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Implementation of Zero Emission Fast Shortsea Shipping and Design of Demonstrator

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The paper describes the implementation of state-of-the-art "Industry 4.0" methods and tools, of a holistic ship design optimization and of modular production methods, as well as of advanced battery technologies in the development of an innovative, fully electrical, fast zero-emission catamaran for waterborne urban transport. The design of a fast catamaran passenger ferry (Medstraum), planned for operation as a waterborne shuttle in the Stavanger/Norway area and of a replicator for operation at Thames River/London are elaborated, including on land infrastructural issues that are necessary for their operation. The presented research is in the frame of the H2020 funded project "TrAM – Transport: Advanced and Modular" (www.tramproject.eu).

KEY WORDS: Industry 4.0; hydrodynamic optimization; modular production; holistic ship design; zero-emission fast maritime transport; battery and charging technology; SMART city integration.

INTRODUCTION

The international maritime community is amassing momentum in its efforts towards a drastic reduction of greenhouse gas (GHG) emissions. This is expected to be further accelerated after the upcoming COP26[1] (COP26: UN Climate Change Conference of Parties) in Glasgow in autumn 2021. The maritime industry is examining alternative ways to contribute actively to this endeavor, despite the additional challenges posed by the Covid-19 pandemic.

A significant part of the global fleet facing unique challenges is short-sea shipping (SSS) and especially fast passenger ferries. Their smaller size and their inherent target for minimizing their lightship weight, while meeting demanding operational requirements for speed and endurance, whilst complying with an increasingly more demanding regulatory framework, constitute a challenging design problem (Boulougouris et.al. 2020, Papanikolaou, 2020b). Among other Zero-Carbon alternatives, battery-driven propulsion offers a cost-effective and environmental-friendly life-cycle solution that can be readily integrated into smart cities' transportation network (Sachs et.al. 2021). The H2020 funded project "TrAM – Transport: Advanced and Modular" (www.tramproject.eu) demonstrates the feasibility and competitiveness of such a concept by designing and constructing a fast catamaran passenger ferry for operation as a waterborne shuttle bus in the Stavanger/Norway area (Dahle 2020) and a replicator for the London's Thames River and the Belgium canals.

The Horizon 2020 TrAM project (https://tramproject.eu/) is elaborated by 13 partners across Europe which are representative of the European maritime shipbuilding and shipping industry, of research and development institutions. The TrAM project aims to develop a zero-emission fast going passenger vessels through advanced modular production. New design and manufacturing methods will contribute to 25 per cent lower production costs and 70 per cent lower engineering costs. The project is revolutionary both in terms of zero-emission technology and manufacturing methods and will contribute to making electric-powered high-speed vessels competitive in terms of cost, travelling comfort and environmental footprint.

Norway has been at the forefront of introducing low- or zero-emission car ferries. During 2020 26 ferry routes were electrified and by 2022 approximately 70 electric ferries will be operating routes in Norway (Meld. St. 13 "Klimaplan for 2021-2030"). In late 2020, the Norwegian government introduced new requirements for ferries and fast-ferries ("Klimaplan for 2021-2030"), stating that all new ferries and fast-ferries shall be low- or zero-emission within the next few years, namely 2023 and 2025, respectively. In Norway, there are approximately 100 fast-ferry routes and the number of new low- or zero-emission fast ferries to be developed over the coming years is therefore significant.

Fast passenger ferries have a CO_2 emission per passenger-kilometer that exceeds most other means of public transport modes. However, in many places, these fast passenger ferries are the only realistic mean of public transport (e.g. for islands without any road infrastructure). Figure 1 below shows the CO_2 emissions per passenger-kilometer for various means of transport. The numbers in this figure were deduced from TØI (2014), FIVH (2019) and SSB (2018).

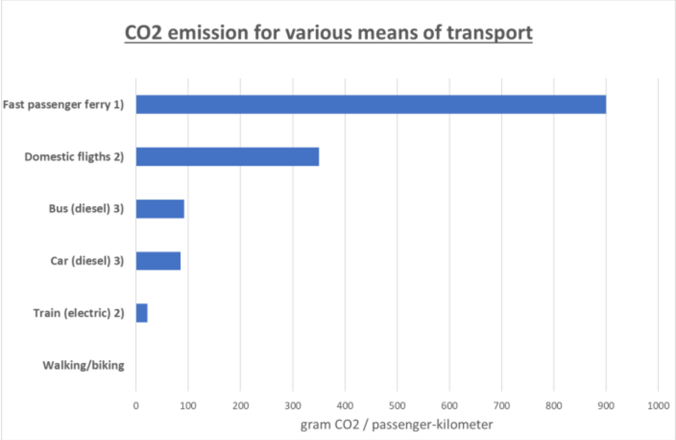

Figure 1. CO_2 emissions per passenger-kilometer for various means of transport (Norway)

The Norwegian transport operator Kolumbus operates 3 ferries, 10 fast-ferries and approximately 450 buses in Rogaland county. The transport within Kolumbus contributes to CO_2 emissions of approximately 54,600 tons, where over 30,000 tons is the result of the boat transport (Kolumbus 2020). With an ambitious target to offer fossil-free transport by 2024, developments of zero-emission fast-ferries is an important part of the total reduction of CO_2 emissions. In addition to the TrAM project, Kolumbus is also involved in a project where existing hybrid fast-ferries are being rebuilt to become fully electrical with targeted completion in 2022. Rogaland county, through Kolumbus, is therefore likely to be the first county in Norway (and maybe in whole Europe) to offer zero-emission fast-ferries in operation.

In the course of the TrAM project, the Stavanger Demonstrator vessel is being developed; it will be built and start operation before the end of the project in summer 2022. In addition, two replicator vessels for the canals in Belgium and the River Thames in London will be designed, proving the TrAM methodology for cases that vary significantly in geographical location, regulatory requirements, size, speed and operational mode.

The present paper describes the implementation of state-of-the-art "Industry 4.0" holistic ship design optimization (Papanikolaou 2010; Papanikolaou et.al. 2020a) and production methods, as well as advanced battery and charging technologies, as facilitators for enabling these fully electrical fast zero-emission vessels. Furthermore, critical issues affecting the feasibility of battery-driven solutions, namely the land-based electrical network infrastructure, are presented and the authors' view for the way forward is outlined.

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[1] COP26: Next UN Climate Change Conference of Parties

HULL FORM & HYDRODYNAMICS

Hydrodynamic Optimization

The hydrodynamic optimization of catamarans and multi-hull vessels, in general, is a multiparametric mathematical and engineering problem with several objectives and constraints. We restrict herein our optimization problem to the design of small passenger catamarans of semi-displacement type (Papanikolaou et al. 1996) and assume the specification of a certain payload capacity (for passengers and light cargo), of a basic general arrangement of spaces (at least the deck layout) and the service speed and range by the end-user. It is the designer's task to find the vessel's optimal dimensions (length, overall beam, demihulls' beam and separation distance), hull form and displacement, the latter in dependence on the ship's lightship weight (weight of the structure, machinery and outfitting). The optimization refers in general to the ship's calm water performance, thus minimization of ship's resistance and the required propulsion power, by maximization of the propulsive efficiency. The optimization of the catamaran's seakeeping performance is herein addressed by operational measures based on conducted seakeeping analysis for the environmental conditions in the area of operation. Also, the maneuvering performance of twin-hull vessels is in general, not a difficult optimization issue due to their inherent maneuvering capability of catamarans in view of turning moment generated by the fitted set of Controllable Pitch (CP) propellers on the demihulls, which are very often also supported by a set of bow thrusters.

For a *battery-driven, fast* catamaran the hydrodynamic optimization appears even more urgent than for a conventional high-speed craft because the weight and space constraints imposed by the fitting of the battery-racks for the required battery capacity and of the e-motors driving the propellers more significantly affect the ship's design and the associated displacement-speed-power profile. In fact, the feasibility of a fast, battery-driven catamaran decisively depends on the achieved hydrodynamic efficiency, setting the limits for the achievable speed in relation to the vessels size and displacement (Papanikolaou, 2020b).

Given the many unknown parameters involved in the set optimization problem, which make an exhaustive exploration of the design space practically impossible, it is advisable to reduce the number of unknown parameters to the extent feasible, while not compromising in the search for the optimal solution. This parameter reduction process is based on the designer's experience and background fundamental studies on the effect of certain design parameters on the ship's properties (herein mainly on ship's weight and displacement) and on her hydrodynamic performance (here total calm water resistance and its components).

An increase of demihull's length or the length to bream ratio (slenderer demihulls for given displacement) generally leads to an increased wetted surface and of frictional resistance, while the decrease of wave resistance is modest at higher speeds, for high Froude numbers[2] over about 0.60 (Papanikolaou 2020b). An increase of the demihulls' separation distance leads to a reduction of the interaction effect that increases ship's wave resistance at medium Froude numbers below about 0.60, but at the expense of a higher structural weight for the strength of the deck support structure, which leads to an increased displacement and losses of the achieved gains in the wave resistance account. An asymmetry of the demihulls may be beneficial for the wave resistance at certain speeds, but benefits depend on the operational Froude number. An optimization of the lengthwise displacement distribution may lead to a favorable (negative) demihull interaction effect for some twin-hull types (e.g. SWATH ships), as shown in Papanikolaou et al. (1996).

Based on this reasoning, it proves very efficient in practice to proceed with a two-stage optimization procedure, namely, first, a *global* one referring to the determination of ship's main dimensions and its integrated hull form characteristics, followed by a *local*[3] one referring to details of ship's hull form and its propulsion system. The various steps on this pathway to the selection of the final best hull form are outlined in Figure 2.

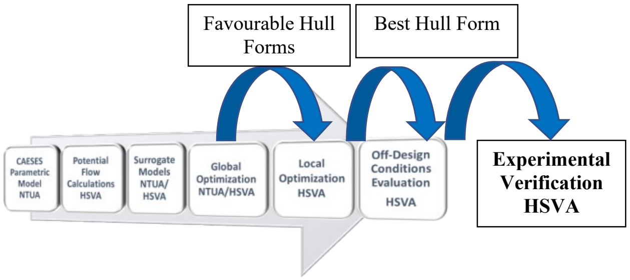
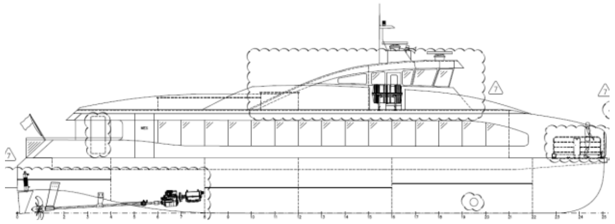


Figure 2. Multi-stage numerical optimization and experimental verification



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[2] Froude number: dimensionless speed ratio $V/(g\,L)^{1/2}$

[3] The terms global and local optimization are often used differently in optimization theory, namely with respect to the identification of global and local optima in optimization problems involving rapidly changing objective function(s), what is herein not the case.

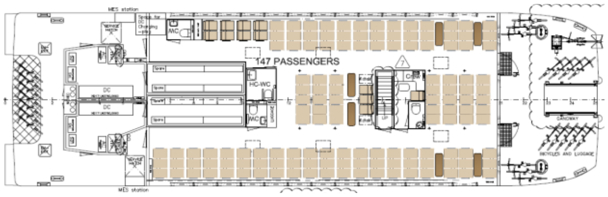


Figure 3. Preliminary general arrangement of the Stavanger Demonstrator (LOA=30m, BOA=9m)

This optimization procedure relies on the development of a parametric model for the variation of the geometry of demihulls' hull form and their separation distance that can be readily accomplished by use of the software platform CAESES® (Harries et al. 2019). The parametric model of the hull form for the TrAM project Stavanger demonstrator was based on 20 design hull form parameters, referring to the catamaran's main dimensions, as well as to local hull details, such as the width, immersion and shape of the transom and the shape of the bow area of the vessel (Kanellopoulou et al., 2019). It is noted, however, that the deck layout/boundary, thus LOA x BOA, was specified by the end-user (see Figure 3).

The parametric model offers the possibility to automatically generate smooth hull forms in the specified range of the main particulars of the demihulls along with the possibility to control and modify a series of important hull form details. A preliminary exploration of the design space while considering the set design constraints allowed the drastic reduction of the free design parameters. Finally, based on 4 main design parameters (waterline length, demihull beam, draft and transom stern width), a large number of about 1,000 alternative hull forms was generated and their total resistance was assessed with the use of the 3D panel code v-SHALLO of HSVA (Gatchell et al. 2020) to form the basis for the development of *surrogate* models (response surfaces) for the estimation of calm water resistance. Global optimization studies were carried out using the NSGA-II genetic algorithm, and two of the most promising designs were selected for the more refined local optimization. These hull forms were further optimized using 6 new parameters of the CAESES® parametric model referring to the definition of the tunneled transom stern area and 4 parameters for the propeller diameter, its position and inclination. Also, 8 constraints referring to the inclination and fitting of the propeller shaft and electric motor, as well as propeller clearances from the hull for low vibrations were considered (see Figure 4).

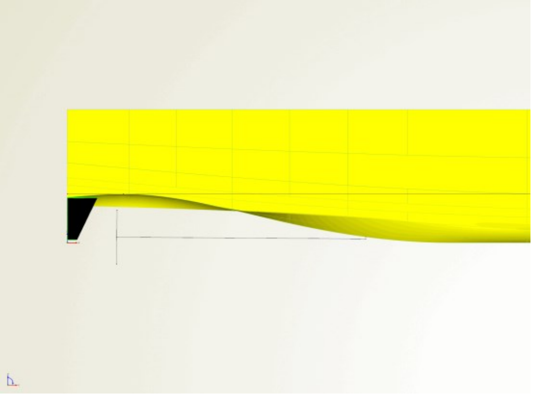


Figure 4. The parametric model for local hull form optimization showing the propeller position and inclination

Optimization runs were with HSVA' s URANS tool FreSCo$^+$ (Hafermann 2007) while focusing on the optimization of the propulsive efficiency by carefully analyzing the performance of the unique tunneled transom-stern and its interaction with the fitted propellers (2 CP propellers), propeller shaft, brackets and rudder (2 twisted rudders).

The seakeeping of fast catamarans is an important issue to be considered in vessel's design and operation. In the present case the vessel is planned to operate in a protected area around the city of Stavanger in NW Norway, where the sea conditions practically never develop over 1.0m significant wave height (probability of occurrence of a wave height over 1.0 m is less than 1%). At the request of the classification society DNV, we have conducted a dedicated seakeeping study for the area of operation and various ship speeds, while considering the year-round wave conditions and the performance criteria of the IMO International Code of Safety for High-Speed Craft (HSC Code) 2000 Chapter 17, supplemented by IMO HSC 2000 Annex 3 and Annex 9 (Dafermos et.al, 2021). Except for the beam seas condition, where the level 1 (0.2g) comfort criterion for the horizontal acceleration is violated for sign. wave height of 1.0m (and higher), but not the level 2 (0.35g) safety criterion, for all other headings and operational conditions both HSC Code criteria are met.

Details of the hydrodynamic analysis of the Stavanger demonstrator and the Thames Clippers replicator are given in a later section.

INNOVATIVE TECHNOLOGY & OPERATIONAL ISSUES

Modular Production

Ship design is characterized by individual solutions hardly found in other industries. Typically, almost every new ship is developed from scratch to meet the specific requirements for the later planned route, according to the requirements of the designated operator and the national regulations. The ship design itself is highly complex and involves great effort and experienced naval architects who play a major role in the development of new ships (Papanikolaou 2014). Product development in shipbuilding is mainly characterised by complex product structures and unique or small series production (Hoffmann 2017).

The design process may follow two basic approaches, namely it may be the result of an Research and Technological Development (RTD) process or be based on the cooperation with a customer who may place an order. The aim of cooperation with a customer is usually the conclusion of a contract and the construction of the ship. The focus is mainly on economic aspects, while innovations regularly play a subordinate role (Vossen et al. 2013). To keep the risk low and to comply with the customer's economic expectations, the developer usually exploits reference data from comparable, proven ship designs, but this is only possible to a limited extent. In contrast, a RTD based design focuses on innovation. The market is analysed in detail and new ideas and concepts are being considered with the aim of developing a completely new ship design (Vossen et al. 2013).

Design methods to implement one of the described approaches are in general using an iterative process to refine the design step by step. Examples are the traditional design spiral method according to Evans and the system-based ship design according to Levander (Papanikolaou, 2014), while the holistic approach to ship design on the basis of the synthesis of parallel running design processes is showing the way ahead (Papanikolaou et al, 2020a)

The final ship design is the result of a multi-objective optimization process in which the best solution is selected from a range of possible alternative solutions. Those variants are based on a variety of optimization criteria such as stakeholder requirements and economy, life-cycle operational performance and cost, while considering class society rules and national/international safety and environmental regulations.

As the need for environment-friendly fast ferries is growing, the design and building of a large number of these for different routes, passengers and use-cases are of serious concern. However, the current one-off design and building methods are seem not suitable to meet these challenges. In order to solve the contradiction of individuality and standardization, modularisation is an established methodology from other industries, providing the necessary instruments to meet these challenges.

The automotive and aviation sectors are of particular interest, as they face similar challenges to fulfil similar functions with their products. With the general target to move people safely from one place to another the product needs to adapt to the specific use-case of the customer. By developing modular product architectures, it is possible to combine individual modules that adapt the product to individual customer needs or boundary conditions. At the same time, the reuse of modules allows shortening development and production times.

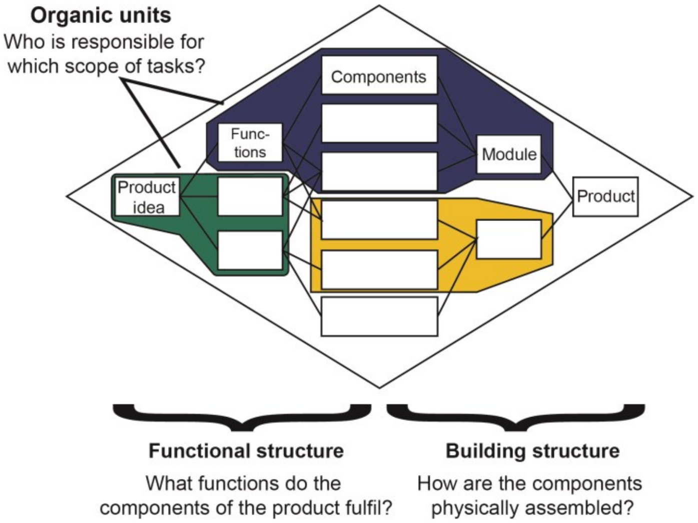


Figure 5. Modular product architecture according to Göpfert

Initially, all modularization approaches start with the gathering of requirements for the product to be designed, followed by the definition of functions to be fulfilled. To design a modular product those functions must be defined to be independent of each other (functional decomposition). This enables corresponding physical elements to be independent of each other as well. The change of a single requirement would, in an ideal world, lead to the change of only one function and consequently to the exchange of just one physical element that is then defined as a module. In real life requirements, functions and components have to be grouped into modules, against the background of having as little impact as possible on other modules when making changes. A well-known illustration to describe this principle is shown in Figure 5 based on the work of Göpfert (Pfeifer at al. 2020).

The separation of functions to identify modules as proposed by Göpfert and others, either with the use of tree diagrams or matrices, is not easily adaptable and feasible for ships. A short example demonstrates the problem of related functions:
Assuming a vessel only has to fulfil the two functions, thrust and transport of goods, this alone creates very strong dependencies. The functions can be linked to the hull and the propulsion. Increasing the required speed usually requires larger and heavier propulsion. This would lead to an adaptation of the hull because more space has to be provided for the propulsion. Since not only two functions are to be fulfilled, but many more, a network of dense interconnections between the individual functions is created (Erikstad 2019).

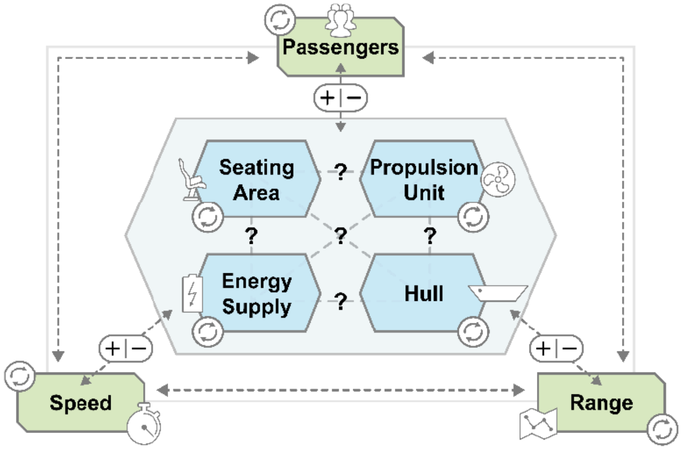


Figure 6. Multidimensional optimization problem in ship design

The example illustrates the special challenge of ship design. The modification of a small component leads to a series of consequential changes due to the close interweaving of the components, which means that even large components of the ship have to be adapted (Chaves et al. 2015). This problem and its dependencies are illustrated in Figure 6.

Due to the strong interweaving of the individual elements in the construction of a modular electric ship, it is not possible to use conventional modularization methods, as these aim to divide the functions of a product into independent modules (Wildemann 2014). The changes to the batteries and the associated weights trigger a lot of other changes to the overall ship design, making this impossible for a battery-driven ship.

Within the Horizon 2020 project TrAM (Transport Advanced and Modular) the adopted solution approach is based on the idea of supporting module identification using a consistent, domain-spanning system model. The logical system architecture is used to analyse relations and connections between system elements and to determine the optimal system interfaces. The proposed design method is structured in three steps: Analysis, Platform Synthesis and System Synthesis. An overview of the method can be found in Figure 7.

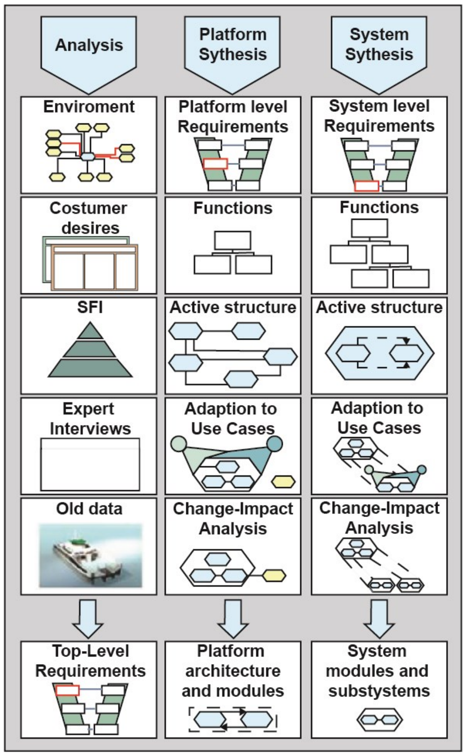


Figure 7. Methodical approach for a modular ship design

As a first step, the various requirements for the modular ferry class are defined. An analysis is carried out for this purpose. In addition to a partial model from CONSENS (CONceptual design Specification technique for the Engineering of complex Systems), the environment model and customer desires are considered (Dorociak 2014). The analysis also includes expert interviews and data from ships already built. Furthermore, the SFI Coding and Classification System, which is used by many shipyards and is often the basis for the construction of new ships, is also part of the analysis to adapt certain elements of the structure. The resulting requirements are not for an individual ferry but a complete class of ships. Therefore, a defined range of use-cases needs to be used as input for this analysis phase. After finishing the first phase, the boundaries for the ferry class are set as well as the combined requirements that are needed to build any ferry that is covered by the ship class.

In the second and third phase of the process, the RFLP method is used as a basis and taken further to develop not individual systems, but entire classes. RFLP stands for Requirements *(R)*, Functions *(F)*, Logical *(L)* and Physical *(P)*. For the second phase, the procedure is to start with the top-level requirements and refine them further to the platform level requirements *(R)*. Based on this the functions *(F)* are developed that are needed to fulfil the defined requirements. This is followed by the creation of an active structure, also known as logical structure *(L)*. Only platform components are mentioned. The more the use-cases that are to be covered by the ship class differ from each other, the more generic the platform elements will be.

The logical structure is a 150% architecture of the class as it covers all platform modules that will be needed to build any ship that fits the ship class. This is followed by an adaptation to the use-case, which describes the physical aspects of the RFLP architecture *(P)*. Here several physical architectures are generated to consider all use-cases used as input to define the ship-class. These are then used to start a change impact analysis where the platform modules get validated. The structure of the platform modules should not change at this point (number of elements, relation between the elements). However, the manifestation can differ for each use-case in geometry, dimension, manufacturer, or other aspects. By analysing the commonalities and differences between all use-case platform modules the elements can be categorised into standard, configurable condition, configurable number, optional and one-of-a-kind elements. Since the use-cases are selected to describe mainly the edge cases of the ship class, it may be necessary to describe additional manifestations of platform modules that cover cases within the ship class. The identified modules for the TrAM ship class as shown in Figure 8.

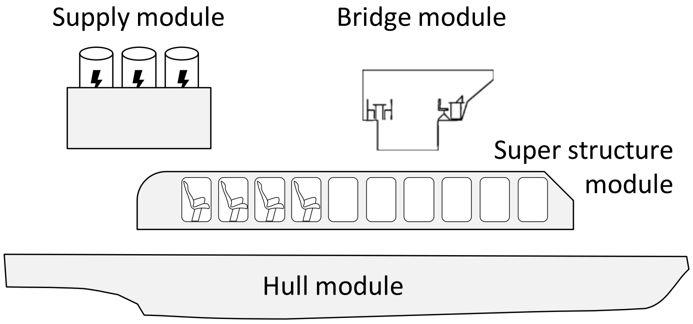


Figure 8. Identified modules for the TrAM ship class

Based on the platform architecture, the same steps can now be carried out on the system level. First, the system-level requirements *(R)* are derived from the top-level requirements and platform level requirements. Then the functions *(F)* on the system level are determined and a corresponding active structure *(L)* is developed for this level. Active structure and functions will be determined for each of the identified platform modules. This is followed by an adaption to use-case *(P)* and the change impact analysis, which validates the categorisation on the platform level. The resulting system modules are then divided into different categories analogous to the platform elements.

In addition to optimizing product design and adapting it to other use-cases, the modular approach also offers considerable potential in the area of production. While the current ship production is based on experience gained by previous projects each ship is an individual project with altering production partners. Because the new modular ship class is not only a one-off but the basis for a complete series of ships, the creation of a multi-company production and development network becomes beneficial.

Moreover, the planned "mass production" with collaborative development and production partners allows completely new types of digitalized production. Since networked production does not focus solely on internal company processes, but includes the entire supply chain, the processes upstream and downstream of production must also be taken into account. This means that all companies along the supply chain are integrated into their value creation processes. This integration is only as successful as the production systems and products designed for it are suitable.

By production and service networking the development and production of each individual module to specialists in the relevant field cost savings can be generated. This is based on several effects. The parallelisation of development leads to a shorter time to market and therefore a competitive advantage. Furthermore, specialised companies generate enough turnover to invest in automated production machines that would not be economic for producing individual solutions.

Furthermore, with specific defined functions and interfaces for each module, quality checks can be carried out module individually and thus independent from other network partners. Because errors are detected earlier in the value chain losses due to defect parts get minimised. These effects have already been documented in the automotive sector: Niemeyer et al. show that the strategic purchasing of car manufacturers now primarily pursues a reduction of the supplier base and concentrates more on the purchase of ready-to-install modules. This strategy has made it possible to significantly reduce the number of suppliers. As a result of this change, the system/module suppliers are now jointly responsible for the development, coordination and scheduling of production or pre-assembly as well as quality assurance (Niemeyer et al. 2014).

Modularization offers enormous potential to boost product development and production of zero-emission fast shortsea shipping.

Electrical system & Infrastructure

A key element of an all-electric ship is the onboard electrical system and the land-based charging infrastructure.

In the onboard electrical system, the control systems, converters, switchboards and batteries are already modular, as these systems are based upon high technology standard modules. These modules are assembled into systems to specifications that fit the overall requirements of each vessel. Transformers are scalable to the purpose, based upon a wide range of predefined sizes. The same is the case for the modules which constitute the systems mentioned above, for example, converter modules and electrical breakers etc. can be chosen to correct size from a large range of available standard modules.

A Single-Line-Diagram (SLD) for the electrical system onboard the Stavanger Demonstrator is shown in Figure 9.

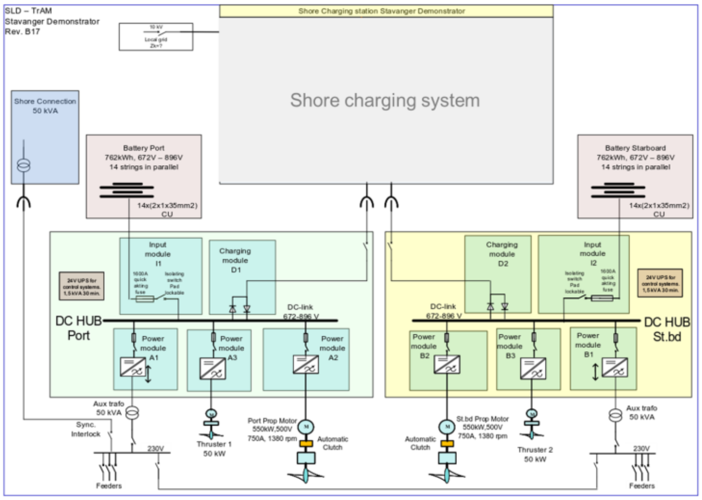


Figure 9: Single line diagram (SLD) for the Stavanger Demonstrator

Electrical Motors

The selection of the electrical propulsion motors of a battery-driven ship, transferring the battery energy to the propeller, presumes an early assessment of the ship's required power for the set operational speeds. In the TrAM project, the selection of the electrical motors followed the modular approach, as described above for the entire electrical system. Based on this approach, the e-motors are normally either chosen as the closest unit in size from a range of predefined motor sizes or rarely are custom-designed to fit the actual size needed. In the airplane market, some companies have in recent years developed electrical motor systems where one large motor can be assembled from an array of smaller motors to come as close as possible to the needed specifications. These also come with converters in modular sizes which fit the motor size. In this way, smaller and lighter motor/converter units can be delivered, since very advanced development processes can aim mainly at developing the modules to a high-tech specification and refining their power to weight ratio in the rpm area suited for electrical airplanes.

In a weight-sensitive market, this is a major advantage compared to the normal approach, where a basic specification is applied while spending some development cost for each project to adapt the unit size to fit the project, or choosing the nearest type from a range of standard units which are not optimized to the purpose. However, the motors optimized for the airplane market do not fit exactly the High-Speed Light Craft (HSLC) market, as their necessary RPMs are higher (even with a gearbox) and the efficiency is lower. The weight vs. efficiency numbers allows more lightweight / "inefficient" motors for airplanes, while the HSLC market favors more efficient / slightly heavier motors. Therefore, if the modular motor/converter approach should be viable, a (range of) optimized highly advanced motor/converter unit sizes combined with efficient reduction gear units would need to be developed. The motors for the TrAM project are therefore custom-sized based upon an existing design, optimized for high power to weight ratio and extremely high efficiency, fitting the RPMs for a high-efficiency gearbox.

Battery Propulsion

For High-Speed Light Craft (HSLC), the energy storage for propulsion power is of great importance. These vessels are in the fossil fuel world very energy consuming and responsible for a very high CO_2 emission per passenger distance compared to land transport. The reason for this is their small, very compact size and high operational speed, compared to other seagoing transport; for instance, the extremely efficient transport of goods on large container ships, which is the most carbon-efficient way of transport available.

To eliminate the carbon footprint of HSLC passenger transport, the TrAM project is developing a system with battery power propulsion. The main parameters for ensuring the success of battery-powered HSLC are the following:

- Safety.
- Energy to weight ratio.
- High lifetime.
- Multiple charging cycles per day.
- Cost.

Batteries in catamarans have previously mostly been located in the demi-hulls, ensuring good stability and also using available empty space in the vessel. However, for the Stavanger Demonstrator vessel, it has been concluded to place the battery rooms on deck level. The advantages of this solution have been found to outweigh the negative impact on stability and space. The main advantages of placing the battery rooms at deck level are:

- Safety
- Fewer constraints in hull form optimization
- Replaceability and ease of maintenance of batteries

The battery type selected for the Stavanger Demonstrator vessel is Corvus Dolphin Power batteries (Corvus Dolphin Power Data Sheet). The Stavanger Demonstrator is equipped with a total of 1524 kWh capacity batteries (2 x 762 kWh) placed in two separate battery rooms at the aft of the main deck. The battery modules are stacked in strings of 7 modules providing 54,4 kWh energy storage each. C-rate for charging for these batteries is by design 1.6. However, the entire system on the Stavanger Demonstrator is currently limited to a maximum total charging capacity of 2.3 MW.

Figure 10: Typical string of Corvus Dolphin Power batteries

Recharging Technology and Land-Infrastructure

Landside charging infrastructure is an indispensable part of projects for the electrification of vessels. For the increased demand for land-based charging systems, the required charging capacity will require strengthening of the local electrical network grid, in addition to the actual power electronics and charging connections at the quayside. The cost and schedule for the implementation of the shore side charging infrastructure may be a significant part of a battery-driven vessel's cost and affects its operational schedule.

Both the Stavanger Demonstrator and the replicator cases have busy timetables with limited time available for charging. A high-capacity charger is therefore required to ensure as much energy as possible can be transferred to the vessel batteries within a very short time.

Figure 11: Stavanger harbor and fast-ferry terminal at Fiskepiren

For the fast-ferry routes that operate in city areas, the available area for charging infrastructure may be limited in busy harbors. In the harbor of Stavanger, the charging will be done from the fast-ferry pier Fiskepiren. This is a very congested area, and the main part of the power electronics and high-voltage system will therefore be located in a space of a parking house at Jorenholmen, some distance away from the Fiskepiren pier. The area is shown in Figure 11. DC cables will then transfer the required power from the charging station at Jorenholmen to the plugs that connect to the vessel at Fiskepiren.

The main parts of the shore side charging infrastructure is shown in the single line diagram (SLD) in Figure 12. The high-voltage cable (10kV) is routed into a 1600kVA transformer to bring the voltage down to 690V. For the Stavanger Demonstrator, it has been concluded to use manual plugs for the charging connection. The selected plugs are standard CCS2 plugs, like those used for most electric vehicles onshore. Each plug is supplied with current routed through an AC/DC rectifier and a DC/DC chopper. Only one charging point will be established for the TrAM vessel, but the charging infrastructure is organised such that an additional charging point can be easily added at a later stage. When the two charging points are connected, this charging station will be able to charge at two different locations, but not at the same time.

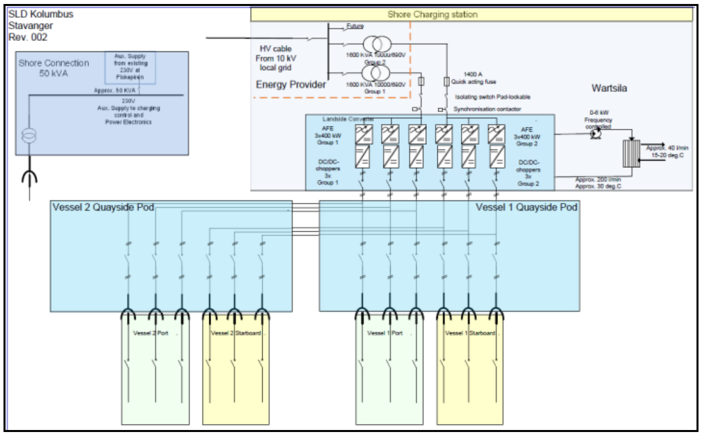


Figure 12: Single line diagram (SLD) for the Stavanger charging station (including future additional charging point)

The maximum capacity of the charging infrastructure for the Stavanger Demonstrator is 2.3 MW.

Figure 13: Draft layout of charging point for the Stavanger Demonstrator at Fiskepiren, Stavanger

For the manual plug-in connection, it is important to have an efficient and safe method. The proposed layout of the charging point will locate the plugs close to the connection point on the vessel and include a working platform for the crew to prevent any accidental slipping or falling incidents. An early draft of the proposed layout is shown in Figure 13.

Operation

Through a detailed review of the energy consumption, estimated losses, route details and operational requirements, the State of Charge (SoC) of the battery package through a normal operating day has been established.

The SoC chart forms the basis for the estimated lifetime of the batteries. Based on early estimates some minor changes to the route timetable and operational profile have been implemented. The primary target for these adjustments has been to avoid deep discharges and thereby increasing the predicted lifetime of the battery package.

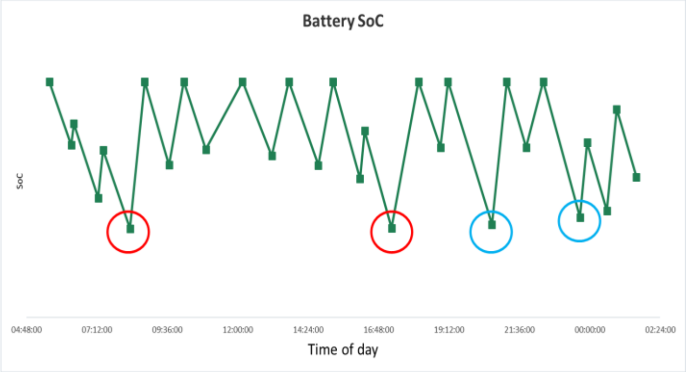


Figure 14. State-of-Charge during one operational day – Stavanger Demonstrator

The design charging capacity of the Stavanger Demonstrator is 2.3MW. Charging times are limited by the route timetable and vary throughout the day from only 5 minutes up to in excess of one hour. From the established SoC chart, there are two types of critical discharge profiles for the Stavanger Demonstrator. The first one is a "cumulative" discharge where the time available for charging is not sufficient to fully charge between each trip. This results in a deeper and deeper discharge for each trip. Typical cumulative discharge is marked with red circles in Figure 14. The second critical discharge is due to demanding single trips, marked with blue circles in the same figure. The battery is then fully charged at the start of the trip, but the length of the trip is such that the required energy causes a deep discharge.

The type of critical discharge will determine what can be adjusted to reduce the depth of discharge. For the cumulative discharge, a small increase in charging time between one or more of the trips will significantly improve the depth of discharge. For the single trip discharge, adding charging time will not improve the situation. Based on model testing results for a wide range of loading conditions and speeds (Papanikolaou et.al., 2020c), it is possible to see the effect on consumption from the selected speed of the fast catamaran. By running the two long trips with a slightly lower speed, the depth of discharge is slightly reduced which again gives a significant impact on the lifetime of the battery package.

Regulatory requirements for worst-case single failure (HSC code 2000) means that a failure of one of the independent propulsion systems has to be considered. This will potentially result in the loss of 50% of the energy storage onboard. To fulfil rules and regulations (DNV) the remaining capacity needs be sufficient to ensure the vessel can sail to a safe harbor or anchorage from the worst possible location along the route. For routes with long distances between safe harbors or anchorage, this requirement may pose challenges. However, for routes in sheltered waters with short distances between each harbor such as the Stavanger Demonstrator route, this requirement will not be governing for the selected battery capacity. It should also be noted that the energy consumption of this vessel at a reduced speed will allow the vessel to travel long distances. As an example, the Stavanger Demonstrator will be able to increase travel distance by more than 700% when reducing cruising speed from 23kn to 8kn.

Smart Cities' integration

In order to maximize the societal benefits of zero-emission passenger ferries, it is important to evaluate their deployment in the context of the smart city. Smart cities aim to improve livability and equity in cities (Hollands, 2008; Caragliu et.al., 2011; Calzada, 2016; EC, 2016) by addressing e.g. environmental, social and economic urban issues with approaches that enhance cooperation and collaboration (Castelnovo et.al., 2015). Sustainable solutions in the areas of transport and energy play a determinant role within the task of smart city planning (Caragliu et.al., 2011; Giffinger et.al., 2007;

Cervero, 2017) especially on the path towards decarbonization (EC, 2020a; EC, 2020b). Hybrid and full-electrical vessels do not only offer the opportunity to replace old transport systems that require high fossil fuel consumption but also to help decongesting road traffic by taking over parts of freight and commuting transport.

European and global authorities have recognized the need to address the environmental effects associated with the use of conventional, i.e. fossil-fueled, propulsion systems and have established goals towards the reduction of GHG emissions, either for the transport sector in general or specifically for waterborne activities. To name a couple of examples, the European Green Deal (UN, 2020) strives the achievement of carbon neutral shipping by 2050, whereas the International Maritime Organization pursues a decline in total annual waterborne-transport-related GHG emissions of at least 50% by 2050 compared to 2008's levels (IMO, 2019). Financial as well as non-financial measures in the context of infrastructure, logistics and environmental policy for inland waterway transport and short sea shipping in Europe do not only focus on optimizing waterborne transport alone but rather on enhancing intermodality by improving the connectivity with landside transport, i.e. road and railway traffic (DG-MOVE, 2020). Here, the simultaneous development of adequate Information and Communication Technologies (ICT) shall be deemed to be of high relevance (Jakovlev et.al., 2013).

The process of electrifying the maritime industry, which includes the development of new energy storage systems (EES) and renewable energy sources (RES), has an indirect impact on the infrastructure offered at ports. The provision of charging infrastructure to power vessels according to the specific needs of their route lengths and operation times is, of course, strictly mandatory (Anwar et.al., 2020). Moreover, this process should be seen as an opportunity to identify areas of improvement at other interfaces between water and land. The improvement of such interfaces, enabled by the digitalization of mobility, should lead to higher efficiency and customer satisfaction in multimodal trips.

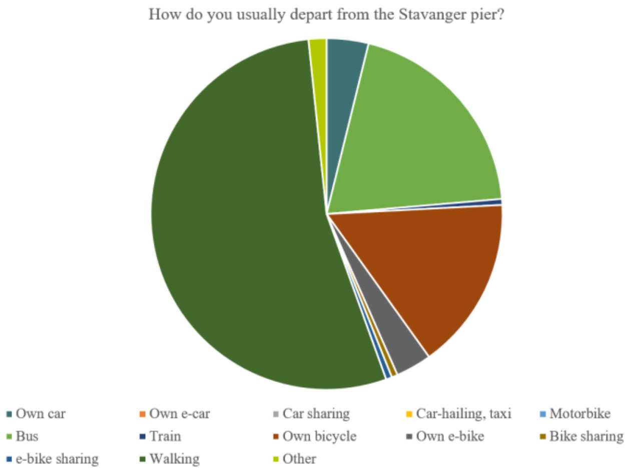


Figure 15. Modal split at Stavanger's pier

In the context of TrAM, the goal has been set up towards the analysis of the interfaces that occur at the different locations along the ferry route Stavanger – Hommersåk, operated by the company Kolumbus. The analysis, which has been supported by a customer survey, includes an evaluation of the utilization of different piers, the modes used to reach each pier or depart from it to reach the final destination, how journeys are planned, and which ticketing systems are preferred among customers. According to (Deloitte, 2020), the inhabitants of Stavanger tend to commute from residential neighborhoods into Stavanger's city center and the industrial areas. The analysis has shown that a high proportion of the Hommersåk – Stavanger route's customers continue their journey walking, riding their own bicycle or taking a bus as shown in Figure 15, which can indicate which modes might need a higher promotion or where the emphasis on infrastructure optimization should be set on. Kolumbus, which is the mobility provider for the complete county of Rogaland, offers over 26 million bus trips and approximately 0.7 million trips by ferry per year. These, together with other mobility solutions, including shared mobility, account for an average of approximately 111,383 daily trips offered by Kolumbus, depicting the relevance of public transport in combination with individual mobility in the region.

Besides identifying relevant characteristics of the interfaces at the piers, the project consortium attempts to explore the possibility of amplifying its service spectrum by offering additional mobility and mobility-related services at the port of Stavanger, i.e. Stavanger's main mobility hub called Fiskepiren, as shown on the concept in Figure 16.Kolumbus has considered the implementation of car and city e-bike sharing as well as a kick-bike rental service, the provision of charging infrastructure for these vehicles and implementation of bicycle parking and repair kitchens. Moreover, the municipality is committed to improving the access routes to and out of the city by pursuing projects that include the construction of an underwater tunnel and a better connection between the port and the railway station. Cycling and walking should be additionally incentivized by dedicating more space for those purposes at the port's area.

Figure 16. Concept of Kolumbus' facilities at Fiskepiren port in Stavanger (Source: Kolumbus AS)

The planning and implementation of such solutions require cooperation among different stakeholders, such as representatives from the municipality and the county, the authorities that regulate the use of the port, owners of parking facilities and energy providing companies, among others. At the same time, it is important to estimate the acceptance of new mobility services by potential users, which partly depend on their sustainability awareness, openness to the introduction of new technologies and price sensitivity. Norway, with its acceptance of electric mobility proven by its electric car penetration share (IEA, 2020) as well as the amount of vessel electrification projects (10), seems to be a suitable candidate for piloting innovative mobility concepts.

Safety

Considering that the safety of fully electric vessels is an aspect of high importance in the maritime sector, a novel approach has been developed to evaluate the safety level of these high-speed catamarans. It follows IMO's Formal Safety Assessment (FSA) procedure (Figure 17). The risk assessment for the considered ships leads to the identification of the involved hazards along with the estimation of their frequency and consequences thus allowing their ranking according to their risk. The estimation of the risk and safety level of the vessel is carried out using the bow-tie approach with a fault tree (FT) and event tree (ET) analysis for the identified top events. Risk control options (RCOs) are proposed for those cases with unacceptably high risk. A cost-benefit assessment is conducted to evaluate the financial impact of selected RCOs. The derived results indicate that the application of a battery power system for high-speed ferries exhibits low and acceptable accident frequencies (Wang et al. 2020). It should be noted that such a risk assessment is mandatory according to the current regulations for battery-powered ships (Wang et al. 2020).

The HAZID is an essential part where participants, including ship operators, technology inventors, manufacturers, assessment investigators and regulation makers, sit down and brainstorm about the potential hazards that the ship might face during its whole lifespan. It also needs to consider the existing database, reports, latest regulations and guidance. The HAZID has confirmed the most concerned hazards for the ferry and provide frequencies and consequence levels for each hazard so that a quantitative risk assessment could determine the risk levels from the risk matrix.

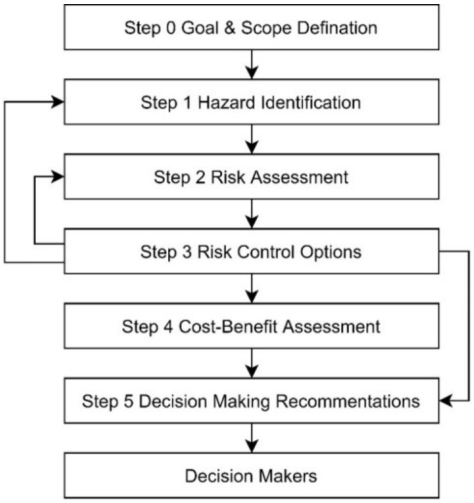


Figure 17. General approach of a formal safety assessment (FSA)

The main findings of the risk and safety assessment are the following:

- The accident frequencies for conventional larger passenger ships and battery-driven ferries are not significantly different.
- The battery-powered system, including the battery management system, does not raise any concerns regarding higher accident frequencies.
- The event trees and the quantitative risk assessment show that the vessel's design is as safe as existing ships.
- Risk control options to further reduce the risk have been examined. Among all the proposed risk control options, the relocation of the battery room on the main deck was the most cost-effective RCO as it significantly reduced the risk.

THE STAVANGER DEMONSTRATOR

Design

The overall design is based on a typical fast ferry design with all passengers arranged on one deck (Figure 18). This requires a large deck area, and a catamaran is in general the ideal solution for this. The main reason for placing all passengers on one deck is related to the manning of the vessel and to keep as low safety manning as possible. Access for disabled people is also far easier placing all passengers on one deck avoiding elevators or stairlifts, since access for disabled persons to all passenger areas being required in this operation. There is arranged a small area for crew toilet and a room for resting due to the regulations related to the operation profile of the vessel.

The passenger areas are placed along ship sides to offer the maximum number of seats along the window, while the wheelhouse is placed on top ensuring view in all directions. The vessel is designed according to IMO High-Speed Code and Norwegian Maritime Directorate regulations in addition to fulfilling class rules according to DNV (Det Norske Veritas).

The absolute size of the vessel may have been sub-optimal for the specified operational speed of 23 knots, but it was chosen from both regulatory limits and size restrictions in the harbors while keeping an appreciably high speed.

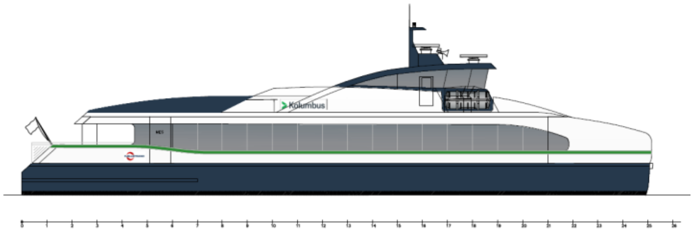
There is a requirement in the High-Speed Code where exceeding 30 m in waterline length will result in a compulsory rescue boat with crane adding a few tons to the design, which is the reason the vessels length is kept below 30 m even though the resistance figures could be improved with a longer waterline length. The width of the vessel of 9 m is also narrowed to a minimum to keep weight down and still not suffer from too much wave interference between the hulls. The main dimensions are shown in Table 1.

The installation of batteries in fast ferries raises several new challenges. A higher weight is the main design issue for most battery-driven ferries dependent on sailing range and speed, while causing extra caution in hydrodynamic hull form optimization, vessel trim and stability, and finding ample place for the batteries and their systems.

Table 1. Main Dimensions of STAVANGER demonstrator

Main dimensions	Value
Length Overall [m]	30
Length at Waterline [m]	29.9
Beam [m]	9
Draft [m]	1.43
Depth at main deck [m]	2.8

The obvious space for the batteries might be in the hulls. However, in this vessel it was found that it was better to place them on the main deck, in the rear part of the passenger accommodation (Figure 18), for the following reasons:



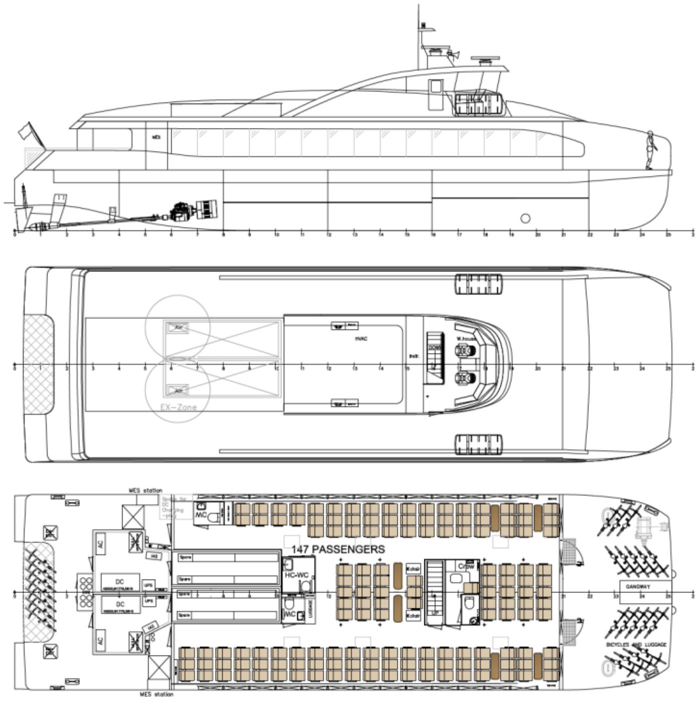


Figure 18. Side view and general arrangement of the STAVANGER demonstrator (Medstraum)

- This creates fewer restrictions on hull design both in width and height to the deck.
- Ventilation of the battery rooms, creating an ex. zone on the outlet is easier to arrange receiving air far away from the water level.
- With open space above this does not require any ducts through the passenger area in order to reach an ex. zone
- The batteries are placed in a zone protected from collisions and avoiding seawater entry into batteries if any leakages occur.
- Access to batteries and their systems is simplified for daily maintenance and inspection.

Practical studies in the route have shown that bow loading of passengers is far more efficient than side loading due to many stops and few passengers per stop. The large bow area is also giving space for bicycles expected to be carried on board by passengers in the future.

The superstructure is based on a design for friction stir welded panels. The passenger module is all flat panels and makes the panel ideal for gluing window panels to the side. The wheelhouse module is designed for an optimum view to the front-loading area for safety in maneuvering as well as the loading/ unloading of passengers. The wheelhouse has windows slanting forward to avoid reflections from instruments and lights. Above the battery rooms, the deck is raised to give extra space for the batteries in order to minimize their deck footprint.

Hydrodynamics

Following the hydrodynamic optimization procedure stated before, extensive hydrodynamic analyses have been performed for the Stavanger Demonstrator to find the best hull form (low resistance and high propulsive efficiency) to allow a battery-driven fast ferry fulfilling its customer services. During the optimization phase, the focus has been put on the lowest resistance and the highest propulsive efficiency on design condition and off-design conditions based on the operational profile given by the end-user. The selected best hull form has been model tested in the large towing tank of HSVA. The test results reveal an excellent propulsion efficiency of the catamaran at and beyond the design speed of 23 knots, such confirm the hull form optimization by CFD conducted before the tests. Studies on the seakeeping and maneuvering behavior of the catamaran are ongoing work and will be reported in the future.

Computational Method

The hydrodynamic assessment of each design alternative in the optimization process was based on HSVA's in-house tools, i.e. the panel code for wave resistance ν-SHALLO and the RANSE code FreSCo+ for the total resistance and the FreSCo+-QCM coupling method for refined local flow simulations at the catamaran's transom.

HSVA's panel code ν-SHALLO is a fully nonlinear, free-surface potential CFD method computing the inviscid flow around a ship hull moving on the free water surface. The code is based on a superposition of a given free stream velocity with the flow induced by a number of 3D Rankine point sources on the ship's hull and the free surface. ν-SHALLO treats the nonlinear free surface boundary condition iteratively by a collocation method and uses a patch method for dealing with the body boundary condition and pressure integration (Jensen, G. et. al. 1986 and Gatchell S. et. al. 2020). The hull and the free surface were discretized by means of triangular and/or rectangular panels, and the individual source strengths were determined by solving a linear equation system resulting from the discretization of a Fredholm integral equation.

The FreSCo+ code (Hafermann, D. 2007) solves the incompressible, unsteady Navier-Stokes-equations (RANSE). The transport equations are discretized with the cell-centered finite volume method. Using a face-based approach, the method is applied to fully unstructured grids using arbitrary polyhedral cells or hanging nodes. Also features such as sliding interface or overlapping grid technique have been implemented into the code.

The method implemented in the "QCM" code (Chao, K. Y. and Streckwall, H, 1989) is a vortex lattice method (VLM). The blades of the propeller are reduced to lifting surfaces which account for camber and angle of attack. The lifting surfaces are built up by section mean lines. The thickness effect is accounted for by prescribed source densities on the lifting surfaces.

Generated designs for local optimization were evaluated by use of HSVA's RANS-QCM coupled method (Xing-Kaeding, Y. et al. 2015), in which the RANSE code FreSCo+ and the propeller panel code QCM are coupled through the actuator disk method at an iterative basis to evaluate the hydrodynamic performance at self-propulsion condition. In this procedure, the free surface, dynamic sinkage and trim of the catamaran have been considered as well. To adapt the sinkage and trim, an efficient free form deformation technique has been applied.

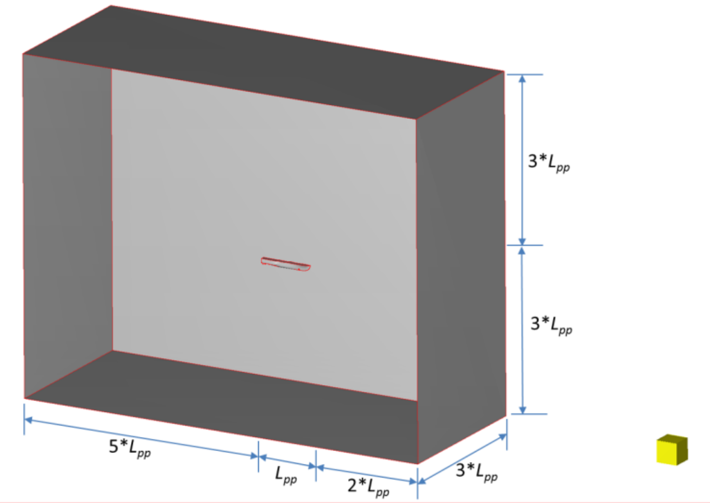


Figure 19. Computational domain used for the resistance and propulsion simulation

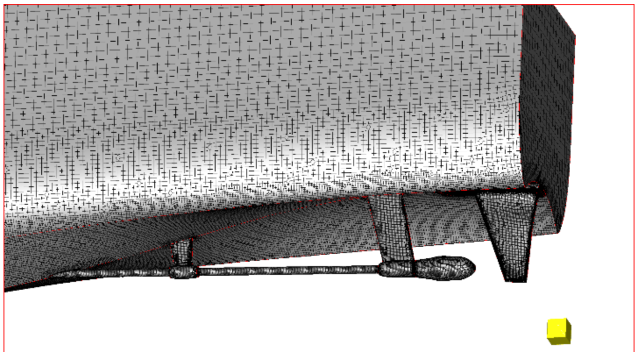


Figure 20. Numerical mesh around the stern tunnel area for the local optimization by FreSCo+ of the Stavanger Demonstrator (5.7M)

Numerical Setup

The computational domain used herein for the resistance and propulsion simulation (both taking into account the free surface effect) extends to 2Lpp in front of, 5Lpp behind of, 3Lpp to the side of the vessel and 3Lpp below the vessel and is shown in Figure 19. A symmetry boundary condition has been applied to the symmetry-plane of the catamaran. Local grid refinement has been applied to the tunnel, propeller, appendages and free surface region, shown in Figure 20. The generated numerical mesh contains a total number of 5.7 Million cells.

Both the computational domain and the mesh generation comply with the HSVA internal best practice guidelines, which are based on a large number of numerical grid studies in the past.

Experimental and Numerical Results

As an essential part of the design process of a highly complex and innovative ship, physical model tests play a very important role considering the verification of the prediction of full-scale speed-power performance.

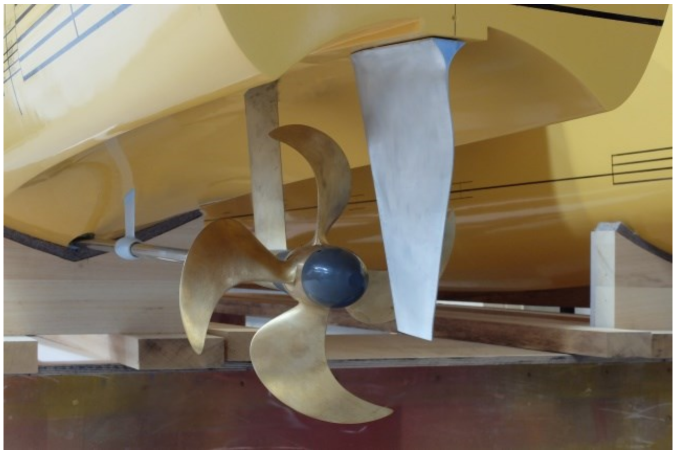


Figure 21. View of the tested Stavanger model

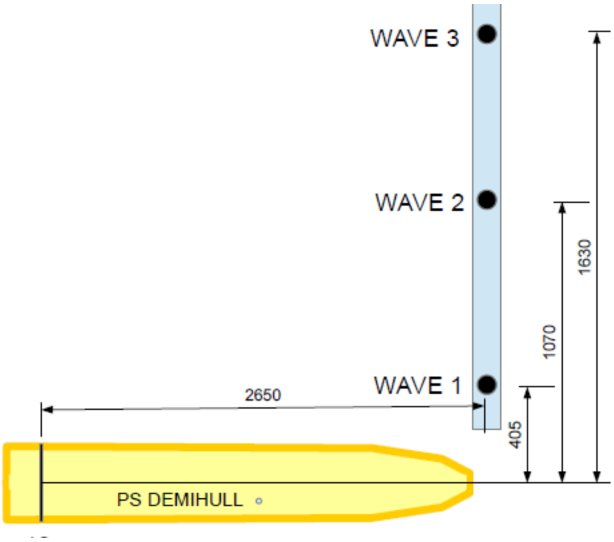


Figure 22. Y- Position of the wave probes relative to demihull

The determination of a suitable model scale ratio is one of the first and most important steps at the beginning of planning a model test campaign. Minimizing scale effects and measuring errors by building a model as large as possible is an essential goal to be balanced with limiting factors such as basin constraints, carriage speed, estimated loads, measurement equipment and certainly building costs. For the TrAM model, a very good trade-off between these factors resulted in a scale ratio of 1/5.6, namely a 5.34m long catamaran model. The two separate demi-hull models were manufactured out of thin layer wood and were coupled by high-strength metal beams. Proper alignment and positioning of the demi-hulls were ensured by special high precise measurement gauges individually designed for this test setup. A view of the stern area of the model with fitted CP propellers and (twisted) rudders is shown in Figure 21.

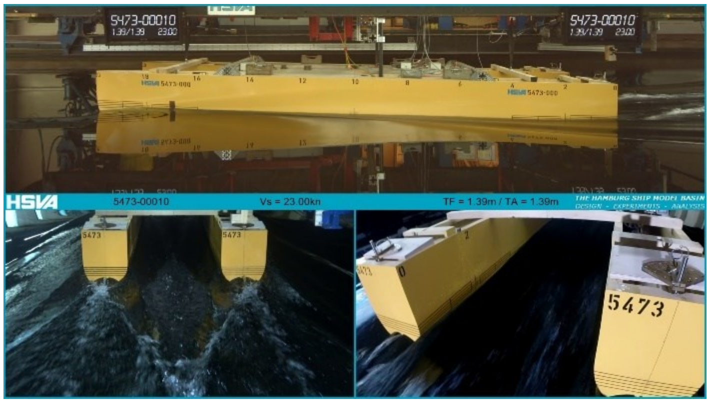


Figure 23. Self-propulsion model of the Stavanger demonstrator at 23 knots full-scale speed

The calm water model tests were carried out in HSVA's large basin which is 300 m long, 18 m wide and 6 m deep. The speed of the model ranged from 1.5 to 6.5 m/s which corresponds to a ship speed of 8 to 29 knots. During the test runs all relevant forces and movements of the model have been recorded, while also including wave profile measurements for the generated wave wash downstream (see Figure 22 for the wave probe positions). The test program included both towing resistance and self-propulsion tests for three different displacements Δ1, Δ2, Δ3 and a range of trims. Besides the variation of the calm water resistance for tested conditions, special attention was paid to the propulsive efficiency of the fitted propulsion plant and the hull-propeller-rudder interaction (wake and thrust deduction factors). It should be also noted that a 1st test campaign with the originally optimized hull form (battery racks placed in the demihulls) was conducted in December 2019 and a 2nd campaign repeated the test series for the finally selected hull form in May 2020. The entire test series was live-broadcasted ("live-stream") and recorded by several cameras showing the model and the flow around it from different perspectives (Figure 23). This allowed a detailed observation of the vessel's hydrodynamic behavior remotely and even after the tests, as necessary.

The numerically predicted model and full-scale values obtained by CFD simulations could be very well confirmed by the test campaigns. In the conducted second test series with the revised hull form (May 2020) the resistance and propulsion power could even be reduced significantly for the relevant speed range above 14 knots (see Figure 24 and Figure 25). A remarkable result of the model tests was the extraordinarily high propulsive efficiency (Figure 26) that could be achieved by the refined local optimization of the hull-propeller interaction. The very low thrust deduction fraction (Figure 28) on the one hand and the achievement of a low wake fraction (Figure 27) and a hardly disturbed propeller inflow condition (Figure 29) on the other side resulted in a propulsion efficiency of up to 80% at higher speeds.

The measured free surface elevation at three wave probes are compared with the CFD results in Figure 30-, Figure 31 and Figure 32. The agreement is very good the primary wave system. With further propagation of the waves and their interaction, the simulation results predict the same trend but give slightly lower wave amplitudes than the measured values.

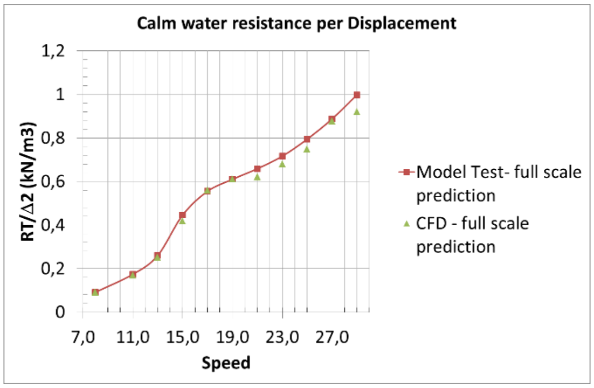


Figure 24. Prediction of the rated full-scale calm water resistance for the Stavanger Demonstrator based on model experiments and CFD calculations by HSVA (revised hull form, battery racks on deck)

A systematic variation of the static pre-trim of the vessel delivered valuable information for a beneficial arrangement of the ship's weight distribution in terms of power reduction, see Figure 33. A moderate stern-down trim of less than 30 cm in full scale would lead to a small power increase at design speed or even decrease at higher speeds, while a bow down trim would only be beneficial at lower speeds as indicated by CFD predictions.

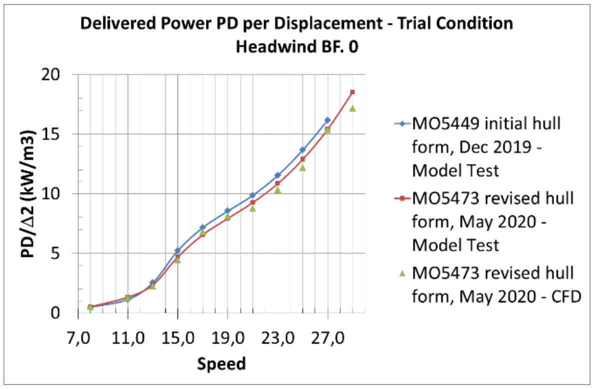


Figure 25. Prediction of rated delivered horsepower under trail condition for the Stavanger Demonstrator on the basis of model experiments and CFD calculations by HSVA (originally optimized and revised hull form)

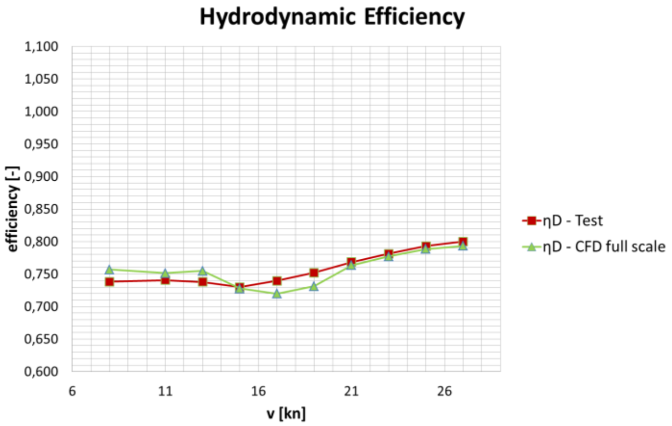


Figure 26. Hydrodynamic Efficiency from model tests and full-scale CFD for the Stavanger Demonstrator

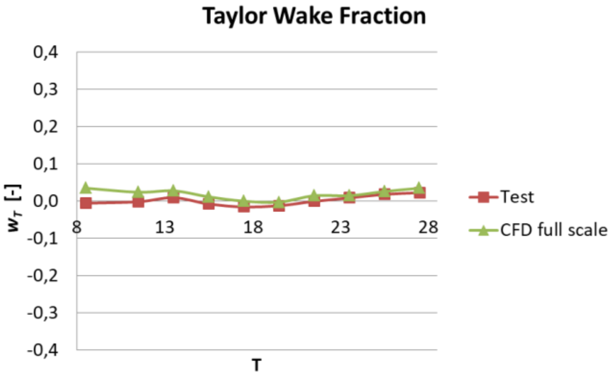


Figure 27. Taylor wake fraction from model tests and full-scale CFD for the Stavanger Demonstrator

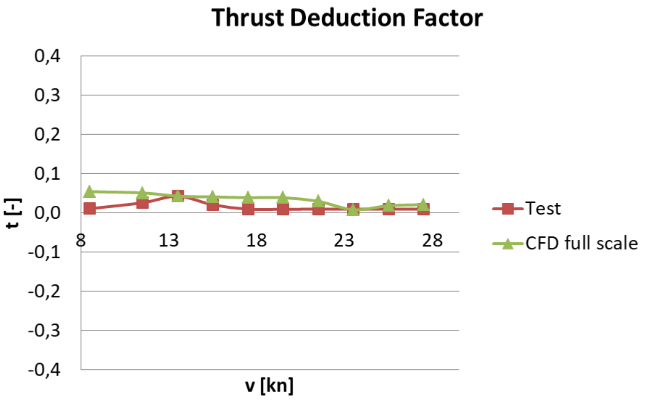


Figure 28. Thrust deduction factors from model tests and full-scale CFD for the Stavanger Demonstrator

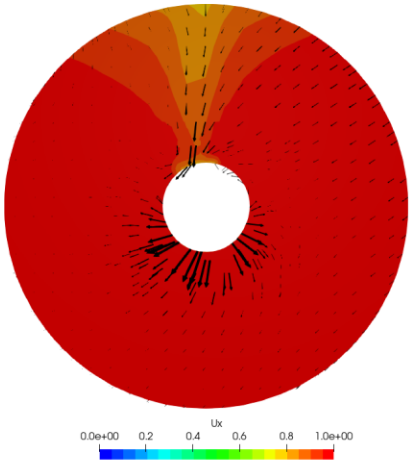


Figure 29. Computed nominal axial velocity contours and transversal velocity vectors at the (port side) propeller plane for ship speed at 23 knots (view from behind)

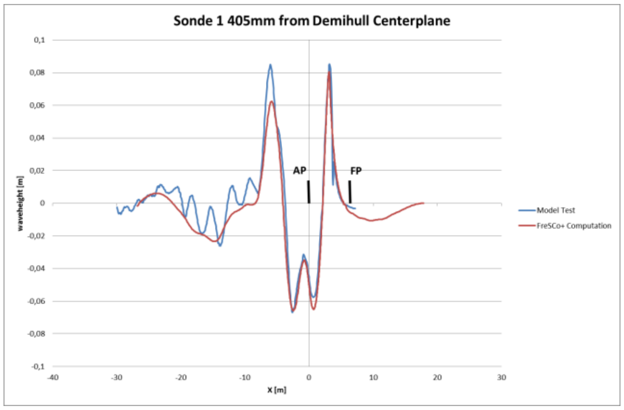


Figure 30. Comparison of Wave probe 1 (Y = 405 mm) between Test and CFD

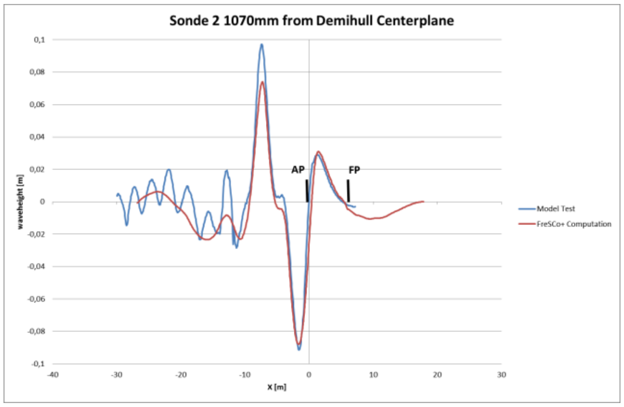


Figure 31. Comparison of Wave probe 2 (Y = 1070 mm) between Test and CFD

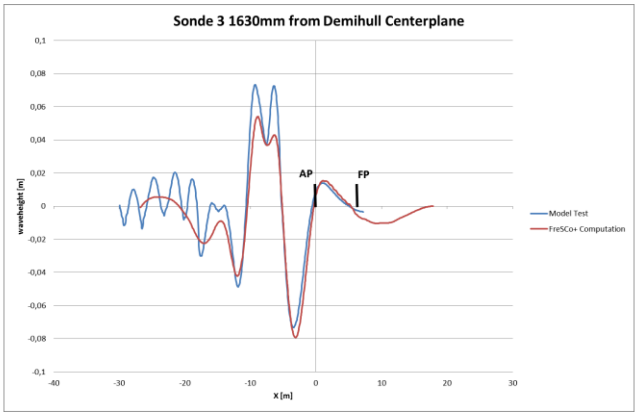


Figure 32 Comparison of Wave probe 2 (Y = 1630 mm) between Test and CFD

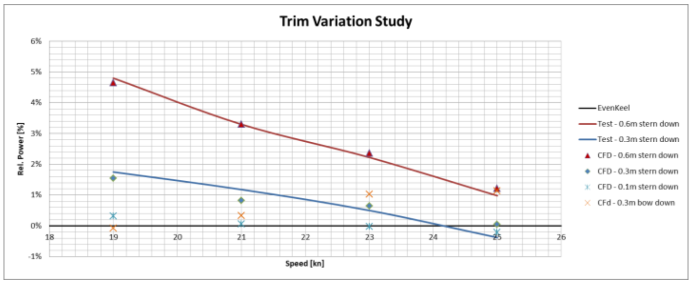


Figure 33. Results of Trim Variation Studies from Model Tests and CFD

THE THAMES REPLICATOR

Design

The Thames River Demonstrator is a slightly different case. It is a battery-driven, zero-emission passenger ferry to be operated by the Uber Boat by Thames Clippers (UBTC), the largest passenger ferry operator in London. UBTC's boats are facing competition from both other transportation modes and amounting pressure to move to net-zero carbon operations in the city of London. Therefore, UBTC seeks viable alternatives by applying the TrAM Modularity Concept.

UBTC vessels are specific to the operating requirements of the Thames. Low air draft and shallow water draft are crucial due to the 7m+ tidal cycle. With a maximum tidal speed of 5 knots, these vessels have to cope in some challenging conditions. High service speed and increased maneuvering capabilities are critical not only for safely navigating on the Thames, but also to compete in transit times compared to other forms of transport. In the past the preferred UBTC main propulsion system were the fixed blade propellers. These gave good service speed but suffered from engine stalling if operated outside operating guidance. Therefore, all new vessels from 2015 are fitted with waterjets. These allow for the same high speed, increased maneuvering and decrease significantly the crush-stop distance.

All UBTC vessels are certificated under the MCA High Speed Craft Code (HSCC) and are licensed to operate up to a maximum water height of 1.4m.

The limitations for the main dimensions provided by UBTC are summarized in Table 2.

Table 2. Thames Replicator Design Constraints

Design Constraint	Value
Air draught [m]	< 5.0
Breadth overall [m]	< 10.0
Draught max [m]	< 1.2
Length overall [m]	< 40.0
Lightship [t]	< 100

The catamaran geometry in this case is a round bilge hull, similar to the NPL series. A parametric hullform definition was created in the CAESES® software. The main particulars of the design are depicted in Figure 34. The parametric design consists of 24 parameters in total, controlling not only the main particulars (e.g. length, breadth and draught of each demihull) but also the shape at specific areas of the hull (e.g. transom stern shape, deadrise angle, etc.). A parametric design of the superstructure has also been developed, controlled by 18 parameters (Figure 35).

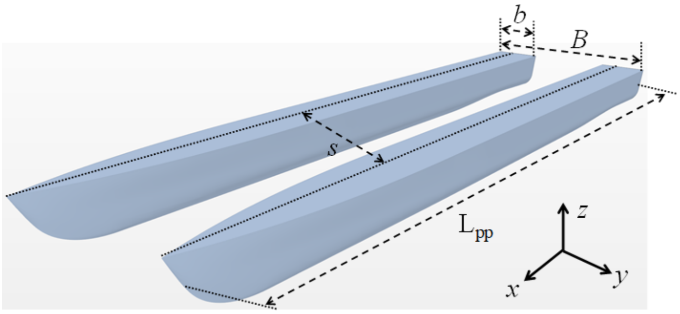


Figure 34. Geometry of Thames Replicator

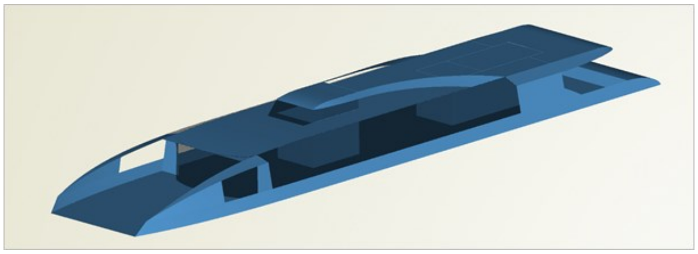


Figure 35. Superstructure design of Thames Replicator

The development of a complete design for the Thames replicator allows the monitoring of the structural weight through the definition of a parametric structural design of the vessel (36). As mentioned earlier, the main dimensions of the design, such as the length and the breadth, have a significant impact on the frictional and wave resistance components through the resulting wetted surface area and separation distance between the two demihulls. On the other hand, the same parameters affect the structural weight of the vessel. By incorporating the minimization of the structural weight in the optimization process of the Thames replicator, the optimal combination of a lightweight, yet hydrodynamically efficient design can be achieved. In addition, the reduction of the structural weight can potentially provide a further allowance for the available battery capacity, resulting in higher endurance values.

Another aspect specific to the Thames replicator case is the restrictions imposed with regard to the wake wash produced by the vessels operating in the Thames. Therefore, the wake height produced by the vessel becomes one of the main constraints of the design process, along with the dimensional limitations mentioned in Table 2.

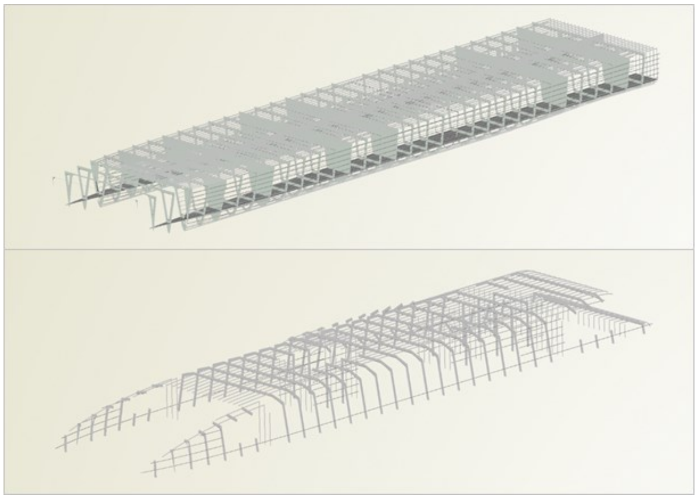


Figure 36. Hull (above) and superstructure (below) internal structure of Thames Replicator

Following the optimization process used for the Stavanger demonstrator, the optimization of the Thames replicator is conducted in two stages; first, a global optimization study is performed to identify the best overall design, focusing on the minimization of the structural weight and calm water resistance. Then, a local optimization study is used, aiming at the improvement of the hull area around the stern, where the waterjet will be installed, to further improve the hydrodynamic performance of the design.

Benefiting from the available data obtained during the design procedure of the Stavanger demonstrator, we can fine-tune and correct the resistance prediction methods used in the Thames replicator. Hence, we can avoid the utilization of time-consuming approaches such as CFD simulations in the global optimization stage, by opting for faster, yet reliable methods, such as the Slender Body or other available panel code methods, for the estimation of the calm water resistance and the wake wash. These fast approximation methods are compared with validated CFD codes and corrected accordingly to be used in the first stage of the design optimization, where thousands of design variants are explored for the identification of the optimal design. More robust CFD tools will be used in the second stage for verification and further improvement of the optimal design (Figure 37).

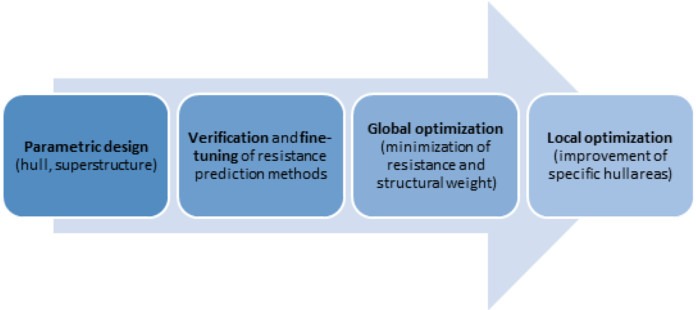


Figure 37. Multi-stage design optimization procedure for the Thames Replicator

Hydrodynamics

The calm water-resistance of the TrAM Thames Replicator is carried out using the commercial software Star CCM+ 14.06. The main dimensions of the catamaran are given in Table 3. The numerical methods and settings are validated against the experimental test of TrAM Stavanger demonstrator and the result is demonstrated in **Error! Reference source not found.** The difference between the experiment and numerical simulation is below 1.5%.

Table 3. Main dimensions of TrAM Thames Replicator catamaran design #1

Dimension	***Symbol***	***Value***[*]
Overall breadth	B/L_{pp}	0.255
Demihull breadth	b/L_{pp}	0.068
Separation	s/L_{pp}	0.187
Draught	T/L_{pp}	0.033
Water depth	H/T	2.0

[*] All values are dimensionless

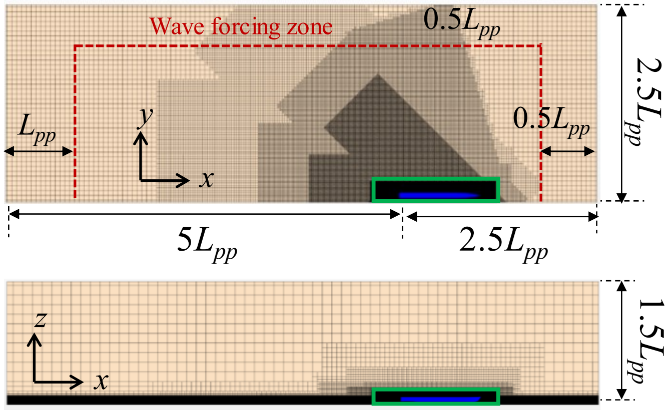


Figure 38. CFD mesh and domain size used for shallow water

Table 4. Comparison of the resistance coefficient of Stavanger demonstrator between model test and CFD simulation

Fn	$C_{T,CFD}\times10^3$	$C_{T,Exp}\times10^3$	***Error***
0.57	5.476	5.520	-0.79%
0.63	4.844	4.899	-1.11%
0.69	4.404	4.437	-0.74%
0.75	4.098	4.157	-1.42%

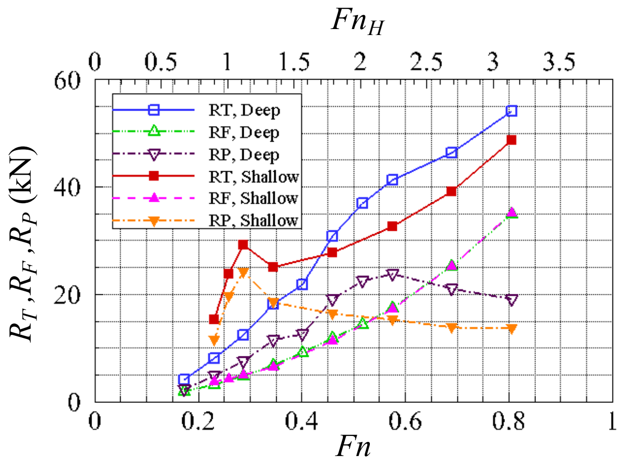


Figure 39. Resistance of the full-scale Thames Replicator (#1) in deep and shallow water

With the validated numerical methods and settings, the shallow water effect on the full-scale resistance of the TrAM Thames Replicator (design #1) is investigated. The CFD grid and computational domain size are illustrated in Figure 38. The comparison of the resistance between deep and shallow water cases is shown in Figure 39. It can be observed that in deep water the total resistance (R_T) rises monotonously as the increase of the speed while in shallow water the R_T curve witnesses a hump near the critical speed ($Fn_H = 1.1$), after which R_T increases continuously. For both deep and shallow water cases, the maximum total resistance is achieved at the highest speed, where the catamaran generates less resistance in shallow water. An observation of the components of the total resistance reveals that the frictional resistance (R_F) in deep and shallow water is basically the same. The difference is mainly caused by the pressure resistance (R_P), which is closely associated with the wave system created by the catamaran.

As observed in Figure 40, a significant wave elevation is generated in front of the catamaran near the critical speed ($Fn = 0.29$) in shallow water, which leads to a much higher trim angle and results in the hump in the total resistance curve observed in Figure 39. At a higher speed ($Fn = 0.58$), in deep water, noticeable troughs are created between the demihulls and near the stern. In contrast, such troughs are not seen in the shallow water case. Moreover, significant crests are generated at midship, which, together with the disappearance of the troughs near the stern, leads to a decrease in both sinkage and trim. This further leads to a reduction of the total resistance in shallow water at higher speeds. More details regarding the shallow water effects on the resistance of the Thames Replicator (#1) can be found in Shi et al. (2021).

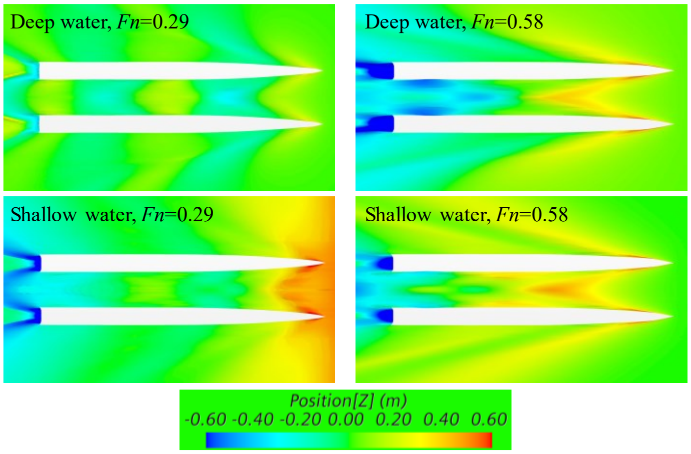


Figure 40. Wave patterns generated by the Thames Replicator (#1) in deep and shallow water at two different speeds

The numerical simulations have also been carried out for the model-scale Thames Replicator (design #1) and the resistance is extrapolated to the full-scale value and compared with that computed using CFD. In the extrapolation, the residual resistance coefficients for model and full scales are assumed to be identical. The frictional resistance coefficient is calculated according to the ITTC 1957 correlation line formula and the correlation allowance coefficient is set to the same value used for the TrAM Stavanger demonstrator. Table 5 shows the comparison between the extrapolated ($C_{T,\ Ext}$) and computed ($C_{T,CFD}$) full-scale resistance coefficients in both deep and shallow water. Overall, the extrapolated resistance is higher than the computed ones. The difference at the lower speed is within 5% for both deep and shallow water while the difference can up to 12.5% at the higher speed.

Table 5. Comparison of the full-scale extrapolated and computed total resistance coefficients

	Fn	**$C_{T,\ Ext}\times10^3$**	**$C_{T,CFD}\times10^3$**	**Diff.**
Deep	0.345	5.252	5.061	4.6%
Deep	0.805	2.902	2.511	12.5%
Shallow	0.345	7.294	7.160	2.5%
Shallow	0.805	2.579	2.254	11.9%

The CFD results are also compared with those obtained using the slender-body (SB) method at three different displacements in deep water. As shown in Figure 41, for both model and full-scale cases, the slender-body method underestimates the total resistance at the lower speed while overestimating it at the higher speed. Despite the difference between the two methods, it is emphasized that the ranking is consistent for all three displacements.

Energy Model

An energy storage model has been developed to analyze the energy required and weight of the battery packs. The model takes into account a series of parameters as inputs to estimate:

- The energy requirement,
- The running order,
- The energy charging,
- The battery capacity,
- and finally, the weight and cost.

To estimate the energy requirement, the effective power is predicted from the given operational data from the existing vessels with an estimated energy requirement of 650kWh. The efficiencies of the power train are provided and validated by the experts within the consortium. They include the Discharge loss (End Of Life, EOL), Converter loss, Motor loss, Gear loss, Waterjet loss, and Sea margin (Figure 42).

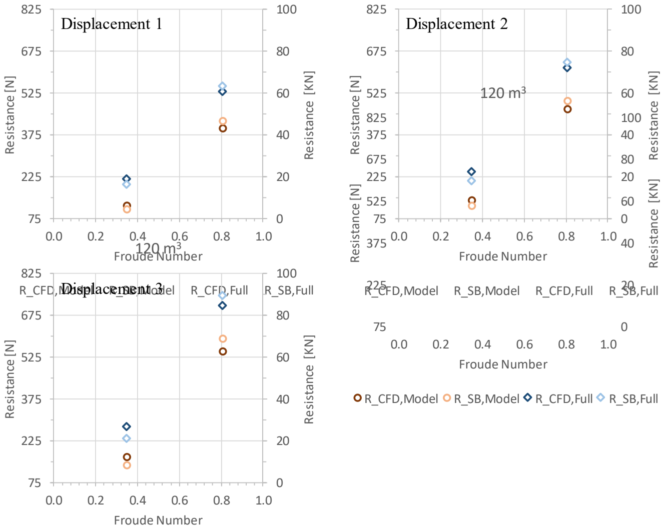


Figure 41. Total resistance calculated using CFD and slender-body method

The running orders are provided by the ship operator with the information of Operation hours per round trip (2 hours), number of round trips per day (5 per day), operation days per year (365 days), number of Accelerations (12), number of Dockings (12) and expected battery lifetime (10 years). Three running orders have been tested with various charging pattens:

- Charging every two round trips for 30 mins.
- Charging every round trip for 120 mins.
- Charging every round trip to full state – 41 mins.

Figure 42. Power train of battery powered system

The energy-charged can be determined using the following parameters: Charging time in destination and Charging intervals according to charging pattens), Charging power and Charging connection & disconnection time. According to the Stavanger Demonstrator, the charging power and the connection/disconnection time are 2MW and 1 minute respectively. The same assumptions were made for this case.

Table 6. Battery weight and cost estimation

	Existing	SD	New		Unit
Running order	1	-	1	2 3	
Depth of Discharge	-	0.70	0.71	0.54	
Capacity	**-**	**1,604**	**9,239**	**3,325**	**kWh**
Weight	**-**	**11**	**74**	**27**	**tonne**
Cost	**-**	**194,350**	**1,265,734**	**455,465**	**$**

To finalize the battery capacity, the energy required will be deducted by the energy-charged. Furthermore, the relationship between discharge cycle and lifetime of a battery is provided by the manufacturer and hence, the depth of discharge can be determined from the discharge cycles per day. With a capacity ratio (80%) between EOL and Beginning Of Life (BOL) stages, the battery capacity can be estimated. The developed model can also predict the weight and cost (see Table 6) with the provided battery energy density (125Wh/kg) and price (156$/kWh) based on manufacturer and literature data (Corvus, 2021; BloombergNEF, 2020).

CONCLUSIONS

The appeal for a drastic reduction of greenhouse gas (GHG) emissions has introduced unique challenges to ship design and operation. These challenges are enhanced in the short-sea shipping (SSS) sector and especially in the fast passenger ferries transport. In TrAM, leading European research and industrial companies are developing and validating a zero-emission concept for waterborne transport by implementing modular design and production methods, with the main focus on electrically powered vessels operating at high speed in protected waters (coastal areas and inland waterways). TrAM clearly moves beyond the state-of-the-art in waterborne transport, with considerable innovation potential, by developing a new design concept for modular production of vessels while at the same time expanding the capabilities of electrically powered vessels to higher speeds of operation. This is achieved by a state-of-the-art hydrodynamic optimization of vessels' hull form and propulsion system. The project development includes the land-based infrastructure of recharging stations and the interface to land-based transport by the use of the SMART city integration concept. The developed zero emission transport concept is being validated by the development of the Stavanger demonstrator (*Medstraum*), presently under construction at Fjellstrand Shipyard and expected to be launched in May 2022. The vessel is planned to go into operation in the second half of 2022.

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