1 has been performed for the conventional speed range of CEMT II class vessels, which is 12 to 14 km/h. Also, the influence of restricted canal width is not included in the present estimations. Further elaboration of power requirements will therefore be performed in Task 4.3, which is focused on the hydrodynamic optimization of the ship hull and the propulsor designs.

The performed analysis of the current propulsion arrangement in the aft ship indicates that it might be possible to increase the propeller diameter of the ducted azimuth thrusters from 0.8 m to 0.85 m or even 0.9 m, observing the required clearances to the base plane and to the water surface (submergence). Such an increase would be advantageous for both the propulsive efficiency and course stability of the vessel. Optimization of propulsor dimensions and choice of optimum diameter/RPM combination within the design constraints will be addressed in Task 4.3.

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12 CONCLUSION AND OUTLOOK

The AUTOFLEX vessel concept developed in Deliverable D4.2 marks a significant step forward in the innovation of inland waterway transport. It supports the strategic goals of the European Commission, including the EU Green Deal and the Sustainable and Smart Mobility Strategy [2], [42]. It demonstrates how modern design processes and engineering tools can be applied to create a technically feasible, fully electric, and uncrewed vessel. The project shows that by combining careful planning, regulatory compliance, and advanced simulation tools, it is possible to meet the future demands of sustainable, flexible, and automated logistics on inland waterways.

The deliverable has shown how multiple design constraints—such as route limitations, lock dimensions, air and water draft restrictions, safety regulations, and the need for autonomy—can be translated into a functional and realistic ship concept. The result is a vessel specifically optimized for the CEMT Class II waterway category. It incorporates key technical elements, including modular and swappable battery containers (ZESpacks), a digital control architecture for uncrewed operation, redundant propulsion systems using azimuth thrusters, and a hull form adapted for shallow-draft navigation in both canals and estuarial zones.

A particular strength of the AUTOFLEX approach is the way it brings together multiple goals within one coherent design. The vessel is intended to:

- Operate autonomously at CCNR Autonomy Level 3
- Navigate restricted Class II waterways, including exposed Zone 2 estuary routes
- Carry modular containerized cargo alongside standardized battery packs
- Provide flexibility in terms of cargo capacity as being able to efficiently stow TEU, FEU, and palette-wide containers
- Meet safety and design standards from ES-TRIN [7], Bureau Veritas [6], and UNECE Resolution No. 61 [9] to the extent possible (considering that the existing regulations do not contain requirements for uncrewed vessels)

The development relied on a systematic design spiral approach supported by simulation tools such as Rhino 3D, Orca3D and NAPA. These tools were used to validate hydrostatics, estimate lightship weight, evaluate stability under various load conditions, and verify internal system layouts. The integration of a 3D digital model also helped to coordinate contributions from different project partners and to ensure that the vessel geometry supports accessibility, maintainability, and energy system integration.

While the AUTOFLEX concept presented here does not yet represent a construction-ready vessel, it serves as a robust and practical foundation for further engineering work. In Task 4.3, the concept will be further refined and tested to bring it closer to real-world application. Key next steps will include:

- Detailed CFD-based hull optimization to reduce resistance and enhance energy efficiency

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- Structural adjustments for production readiness, including material selection and construction detailing
- Modelling of energy demand and voyage profiles under different loading and operational scenarios
- Implementation planning for automation, remote monitoring, and control technologies
- Evaluation of lifecycle cost, emissions savings, and scalability across multiple vessel sizes or types

In addition to technical goals, the concept also supports broader strategic aims. It contributes to the EU's Green Deal and digital transition agendas by showing how zero-emission vessels can be effectively integrated into the existing inland transport system. The design also aligns with the goals of improving the competitiveness and attractiveness of inland shipping by making operations simpler, safer, and more predictable.

The results presented in this deliverable form a strong basis for stakeholder engagement and further system integration. The vessel design can be used as a reference for follow-up studies, pilot testing, and investment planning. Moreover, the modular and standardized approach makes the concept adaptable to different cargo types and regions.

In the upcoming phase (T4.3), the focus will shift to validation and fine-tuning. The technical concept will undergo further refinement through hydrodynamic simulations, structural detailing, and functional integration. Stakeholder feedback and real-world operational data will also play an essential role in improving the design's performance and usability.

To complement the conclusions of this report, an overview of the AUTOFLEX vessel's main dimensions and technical characteristics is provided in the following Table 12-1.

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Table 12-1: Main particulars of AUTOFLEX CEMT II vessel

AUTOFLEX CEMT II Vessel Data	
Length overall, L_{oa}	**53.00 m**
Beam overall, B_{oa}	**6.60 m**
Draught at LC2, T_{LC2}[3]	**1.93 m**
Minimal draught, $T_{minimal}$	**1.33 m**
Depth to main deck, D	**2.60 m**
Displacement at LC2	**624.2 tons**
Lightship weight	**118 tons**
Deadweight	**506 d.w.t.**
TPC	**3.41 t/cm**
Block coefficient at LC2, $c_{b,LC2}$	**0.903**
Prismatic coefficient at design draught, $c_{p,LC2}$	**0.907**

Additionally, a lines plan illustrates the adopted hull geometry, which has been optimized for shallow-water navigation and compact container arrangement (see Figure 12-1). These elements serve as a visual and numerical reference for the finalized concept configuration.

Overall, the AUTOFLEX concept demonstrates how innovation in inland vessel design can meet the twin goals of decarbonization and digitalization. It serves as a concrete and forward-looking example of how future-proof inland shipping solutions can be developed and brought closer to implementation.

[3] *LC2 (Loading Condition 2): ZESpacks placed in the last bay of the cargo hold, see Chapter 10*

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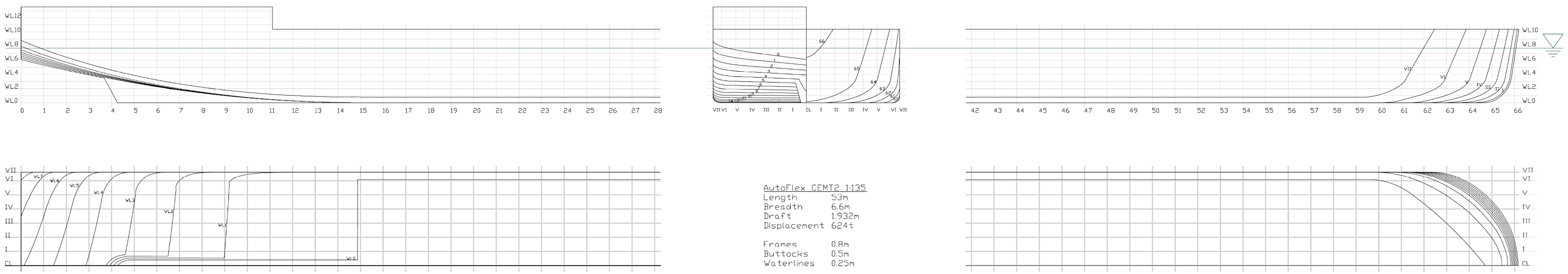

Figure 12-1: Lines plan of the AUTOFLEX vessel

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13 REFERENCES

[1] 'AUTOnomous small and FLEXible vessels | AUTOFLEX Project | Fact Sheet | HORIZON', CORDIS | European Commission. Accessed: Mar. 27, 2025. [Online]. Available: https://cordis.europa.eu/project/id/101136257

[2] 'The European Green Deal - European Commission'. Accessed: Mar. 28, 2025. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[3] *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy – putting European transport on track for the future*. 2020. Accessed: Mar. 27, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0789

[4] 'AUTOFLEX_Part_B, Call: [HORIZON-CL5-2023-D5-01-16] — [Developing small, flexible, zero-emission and automated vessels to support shifting cargo from road to sustainable Waterborne Transport]'.

[5] D. G. M. Watson, 'Practical Ship Design', *ELSEVIER OCEAN ENGINEERING BOOK SERIES*, vol. 1, 1998.

[6] '217-NR_Consolidated_2021-06, Bureau Veritas – Rules for Inland Navigation Vessels'.

[7] 'ES_TRIN_2025_signed_en.pdf'. Accessed: Feb. 10, 2025. [Online]. Available: https://www.cesni.eu/wp-content/uploads/2024/11/ES_TRIN_2025_signed_en.pdf

[8] 'Klassifikations- und Bauvorschriften Schiffstechnik.pdf'.

[9] Vereinte Nationen, Ed., *Recommendations on harmonized Europe-wide technical requirements for inland navigation vessels: resolution No. 61*, Rev. 1. in United Nations publication. New York: United Nations, 2011.

[10] H. Ligteringen, *Ports and Terminals*. TU Delft OPEN Publishing, 2022. doi: 10.5074/T.2021.005.

[11] 'Project 1'. Accessed: Oct. 11, 2024. [Online]. Available: https://www.vanmeegen.com/vanmeegen-project-1

[12] 'Rhino - Rhinoceros 3D'. Accessed: Mar. 21, 2025. [Online]. Available: https://www.rhino3d.com/

[13] 'Orca3D Marine Design for Rhinoceros', Orca3D, LLC. Accessed: Mar. 21, 2025. [Online]. Available: https://orca3d.com/

[14] 'Zentralkommission für die Rheinschifffahrt'. Accessed: Mar. 27, 2025. [Online]. Available: https://www.ccr-zkr.org/

[15] 'Comité européen pour l'élaboration de standards dans le domaine de la navigation intérieure (CESNI)', CESNI - Comité Européen pour l'Élaboration de Standards dans le domaine de la Navigation Intérieure. Accessed: Mar. 27, 2025. [Online]. Available: https://www.cesni.eu/

[16] 'European_inland_waterways_-_2012.pdf'. Accessed: Oct. 17, 2024. [Online]. Available: https://unece.org/fileadmin/DAM/trans/main/sc3/European_inland_waterways_-_2012.pdf

[17] 'alcor.pdf'. Accessed: Aug. 01, 2024. [Online]. Available: https://www.gtsschepen.nl/en/ships/alcor/?pdf

[18] 'anna.pdf'. Accessed: Aug. 01, 2024. [Online]. Available: https://www.gtsschepen.nl/en/ships/anna/?pdf

Funded by the European Union

Grant Agreement: 101136257

[19] 'elsa.pdf'. Accessed: Aug. 01, 2024. [Online]. Available: https://www.gtsschepen.nl/en/ships/elsa/?pdf
[20] 'empresa.pdf'. Accessed: Aug. 01, 2024. [Online]. Available: https://www.gtsschepen.nl/en/ships/empresa/?pdf
[21] 'Scheepstypes_BVB_nieuw1.pdf'. Accessed: Apr. 17, 2025. [Online]. Available: https://bureauvoorlichtingbinnenvaart.nl/wp-content/uploads/2021/04/Scheepstypes_BVB_nieuw1.pdf
[22] I. E. Müller, 'Project full title: European Strategies to Promote Inland Navigation', 2003.
[23] 'schavuit.pdf'. Accessed: Aug. 01, 2024. [Online]. Available: https://www.gtsschepen.nl/en/ships/schavuit/?pdf
[24] 'HKH PRINSES MAXIMA DER NEDERLANDEN | 02325361 | Motorvrachtschip | Binnenvaart.eu'. Accessed: Mar. 24, 2025. [Online]. Available: https://www.binnenvaart.eu/motorvrachtschip/30430-hkh-prinses-maxima-der-nederlanden.html
[25] 'KREFELD | 02324498 | Motorvrachtschip | Binnenvaart.eu'. Accessed: Mar. 24, 2025. [Online]. Available: https://www.binnenvaart.eu/motorvrachtschip/6166-krefeld.html
[26] 'SJORS | 02325291 | Motorvrachtschip | Binnenvaart.eu'. Accessed: Mar. 24, 2025. [Online]. Available: https://www.binnenvaart.eu/motorvrachtschip/9116-sjors.html
[27] 'VERSTEIJNEN | 02324671 | Motorvrachtschip | Binnenvaart.eu'. Accessed: Mar. 24, 2025. [Online]. Available: https://www.binnenvaart.eu/motorvrachtschip/260-versteijen.html
[28] 'Home', Seafar. Accessed: Mar. 25, 2025. [Online]. Available: https://seafar.eu/
[29] Text:Marketing & Communication Department Photo:KONGSBERG, 'Autonomous electric barges being developed by Kongsberg Marine and its partners will help ensure a Norwegian retail giant becomes a global pioneer in sustainable logistics'. Accessed: Mar. 27, 2025. [Online]. Available: https://www.kongsberg.com/newsroom/stories/2020/12/asko/
[30] 'The official AEGIS videos are now out there! - AEGIS'. Accessed: Mar. 27, 2025. [Online]. Available: https://aegis.autonomous-ship.org/2023/12/4015/
[31] '641-NI_2019-10.pdf'. Accessed: Jun. 26, 2024. [Online]. Available: https://erules.veristar.com/dy/data/bv/pdf/641-NI_2019-10.pdf
[32] '20ft Pallet Wide Container | Pallet Wide Shipping Container'. Accessed: Mar. 19, 2025. [Online]. Available: https://www.lotus-containers.com/de/container/20-pallet-wide/
[33] T. Canada, 'Study Guide for Applicants to the Fourth-class Engineer Certificate with STCW Endorsement - TP 14609 E', Transport Canada. Accessed: Mar. 19, 2025. [Online]. Available: https://tc.canada.ca/en/marine-transportation/marine-safety/study-guide-applicants-fourth-class-engineer-certificate-stcw-endorsement-tp-14609-e
[34] 'CDS-Dry-Cargo-532-vouwvel-2405-plano.pdf'. Accessed: Mar. 19, 2025. [Online]. Available: https://concordiadamen.com/wp-content/uploads/2024/05/CDS-Dry-Cargo-532-vouwvel-2405-plano.pdf
[35] 'PLATINA3_D2.2-Climate-resilient-vessels'.
[36] H. Schneekluth and V. Bertram, *Ship design for efficiency and economy*, 2nd ed. Oxford Boston: Butterworth-Heinemann, 1998.
[37] R. G. Hekkenberg, *Inland ships for efficient transport chains*. S.l.: s.n., 2013.
[38] I. Bačkalov, *International Maritime Regulations: Ship Safety*. Belgrade: Mašinski fakultet Univerziteta u Beogradu, 2017.

Funded by the European Union
Grant Agreement: 101136257

[39] 'ADN 2021 - European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways | UNECE'. Accessed: Mar. 26, 2025. [Online]. Available: https://unece.org/transport/dangerous-goods/adn-2021
[40] 'AUTOFLEX_Deliverable_4.1_Design_impacts.docx'.
[41] 'SRP SCHOTTEL RudderPropeller'. Accessed: Mar. 26, 2025. [Online]. Available: https://www.schottel.de/portfolio/produkte/produkt-detail/srp-schottel-rudderpropeller
[42] 'Mobility Strategy - European Commission'. Accessed: Mar. 28, 2025. [Online]. Available: https://transport.ec.europa.eu/transport-themes/mobility-strategy_en
[43] Kossmann, B., el Moctar, O., Schellin, T.E. 'Effects of ventilation on open water characteristics of azimuth propellers under shallow water conditions', Ocean Engineering 311 (2024) 118888.

[44] Wennersberg, L.A.L., Maidana, R.G., Nordahl, H., Krasilnikov, V. 'Technical feasibility of autonomous vessels in inland waterway transport', Preprint submitted to Elsevier, 2025.

[45] Bačkalov, I., Burmeister, H.C., Isidorović, L., Jasa, J., Josipović, M., Kloch, K., Koimtzoglou, A., Krasilnikov, V., Krause, S., Mateienko, D., Nordahl, H., Reinach, N. 'Impact of automation and zero-emission propulsion on design of small inland cargo vessels', in: Proceedings of the International Maritime and Port Technology and Development Conference and the 6th International Conference on Maritime Autonomous Surface Ships, IOP Publishing, 2024.

[46] Carlton, J.S. ' Marine Propellers and Propulsion', 2nd edition, Butterworth-Heinemann, 2007, ISBN: 978-07506-8150-6.

[47] Brunvoll Tunnel Thrusters. Accessed: Apr. 20, 2025. [Online]. Available: https://www.brunvoll.no/products#tunnel-thrusters

[48] Schottel TransverseThruster. Accessed: Apr. 20, 2025. [Online]. Available: https://www.schottel.de/en/portfolio/products/product-details/stt-schottel-transversethruster

[49] European Committee for drawing up Standards in the field of Inland Navigation (CESNI). European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN), Edition 2019/1. Accessed: Apr. 15, 2025. [Online]. Available: https://www.cesni.eu/wp-content/uploads/2018/12/ES_TRIN_2019_en.pdf

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A. APPENDIX

Table A 1: Extended lightship weight data of AUTOFLEX CEMT II vessel

Object Name	Material	Weight (tonne-f)	*LCG* (m)	*TCG* (m)	*VCG* (m)
Layer: Shell					
TrimSrf	S 235 JRG2 5 mm	11,872	26,427	2,275	0,689
TrimSrf	S 235 JRG2 5 mm	11,872	26,427	-2,275	0,689
SubTotal		23,744	26,427	0,000	0,689
Layer: Bow thruster bulkhead					
surface	S235 4 mm	0,264	49,294	1,622	1,321
surface	S235 4 mm	0,264	49,294	-1,622	1,321
SubTotal		0,529	49,294	0,000	1,321
Layer: Colision Bulkhead					
surface	S235 4 mm	0,246	50,297	-1,523	1,362
surface	S235 4 mm	0,246	50,297	1,523	1,362
SubTotal		0,492	50,297	0,000	1,362
Layer: Cargo Hold_bulkheads					
surface	S235 4 mm	0,317	46,294	1,603	1,538
surface	S235 4 mm	0,317	46,294	-1,603	1,538
surface	S235 4 mm	0,307	9,094	-1,598	1,583
surface	S235 4 mm	0,307	9,094	1,598	1,583
SubTotal		1,248	27,970	0,000	1,560
Layer: Aft peak bulkhead					
surface	S235 4 mm	0,184	2,094	-1,650	2,272
surface	S235 4 mm	0,184	2,094	1,650	2,272
SubTotal		0,368	2,094	0,000	2,272
Layer: Full floor					
surface	S 235 JRG2 5 mm	0,064	28,706	1,639	0,251
surface	S 235 JRG2 5 mm	0,064	19,590	1,639	0,251
surface	S 235 JRG2 5 mm	0,064	37,706	1,639	0,251
surface	S 235 JRG2 5 mm	0,064	28,706	-1,639	0,251
surface	S 235 JRG2 5 mm	0,064	19,590	-1,639	0,251
surface	S 235 JRG2 5 mm	0,064	37,706	-1,639	0,251
SubTotal		0,386	28,668	0,000	0,251
Layer: Floor					
SubTotal		7,553	27,789	0,000	0,252
Layer: Floor brackets					
SubTotal		1,356	48,789	0,000	0,398
Layer: DB stiffeners_HP120x7					
polysurface	HP	0,284	27,694	-1,799	0,432
polysurface	HP	0,284	27,694	-0,899	0,432
polysurface	HP	0,284	27,694	1,799	0,432
polysurface	HP	0,284	27,694	0,899	0,432
polysurface	HP	0,263	29,043	0,899	0,068
polysurface	HP	0,263	29,045	1,799	0,068
polysurface	HP	0,263	29,043	-0,899	0,068
polysurface	HP	0,263	29,045	-1,799	0,068

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polysurface	HP	0,021	10,442	-1,799	0,105
polysurface	HP	0,021	10,442	-0,899	0,105
polysurface	HP	0,021	10,442	1,799	0,105
polysurface	HP	0,021	10,442	0,899	0,105
SubTotal		2,272	27,696	0,000	0,251
Layer: Longitudinal stiffeners_HP100x6					
polysurface	HP	0,200	27,694	3,243	0,993
polysurface	HP	0,200	27,694	3,243	2,002
polysurface	HP	0,200	27,694	3,243	1,503
polysurface	HP	0,200	27,694	2,758	2,002
polysurface	HP	0,200	27,694	2,758	1,503
polysurface	HP	0,200	27,694	2,758	0,993
polysurface	HP	0,200	27,694	-3,243	2,002
polysurface	HP	0,200	27,694	-3,243	1,503
polysurface	HP	0,200	27,694	-3,243	0,993
polysurface	HP	0,200	27,694	-2,758	2,002
polysurface	HP	0,200	27,694	-2,758	1,503
polysurface	HP	0,200	27,694	-2,758	0,993
SubTotal		2,395	27,694	0,000	1,499
Layer: Poop deck					
surface	S235 6 mm	1,413	4,547	1,650	3,160
surface	S235 6 mm	1,413	4,547	-1,650	3,160
SubTotal		2,827	4,547	0,000	3,160
Layer: Stringer deck					
surface	S235 6 mm	0,888	49,209	-1,522	1,452
surface	S235 6 mm	0,888	49,209	1,522	1,452
SubTotal		1,776	49,209	0,000	1,452
Layer: Forecastle deck					
surface	S235 6 mm	0,933	49,336	-1,547	2,600
surface	S235 6 mm	0,933	49,336	1,547	2,600
SubTotal		1,866	49,336	0,000	2,600
Layer: Tanktop foreship					
surface	S235 6 mm	0,257	51,210	1,199	0,760
surface	S235 6 mm	0,257	51,210	-1,199	0,760
surface	S235 6 mm	0,484	47,852	-1,649	0,760
surface	S235 6 mm	0,484	47,852	1,649	0,760
SubTotal		1,482	49,016	0,000	0,760
Layer: Longit. stiffeners_HP100x6					
polysurface	HP	0,035	49,525	0,963	2,543
polysurface	HP	0,034	49,462	0,966	1,401
polysurface	HP	0,031	49,184	2,000	2,543
polysurface	HP	0,035	49,525	-0,963	2,543
polysurface	HP	0,031	49,184	-2,000	2,543
polysurface	HP	0,034	49,462	-0,966	1,401
polysurface	HP	0,011	51,046	-1,799	0,692
polysurface	HP	0,015	51,296	-0,899	0,692
polysurface	HP	0,015	51,296	0,899	0,692
polysurface	HP	0,011	51,046	1,799	0,692
polysurface	HP	0,023	47,794	1,799	0,692
polysurface	HP	0,023	47,794	0,899	0,692
polysurface	HP	0,023	47,794	-0,899	0,692

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polysurface	HP	0,023	47,794	-1,799	0,692
SubTotal		0,343	49,248	0,000	1,539
Layer: Cargo Hold_longit bulkheads					
surface	S 235 JRG2 5 mm	3,884	27,694	2,701	1,830
surface	S 235 JRG2 5 mm	3,884	27,694	-2,701	1,830
SubTotal		7,768	27,694	0,000	1,830
Layer: Side keelsons					
surface	S 235 JRG2 5 mm	0,726	27,785	2,701	0,251
surface	S 235 JRG2 5 mm	0,726	27,785	-2,701	0,251
surface	S 235 JRG2 5 mm	0,251	6,111	0,700	0,905
surface	S 235 JRG2 5 mm	0,245	6,189	1,400	0,904
surface	S 235 JRG2 5 mm	0,239	6,258	2,100	0,904
surface	S 235 JRG2 5 mm	0,251	6,111	-0,700	0,905
surface	S 235 JRG2 5 mm	0,245	6,189	-1,400	0,904
surface	S 235 JRG2 5 mm	0,239	6,258	-2,100	0,904
SubTotal		2,923	16,920	0,000	0,580
Layer: Centre keelson					
surface	S 235 JRG2 5 mm	0,165	49,319	0,000	0,380
surface	S 235 JRG2 5 mm	0,351	5,812	0,000	0,738
SubTotal		0,516	19,746	0,000	0,623
Layer: Wash bulkhead					
surface	S 235 JRG2 5 mm	0,172	49,575	0,000	1,117
SubTotal		0,172	49,575	0,000	1,117
Layer: Center keelson					
surface	S 235 JRG2 5 mm	0,730	27,694	0,000	0,250
SubTotal		0,730	27,694	0,000	0,250
Layer: Floors					
SubTotal		2,903	6,164	0,000	0,915
Layer: Tweeendeck_ER					
surface	S235 6 mm	1,227	5,138	-1,606	1,384
surface	S235 6 mm	1,227	5,138	1,606	1,384
SubTotal		2,454	5,138	0,000	1,384
Layer: Engine room_side plates					
surface	S 235 JRG2 5 mm	0,852	5,107	2,701	1,911
surface	S 235 JRG2 5 mm	0,852	5,107	-2,701	1,911
SubTotal		1,705	5,107	0,000	1,911
Layer: Engine room long. bulkhead					
surface	S235 4 mm	0,506	4,558	0,000	2,274
SubTotal		0,506	4,558	0,000	2,274
Layer: Web Frames					
surface	S 235 JRG2 5 mm	0,038	40,706	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	13,590	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	16,590	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	31,706	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	34,706	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	43,706	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	40,706	-3,001	1,557
surface	S 235 JRG2 5 mm	0,038	13,590	-3,001	1,557
surface	S 235 JRG2 5 mm	0,038	16,590	-3,001	1,557
surface	S 235 JRG2 5 mm	0,038	31,706	-3,001	1,557
surface	S 235 JRG2 5 mm	0,038	34,706	-3,001	1,557
surface	S 235 JRG2 5 mm	0,038	43,706	-3,001	1,557

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surface	S 235 JRG2 5 mm	0,038	25,590	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	25,590	-3,001	1,557
surface	S 235 JRG2 5 mm	0,038	22,590	3,001	1,557
surface	S 235 JRG2 5 mm	0,038	22,590	-3,001	1,557
SubTotal		0,609	28,648	0,000	1,557
Layer: Side_Watertight bulkheads					
surface	S 235 JRG2 5 mm	0,049	19,590	3,000	1,550
surface	S 235 JRG2 5 mm	0,049	28,706	3,000	1,550
surface	S 235 JRG2 5 mm	0,049	37,706	3,000	1,550
surface	S 235 JRG2 5 mm	0,049	19,590	-3,000	1,550
surface	S 235 JRG2 5 mm	0,049	28,706	-3,000	1,550
surface	S 235 JRG2 5 mm	0,049	37,706	-3,000	1,550
SubTotal		0,296	28,668	0,000	1,550
Layer: Web frame ER					
surface	S 235 JRG2 5 mm	0,042	4,094	3,000	2,273
surface	S 235 JRG2 5 mm	0,042	5,594	3,000	2,272
surface	S 235 JRG2 5 mm	0,042	7,094	3,000	2,272
surface	S 235 JRG2 5 mm	0,042	8,594	3,000	2,272
surface	S 235 JRG2 5 mm	0,042	4,094	-3,000	2,273
surface	S 235 JRG2 5 mm	0,042	5,594	-3,000	2,272
surface	S 235 JRG2 5 mm	0,042	7,094	-3,000	2,272
surface	S 235 JRG2 5 mm	0,042	8,594	-3,000	2,272
SubTotal		0,334	6,344	0,000	2,272
Layer: Toprail					
extrusion	S235	0,983	27,694	2,710	3,068
extrusion	S235	0,983	27,694	-2,710	3,068
polysurface	S235	0,071	46,303	1,350	3,068
polysurface	S235	0,071	46,303	-1,350	3,068
polysurface	S235	0,071	9,085	1,351	3,068
polysurface	S235	0,071	9,085	-1,350	3,068
SubTotal		2,251	27,694	0,000	3,068
Layer: Hatchway coaming					
SubTotal		0,790	27,864	0,000	2,713
Layer: Shell frame					
surface	S 235 JRG2 5 mm	0,027	47,794	3,112	1,680
surface	S 235 JRG2 5 mm	0,027	48,294	3,112	1,680
surface	S 235 JRG2 5 mm	0,027	48,794	3,112	1,680
surface	S 235 JRG2 5 mm	0,027	46,794	3,112	1,680
surface	S 235 JRG2 5 mm	0,027	47,294	3,112	1,680
surface	S 235 JRG2 5 mm	0,023	49,797	3,088	1,804
polysurface	S 235 JRG2 5 mm	0,028	50,794	2,782	1,680
surface	S 235 JRG2 5 mm	0,027	47,794	-3,112	1,680
surface	S 235 JRG2 5 mm	0,027	48,294	-3,112	1,680
surface	S 235 JRG2 5 mm	0,027	48,794	-3,112	1,680
surface	S 235 JRG2 5 mm	0,027	46,794	-3,112	1,680
surface	S 235 JRG2 5 mm	0,027	47,294	-3,112	1,680
polysurface	S 235 JRG2 5 mm	0,028	51,794	2,096	1,680
polysurface	S 235 JRG2 5 mm	0,028	51,294	2,495	1,680
surface	S 235 JRG2 5 mm	0,023	49,797	-3,088	1,804
polysurface	S 235 JRG2 5 mm	0,028	50,794	-2,782	1,680
polysurface	S 235 JRG2 5 mm	0,028	51,794	-2,096	1,680
polysurface	S 235 JRG2 5 mm	0,028	51,294	-2,495	1,680

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polysurface	S 235 JRG2 5 mm	0,028	52,294	-1,516	1,681
polysurface	S 235 JRG2 5 mm	0,028	52,294	1,516	1,681
surface	S 235 JRG2 5 mm	0,021	52,639	0,572	1,666
surface	S 235 JRG2 5 mm	0,021	52,639	-0,572	1,666
SubTotal		0,581	49,732	0,000	1,689
Layer: Catwalk					
surface	S235 6 mm	1,050	27,695	3,000	2,600
surface	S235 6 mm	1,050	27,695	-3,000	2,600
SubTotal		2,099	27,695	0,000	2,600
Layer: Transom					
surface	S 235 JRG2 5 mm	0,059	0,000	1,650	3,388
surface	S 235 JRG2 5 mm	0,059	0,000	-1,650	3,388
extrusion	S 235 JRG2 5 mm	0,073	0,000	1,650	2,880
extrusion	S 235 JRG2 5 mm	0,073	0,000	-1,650	2,880
SubTotal		0,263	0,000	0,000	3,108
Layer: Bulwark stern					
surface	S 235 JRG2 5 mm	0,153	4,568	3,300	3,386
surface	S 235 JRG2 5 mm	0,153	4,568	-3,300	3,386
surface	S 235 JRG2 5 mm	0,205	4,672	3,300	2,877
surface	S 235 JRG2 5 mm	0,205	4,672	-3,300	2,877
SubTotal		0,717	4,628	0,000	3,095
Layer: Bulwark bow					
polysurface	S 235 JRG2 5 mm	0,156	50,596	2,470	2,852
polysurface	S 235 JRG2 5 mm	0,156	50,596	-2,470	2,852
SubTotal		0,312	50,596	0,000	2,852
Layer: Girder Bow					
surface	S235 6 mm	0,023	52,694	0,000	2,046
SubTotal		0,023	52,694	0,000	2,046
Layer: G_Anchor Chain					
Anchor chain bow	Ancor chain bow	1,500	51,924	0,000	1,865
SubTotal		1,500	51,924	0,000	1,865
Layer: Bow thruster tunnel					
surface	S 235 JRG2 5 mm	0,317	49,787	-1,522	0,598
surface	S 235 JRG2 5 mm	0,317	49,787	1,522	0,598
SubTotal		0,635	49,787	0,000	0,598
Layer: Anchors_bow					
Anchor bow	Bow anchor	0,700	51,968	2,353	1,990
Anchor bow	Bow anchor	0,700	51,968	-2,353	1,990
SubTotal		1,400	51,968	0,000	1,990
Layer: Bow winch					
Bow winch	Bow winch	0,800	50,524	0,000	2,778
SubTotal		0,800	50,524	0,000	2,778
Layer: G_Bow thruster					
Bow Thruster	Bow thruster	1,200	49,797	0,000	0,581
SubTotal		1,200	49,797	0,000	0,581
Layer: Emergency batteries					
Emergency batteries	Emergency batteries	1,600	47,905	0,000	0,893
SubTotal		1,600	47,905	0,000	0,893
Layer: Mast bow					
Mast bow	Mast bow	0,800	47,730	0,000	4,518

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SubTotal		0,800	47,730	0,000	4,518
Layer: Nav. equipment					
Nav. Equipment	Nav. Equipment	0,900	46,711	0,000	1,765
SubTotal		0,900	46,711	0,000	1,765
Layer: G_azimuth thrusters					
Azimuth Thruster 380 kW	Azimuth thruster 350 kW	3,500	1,576	-1,539	0,914
Azimuth Thruster 380 kW	Azimuth thruster 350 kW	3,500	1,576	1,539	0,914
SubTotal		7,000	1,576	0,000	0,914
Layer: Anchor stern					
Anchor stern	Anchor stern	0,700	-0,138	0,000	2,554
SubTotal		0,700	-0,138	0,000	2,554
Layer: Mast stern					
Mast stern	Mast Stern	0,300	0,402	0,000	4,542
SubTotal		0,300	0,402	0,000	4,542
Layer: Converter_Inverter_total weight					
Converter_Inverter	Nav. Equipment	0,900	6,307	0,000	1,771
SubTotal		0,900	6,307	0,000	1,771
Layer: Stern winch					
point	Stern winch	0,800	1,481	0,000	3,343
SubTotal		0,800	1,481	0,000	3,343
Layer: G_corrosion					
Frames_corrosion allowance	Corrosion	10,000	27,219	0,000	0,704
SubTotal		10,000	27,219	0,000	0,704
Layer: Tanktop cargo hold					
surface	S235 6 mm	5,782	27,694	-1,650	0,500
surface	S235 6 mm	0,604	7,097	-1,538	0,500
surface	S235 6 mm	0,604	7,097	1,538	0,500
surface	S235 6 mm	5,782	27,694	1,650	0,500
SubTotal		12,771	25,747	0,000	0,500
Totals		**117,895**	**25,745**	**0,000**	**1,159**

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