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Medstraum: Design and Operation of the First Zero-Emission Fast Catamaran

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The paper deals with the design, construction and the early operation of the worldwide 1st battery driven high-speed catamaran passenger ferry MS Medstraum. The paper elaborates on unique issues of the design process, on the superior hydrodynamic performance, on the modular construction of vessel and on the land-based electrical/charging installation. MS Medstraum was built by Fjellstrand AS and was launched in early June 2022. After successful sea trials that superseded the expectations of designers, builders and operators, achieving a maximum speed of over 27 knots, it started operations in the Stavanger/Norway area in late September 2022. The prototype character of MS Medstraum led to its selection as "Ship of the Year 2022" at the major international maritime exhibition SMM 2022 (September 2022, Hamburg). The presented research is in the frame of the H2020 funded project "TrAM – Transport: Advanced and Modular" (www.tramproject.eu).

KEY WORDS: zero-emissions; fast maritime transport; battery and charging technology; industry 4.0; hydrodynamic optimization; modular production; holistic ship design; 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 recent 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, 2020a). 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, research and development institutions. The TrAM project aims to develop a zero-emission fast going passenger vessel 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. By 2022, Norway will have 72 electrical car ferries in operation (Energi og Klima, energiogklima.no/elektriske-bilferger-i-norge/). 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 (see, also, speech of Norwegian Minister of Transport Dr. J.-I. Nygård, 2022). 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 by far 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). Fig. 1 below shows the CO_2 emissions per passenger-kilometer for various means of transport. The numbers in this figure were deduced from the Norwegian Statistical Office SSB (2020) and consider actual occupancies of transport vehicles.

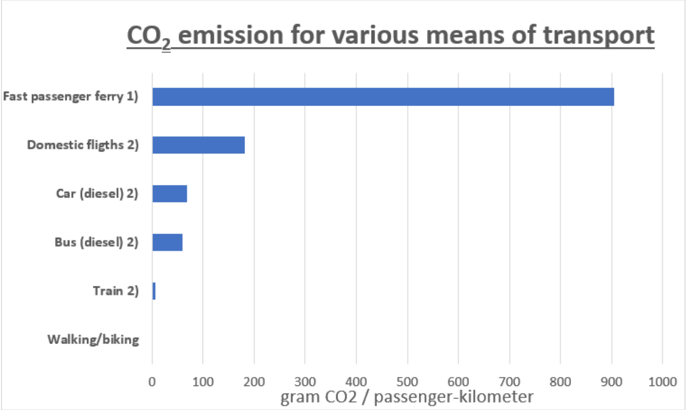

Fig. 1, CO_2 emissions per passenger-kilometer for various means of transport (Norwegian Statistical Office SSB, 2020)

The Norwegian transport operator Kolumbus operates 3 ferries, 10 fast-ferries and approximately 450 buses in Rogaland County. The land- and waterborne transport within Kolumbus contributes approximately 54,600 tons CO_2 emissions, of which over 30,000 tons are coming from waterborne transport (mainly high-speed vessels) (Kolumbus 2020). With an ambitious target to offer fossil-free transport by 2024, developments of zero-emission fast-ferries are 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, if not worldwide) to offer zero-emission fast-ferries in operation.

In the course of the TrAM project, the Stavanger Demonstrator, namely Medstraum, has been developed and started operation in September 2022 on the round-trip route Stavanger-Hommersåk (Fig. 2).

In addition, two replicator vessels for the canals in Belgium and the River Thames in London are designed, proving the TrAM

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[1] COP26: UN Climate Change Conference of Parties, held in Glasgow 2021

methodology for cases that vary significantly in geographical location, regulatory requirements, size, speed and operational mode.

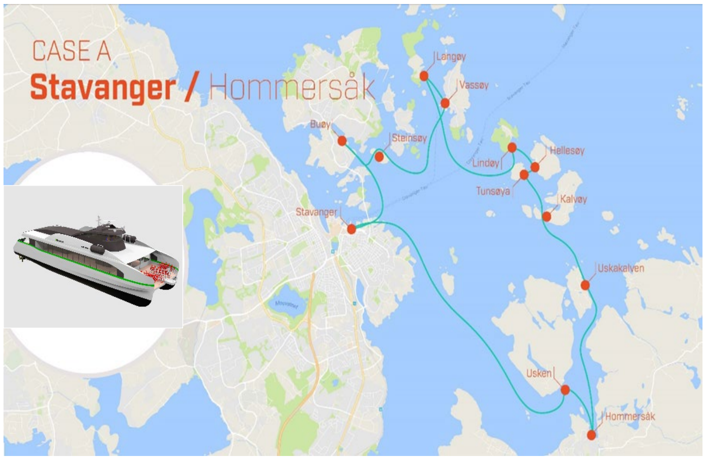

Fig. 2, Stavanger-Hommersåk route of Medstraum (9/2022)

The present paper describes the major steps of development of Medstraum, from the concept inception to vessel's design, construction and first experiences of operation. This refers to an advanced hydrodynamic optimization of ship's hull form and propulsion system, to ship's main design features, the employed modular production methods, the advanced battery and charging technologies, which all enabled the realization of this fully electrical, fast zero-emission vessel, which is the first of this type in the world. 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.

HULL FORM & PROPELLER DESIGN

The hydrodynamic optimization of catamarans and multi-hull vessels, in general, is a multiparametric mathematical and engineering problem with several objectives and constraints (Papanikolaou et al., 1996). 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 concept decisively depends on the achieved hydrodynamic efficiency, setting the limits for the achievable speed in relation to the vessels size and displacement (Papanikolaou, 2020a).

Based on this reasoning, it proved 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*[2] 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 Fig. 3.

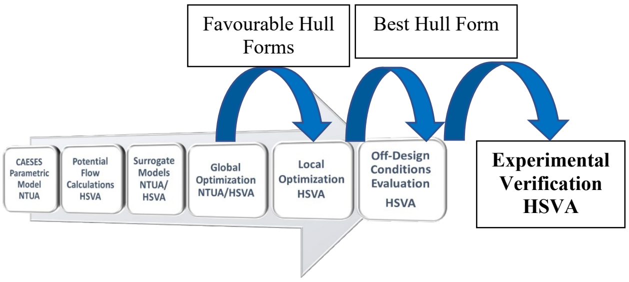

Fig. 3, Multi-stage numerical optimization and experimental verification

This optimization procedure relied 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). CAESES® (by FRIENDSHIP SYSTEMS) is a Computer Aided Engineering environment (CAE) that combines robust Computer Aided Design (CAD) with Process Integration and Design Optimization (PIDO), see Fig. 4. It brings together many diverse tool sets in the context of simulation-driven design (SDD), IT environments and application cases.

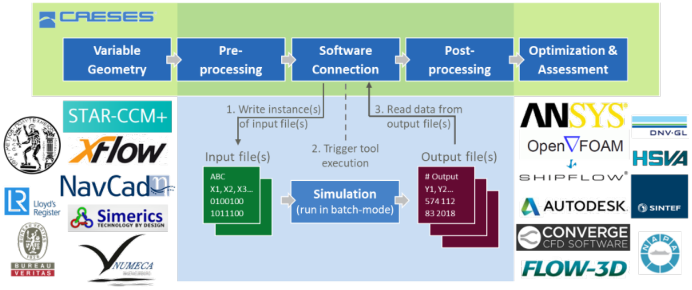

Fig. 4, Overview of CAESES® functionality along with a selection of software systems frequently coupled and providers of tools and systems from the HOLISHIP consortium

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., 2020, Papanikolaou et al., 2020b). It is noted, however, that the deck layout/boundary, thus L_{OA} x B_{OA}, was specified by the end-user (see Fig. 5).

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[2] 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.

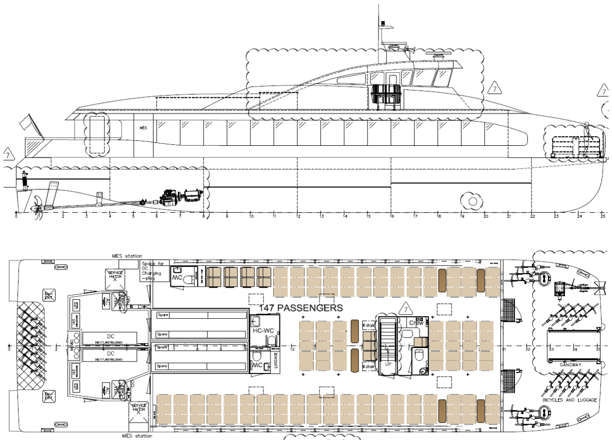


Fig. 5, Preliminary general arrangement of the Stavanger Demonstrator (L_{OA}=30m, B_{OA}=9m)

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., 2000) 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$^{\circledR}$ 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 Fig. 6).

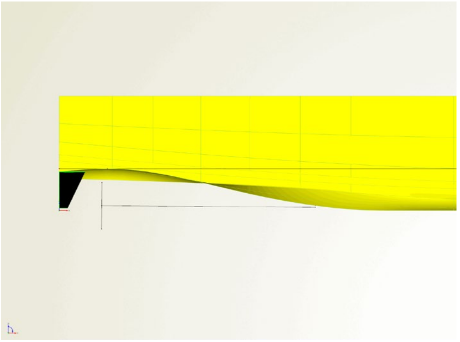


Fig. 6, The parametric model for local hull form optimization showing the propeller position and inclination

Optimization runs were with HSVA' s URANS tool FreSCo^{+} - QCM coupling approach (Xing-Kaeding et al., 2015) 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 computational domain used herein for the resistance and propulsion simulation (both taking into account the free surface effect and dynamic trim and sinkage) extends to 2xLpp in front of, 5xLpp behind, 3xLpp to the side of, and 3xLpp below the vessel. Local grid refinement was applied to the tunnel, propeller, appendages and free surface region, as shown in Fig. 7. The total number of used cells counts 5.7 M.

For the validation of the numerical predictions of the calm water performance of the TrAM Stavanger demonstrator, a large model of 5.34m in length (scale 1:5.6) was tested in the large towing tank of HSVA (300 m length × 18 m width × 5.6 m depth). The tested large model allowed very precise measurements, while minimizing scale effects. A close-up of a demihull's stern area with the fitted CP propeller, shaft, brackets and (twisted) rudder is shown in Fig. 8. The model test results were analyzed by use of HSVA's Standard Correlation Method, which is in accordance with Froude's method. The demihull models were manufactured out of thin layer wood and were cross-connected by high-strength metal beams. A view of the tested model under way at Froude 0.69 (23 knots full scale speed) is given in Fig. 9.

A remarkable result of the conducted model tests was the achieved very high propulsive efficiency, which has reached as high as 78% at design speed (23kn) and even close to 80% at 27 kn. The optimized unique transom stern with a longitudinal and transverse curvature (*transom dome*) creates almost perfect inflow conditions for the propeller, as can be seen in Fig. 10 where the computed nominal wake is presented in axial velocity contours and transversal velocity vectors. The nominal axial wake is very homogeneous except for a small region close to 178 degrees, where the wake of the shaft bracket is visible. This leads to computed and measured very low values (around zero) of wake and thrust deduction respectively from CFD and model tests results (see Figs 11 and 12). This is a remarkable, unique finding in the propulsion theory, essentially meaning that the propeller onset flow is like for a free running propeller, whereas a thrust deduction factor around zero means that there is practically no "thrust deduction" with the propeller working inside the optimized transom dome, but the required propeller thrust to overcome ship's resistance is about the same with the that of the free running ship model w/o propeller.

To complete the validation procedure and check the final performance of the vessel, a speed-power trial has been conducted by HSVA after the delivery of the vessel (Fig. 13). The sea trials have been performed at each engine setting using double runs and in head and following winds according to the recommendation of ISO standard 15016:2002. Factors, such as current, wind, seaway, displacement, water temperature and salinity as well as possible shallow water effect, are considered for the correction of measured results. A final comparison of corrected results of sea trial measurements with the model test and full scale CFD trial prediction can be seen in Fig. 14. In general, a very good agreement has been observed, the deviation between corrected trial measurement, model test and CFD results is below 3% in average along the speed range.

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. More details results can be found in Xing-Kaeding et al. (2022).

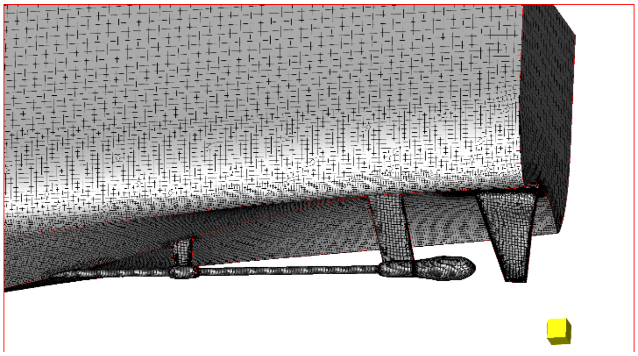


Fig. 7, Numerical mesh around the stern tunnel area for the local optimization by FreSCo+ of the Stavanger Demonstrator (5.7M)

Fig. 8, A close-up view of the stern area with fitted propellers, shafts, brackets and rudders of the Stavanger demonstrator.

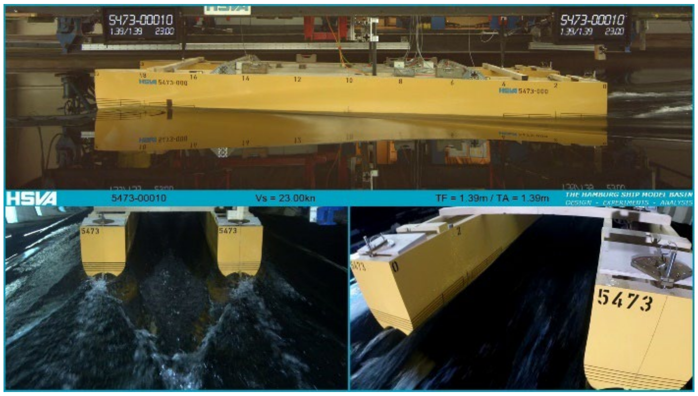


Fig. 9, Self-propulsion model test of the Stavanger demonstrator at Froude number 0.69

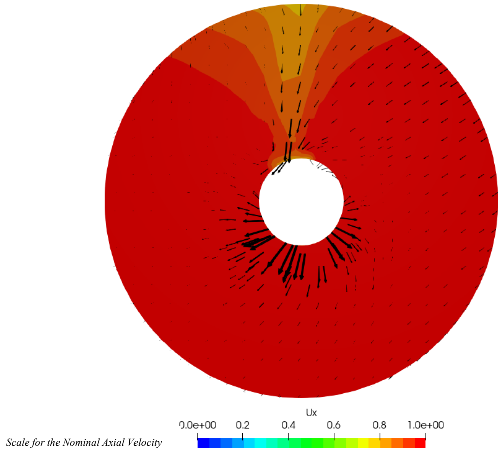


Fig. 10, Computed nominal axial velocity **Ux** contours and transversal velocity vectors at the (port side) propeller plane for ship speed at 23 knots (view from behind).

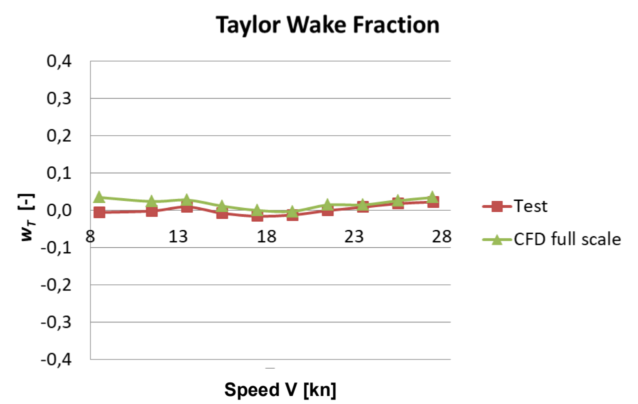


Fig. 11, Taylor wake fraction $\mathbf{W_T}$ (from model tests and full scale CFD for the Stavanger Demonstrator.

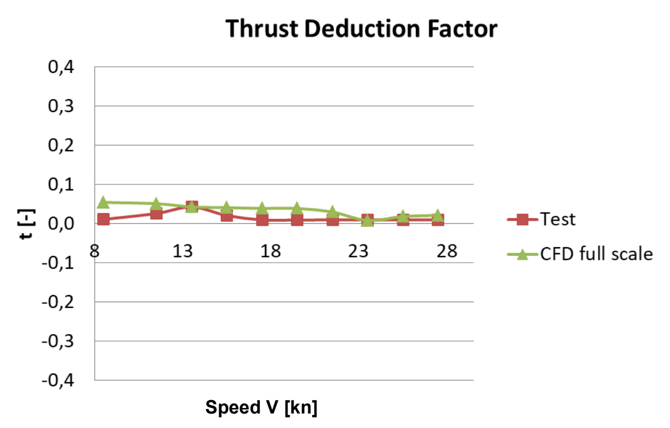


Fig. 12, Thrust deduction factors **t** from model tests and full scale CFD for the Stavanger Demonstrator.

Fig. 13, A photograph during sea trial measurements in Stavanger (July 2022)

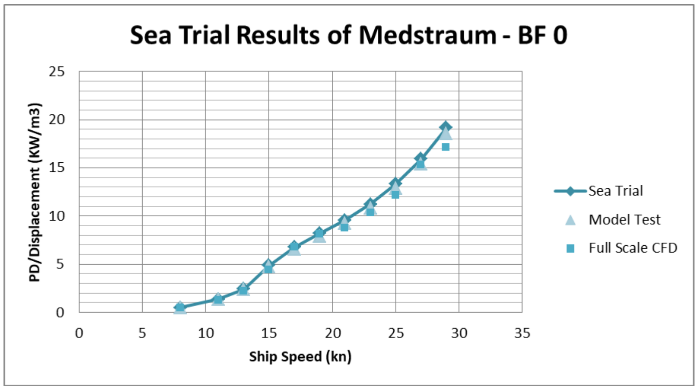


Fig. 14, Sea trial results compared with the model test and full scale CFD prediction for the rated delivered horsepower PD [kW] per Displacement [m^3]

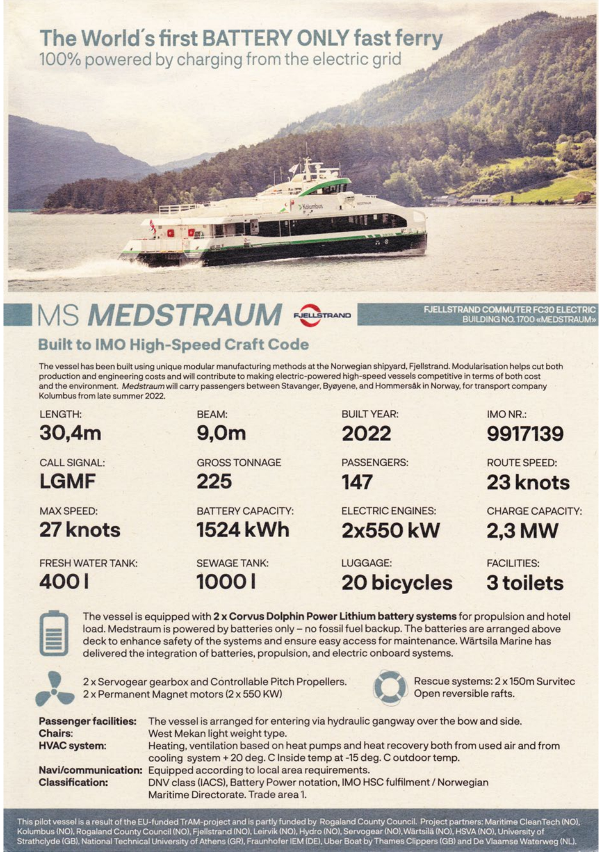
DESIGN

The overall design is based on a typical fast ferry design with all passengers arranged on one deck (Fig. 5). Among other issues, access for disabled people is easier placing all passengers on one deck avoiding elevators or stairlifts. There is also arrangement of 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 length of the vessel has been not optimised for the specified operational speed of 23 knots and may have been slightly larger, but it was chosen from both regulatory limits and size restrictions in the harbors, while keeping an appreciably high speed. In particular, 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 characteristics of the vessel are shown in Table 1.

Table 1. Main Characteristics of MS Medstraum



The World´s first BATTERY ONLY fast ferry
100% powered by charging from the electric grid

MS **MEDSTRAUM**

FJELLSTRAND COMMUTER FC30 ELECTRIC
BUILDING NO. 1700 «MEDSTRAUM»

Built to IMO High-Speed Craft Code

The vessel has been built using unique modular manufacturing methods at the Norwegian shipyard, Fjellstrand. Modularisation helps cut both production and engineering costs and will contribute to making electric-powered high-speed vessels competitive in terms of both cost and the environment. *Medstraum* will carry passengers between Stavanger, Byøyene, and Hommersåk in Norway, for transport company Kolumbus from late summer 2022.

LENGTH: **30,4m**
BEAM: **9,0m**
BUILT YEAR: **2022**
IMO NR.: **9917139**
CALL SIGNAL: **LGMF**
GROSS TONNAGE **225**
PASSENGERS: **147**
ROUTE SPEED: **23 knots**
MAX SPEED: **27 knots**
BATTERY CAPACITY: **1524 kWh**
ELECTRIC ENGINES: **2x550 kW**
CHARGE CAPACITY: **2,3 MW**
FRESH WATER TANK: **400 l**
SEWAGE TANK: **1000 l**
LUGGAGE: **20 bicycles**
FACILITIES: **3 toilets**

The vessel is equipped with **2 x Corvus Dolphin Power Lithium battery systems** for propulsion and hotel load. Medstraum is powered by batteries only – no fossil fuel backup. The batteries are arranged above deck to enhance safety of the systems and ensure easy access for maintenance. Wärtsila Marine has delivered the integration of batteries, propulsion, and electric onboard systems.

2 x Servogear gearbox and Controllable Pitch Propellers.
2 x Permanent Magnet motors (2 x 550 KW)

Rescue systems: 2 x 150m Survitec Open reversible rafts.

Passenger facilities: The vessel is arranged for entering via hydraulic gangway over the bow and side.
Chairs: West Mekan light weight type.
HVAC system: Heating, ventilation based on heat pumps and heat recovery both from used air and from cooling system + 20 deg. C Inside temp at -15 deg. C outdoor temp.
Navi/communication: Equipped according to local area requirements.
Classification: DNV class (IACS), Battery Power notation, IMO HSC fulfilment / Norwegian Maritime Directorate. Trade area 1.

This pilot vessel is a result of the EU-funded TrAM-project and is partly funded by Rogaland County Council. Project partners: Maritime CleanTech (NO), Kolumbus (NO), Rogaland County Council (NO), Fjellstrand (NO), Leirvik (NO), Hydro (NO), Servogear (NO), Wärtsilä (NO), HSVA (NO), University of Strathclyde (GB), National Technical University of Athens (GR), Fraunhofer IEM (DE), Uber Boat by Thames Clippers (GB) and De Vlaamse Waterweg (NL).

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.

The obvious space for the batteries might have been in the demihulls and this was explored first. However, it was found that for this vessel it was better to finally place them on the main deck, in the rear part of the passenger accommodation (Fig. 5), for the following reasons:

- This creates fewer restrictions on hull design especially in terms of width and height of the demihulls.
- 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, inspection and possible fire-fighting, measures.

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.

Very low noise and vibration levels in the passenger areas have been achieved, in the range of 60 dB, what corresponds to normal conversation level (55 dB at bridge).

MODULAR CONSTRUCTION

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).

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 seem not to be 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.

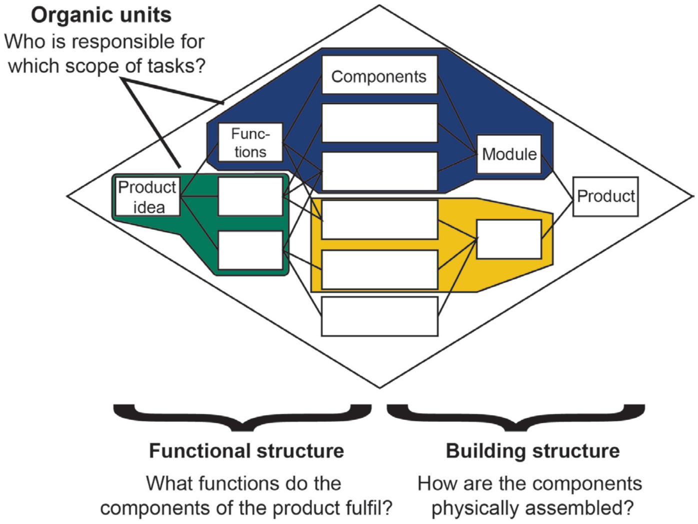


Fig. 15, Modular product architecture according to Göpfert (Pfeifer at al., 2020)

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 Fig. 15 based on the work of Göpfert (Pfeifer at al., 2020).

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 Fig. 16.

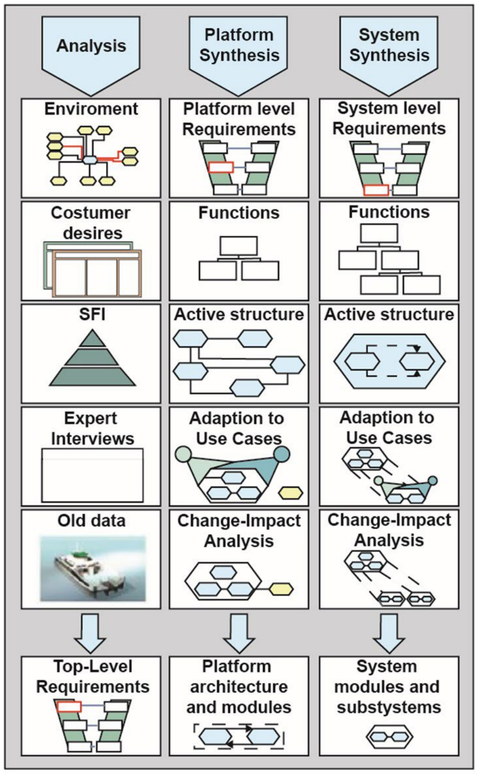


Fig. 16, Methodical approach for a modular ship design

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. The identified modules for the TrAM ship class as shown in Fig. 17.

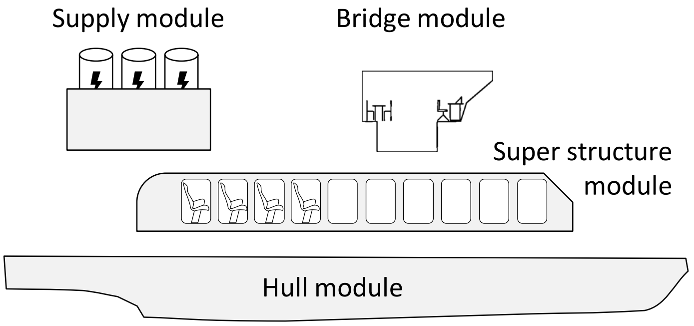


Fig. 17, Identified modules for the TrAM ship class

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 Fig. 18.

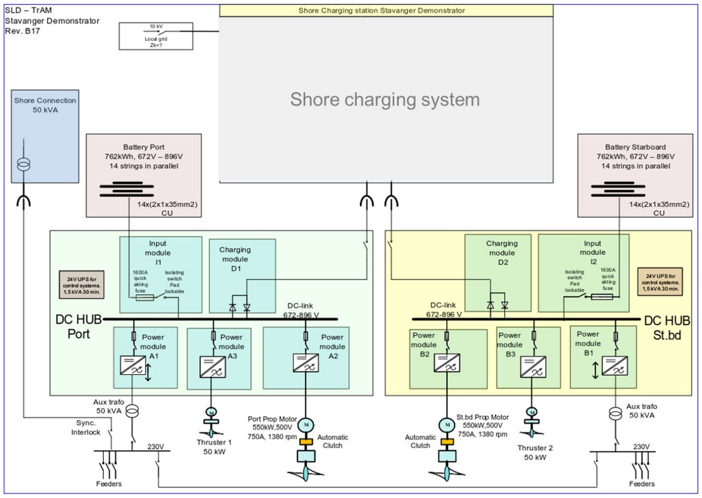


Fig. 18, Single line diagram (SLD) for the Stavanger Demonstrator

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. The motors for the TrAM project are custom-sized based upon an existing design, optimized for compactness in size, high power to weight ratio and extremely high efficiency, fitting the RPMs for a high-efficiency gearbox (Fig. 19).

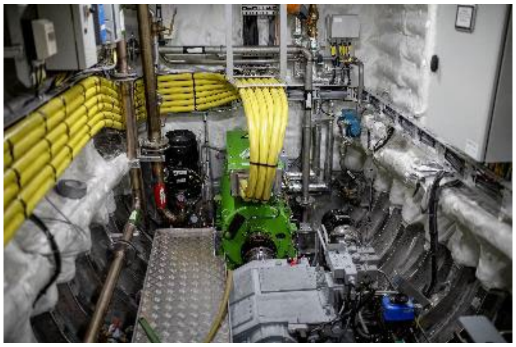


Fig. 19, Engine Room with e-motors

Battery Propulsion

For High-Speed Light Craft (HSLC), as Medstraum is, 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 has developed 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.

The battery type selected for the Stavanger Demonstrator vessel is Corvus Dolphin Power batteries (Corvus Dolphin Power Data Sheet, 2021). 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 (Fig. 20). However, the entire system on the Stavanger Demonstrator is currently limited to a maximum total charging capacity of 2.3 MW.

Fig. 20, 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.

Fig. 21, 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 takes place from the fast-ferry pier Fiskepiren (Fig. 21). This is a very congested area, and the main part of the power electronics and high-voltage system have therefore been located in a space of a parking house at Jorenholmen, some distance away from the Fiskepiren pier. DC cables are transferring 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 Fig. 22. 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 (Fig. 23). Each plug is supplied with current which is 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. It should also serve other vehicles, expected to enter service in the near future.

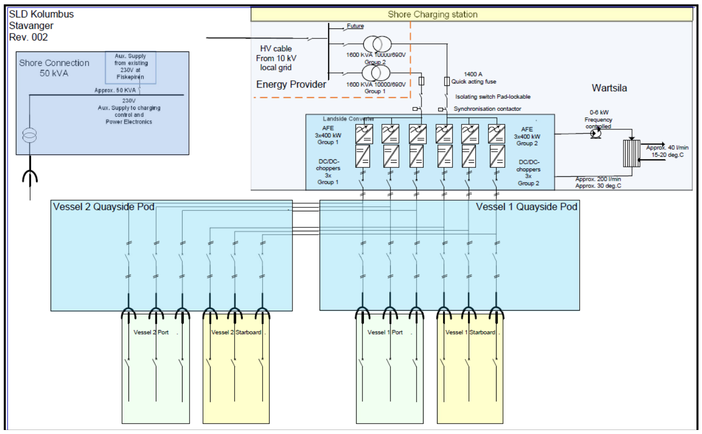


Fig. 22, Single line diagram (SLD) for the Stavanger charging station (including future additional charging point)

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

Fig. 23, Charging point for the Stavanger Demonstrator at Fiskepiren, Stavanger (6 plug-ins)

For the manual plug-in connection, it is important to have an efficient and safe method. The adopted layout of the charging point allows the plugs to be close to the connection point on the vessel and include a working platform for the crew to prevent any accidental slipping or falling incidents.

Economy and Future Technology Considerations

A battery lifespan of around 10 years is the most used value for all large battery planning. However, there are a few dynamic properties in the battery market, which may influence this in conjunction with the low weight restriction for fast ferries:

- In the general battery market, the cost has gradually reduced from 600USD/kWh to 400USD/kWh over some years and forecasts say this cost shall reduce to 100 USD/kWh within 2030. If this forecast comes true it means that using two subsequent batteries with shorter lifetime could be more cost effective than one larger battery with 10 years lifetime.
- Using the same approach, a shorter lifetime should also reduce

the weight of the battery package, which is an advantage for a fast ferry; or, for the same weight of batteries, have more kWh installed, which may lead to a higher operational speed and/or travelling time w/o recharging.

- The development in battery technology is expected to contribute to improvements in battery safety, lifetime and weight, so that in five years from now we shall expect that batteries on the market will be of better quality in many aspects compared to what is available today. This also favors dimensioning with shorter lifetime. However, the reduction in cost and weight is expected to be less than proportional to the reduction in lifetime so the effects from such an approach may be limited, as all forecast based theory it contains uncertainties.

In comparison to the IEC 80005 shore power and other types of charging infrastructure already available on the market, the DC charging system based upon standardized lightweight CCS-2 plugs represent a completely new level of flexibility for high power transfer. It is expected that most future battery powered fast ferries will use CCS or MCS type plugs, to draw advantage from the high level of standardization, cost reduction, flexibility and light weight for the high level of charging power. It is always an advantage to reduce the charging station Capex per vessel, which can be done by letting more fast ferries charge at the same location. Also, the system has the option of extending the connection from the main charging station to a number of landside PODs so that charging from one main charging station can take place in more physical locations given that the total load factor is kept under control.

OPERATION

In order for a fully electrical fast passenger ferry to operate a high-frequency route such as the existing Byøyene-Hommersåk route in Stavanger, the project partners have gone through the design and production phases of the Stavanger Demonstrator, focused on energy efficiency and weight limitation. The final displacement of the Stavanger Demonstrator differed only marginally from the initially assumed design displacement, providing a good basis for achieving the design speed requirements. The Stavanger Demonstrator was designed to a speed of 23 knots. Following full-scale tests of the vessel, it has finally achieved speeds exceeding 27 knots. This was due to the outstanding achieved propulsive efficiency of the vessel (about 80%) and enabled the fitting of batteries of higher capacity with manifold benefits for ship's operation.

The measured full-scale energy consumption is similar to the predicted energy consumption from model testing, providing the Kolumbus with robustness and flexibility for the operation of the Stavanger Demonstrator.

Kolumbus has used time on testing and commissioning of the Stavanger Demonstrator with the charging infrastructure, and to make minor modifications to the vessel in accordance with the experiences gained.

The minor modifications performed following the delivery of the Stavanger Demonstrator have been:

- Modifications initiated at Lindøy quay: due to the added length of the Stavanger Demonstrator compared to the existing vessel operating the route, some modifications to one congested quay at one of the islands stops (Lindøy) is required to improve safety.
- Modification of seawater inlet: the cooling system on a battery electric vessel will run continuously, also while the vessel is at quayside. For the area in Stavanger the water is containing large amounts of biological and waste products that is being sucked into the seawater inlet, resulting in frequent clogging of the filter. An additional filter and a bypass-valve have been introduced to overcome this challenge.
- Modification of gangway: following test-runs of the various quays in the Hommersåk-Byøyene route, it was decided to prolong the gangway to improve access for wheelchair users. The modification has been completed and tested with relevant user groups.


Fig. 24, Medstraum in Stavanger

While minor modifications to improve performance have been incorporated, it is the positive performance that is dominating for Kolumbus, the operator's crew and the public. The Stavanger Demonstrator is silent on board even when operating at full speed, allowing for a significant improvement in the comfort for both crew and passengers. The design with large windows in the passenger module provides passengers with a view of the surroundings in the scenic Byøyene-Hommersåk route.

The charging infrastructure has proven to work according to plan. Manual handling of the charging connections has been timed to approximately 60 seconds for all 6 connectors, which is within the timeframe that has been accounted for in the state-of-charge calculations for Medstraum.

The limited operational period for passenger transport does not provide reliable numbers to assess if the introduction of the Stavanger Demonstrator has had any impact on number of travelers. It should be anyway noted that travel plans and pricing did not change by the operator Kolumbus with the introduction of Medstraum, while the impact on passenger comfort (very low noise and vibration level) and the environment is evident.

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 have developed and validated *a zero-emission, fast waterborne transport transportation concept* by implementing advanced hydrodynamic optimization methods, 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). The project development included the land-based infrastructure of recharging stations and the interface to land-based transport by the use of the SMART city integration concept (Triangulum, 2020). Last but not least, the achieved very high propulsive efficiency makes the whole concept of battery-driven *fast* electric ferry feasible in this case, what cannot be generalized if the achieved propulsive efficiency cannot be kept at high level.

TrAM clearly went beyond the state-of-the-art in waterborne transport, by introducing the first prototype of a fast zero emission ferry. This was acknowledged, among others, by the selection of Medstraum as Ship of the Year 2022 at the major international maritime exhibition Schiff-Maschine-Meerestechnik (https://tramproject.eu/2022/09/06/ms-medstraum-is-ship-of-the-year/). The Ship of The Year is an annual award handed out by the Norwegian shipping magazine, Skipsrevyen.

On the way ahead, it should be noted that the launching of Medstraum has sparked the interest of many operators around the world, several of which have attended the christening ceremony and first round trips; thus, it may be expected that the concept will be widely implemented in relation to the implementation of worldwide measures to decarbonize high-speed craft operations in coastal areas, especially near large and greatly traffic congested cities. It is interesting to note that relevant plans of the Norwegian government consider very tight deadlines for the *greening of fast waterborne coastal transport*, which will accelerate the development process in short and medium term (see address of the Norwegian Minister of Transport, Dr. Jon-Ivar Nygård, during the Christening Ceremony of Medstraum on September 22, 2022).

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