LOGISTICS OPTIMISATION OF A FAST CATAMARAN FERRY – A SELECTION OF OPTIMAL ROUTE CONSIDERING BATTERY WEIGHT AND COST

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ABSTRACT

A study for the decarbonisation of a fast catamaran ferry equipped with a battery-powered propulsion system is presented. This paper identifies the Pareto optimal designs that fulfil the demanding endurance-battery weight-charging time-draught-wake wash limitations in the route. The energy requirement, the weight and cost of the battery packs are estimated.

KEY WORDS

Electric marine vehicles; high-speed catamaran; inland passenger ferry; logistics-based ship design; optimisation; battery powered ferry; life cycle cost analysis

INTRODUCTION

Battery-powered marine vehicles have become one of the most promising solutions to meet the current Greenhouse Gas (GHG) emission control strategies. International Maritime Organisation (IMO) aims to contribute to the Global efforts to address the Climate Change by reducing the total annual GHG emissions from shipping by at least 50% by 2050 compared to their 2008 levels (IMO 2020). The UK and several other countries have set more ambitious targets such as reducing emissions to net zero over the next 30 years (UK Government 2020). The battery powered marine vessels will be able to eliminate their emissions at sea by utilising electric energy stored in their battery packs. However, the weight of the battery packs is a limiting factor as they have currently significantly lower energy density than the fossil fuels they are replacing. Furthermore, the level of the working load, the length of the route and the available recharging time are important factors for the transition to battery-power electric marine vehicle. This paper will present the impact of all these parameters on an inland high-speed battery-powered ferry. It will present a methodology that considers several variants and evaluates their energy requirements to optimise both the vessel and its corresponding operational profile. The ship designs will fulfil the requirements from the ship owner to provide lowest ship resistance and required wake wash. The energy requirement will be determined by applying the in-house Energy Storage Model and the cost of the battery packs will be estimated too with the selected profile considering the depth of discharge (DoD) and replacement of battery.

METHODOLOGY

The methods used for this analysis is presented in Figure 1. First of all, the requirements for the ship design and operation are provided by the ship owners according to their past experience and their commercial purposes. Design variants are developed to meet their requirements and applying optimisation in ship design. The cases with lowest resistance and met the wake wash limitation is selected and fed into the Energy Storage Model (ESM). In the ESM, the operational profile from the ship operator is implemented to determine the energy requirement of the given routes. With the determined energy requirement, the required battery capacity can be estimated according to the estimated power train energy efficiency. According to the energy density from the battery manufacturer, the weight and the size of the required battery packs can be determined. This weight will be checked

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with the weight allowance from the design variants. If the weight allowance is sufficient, the results are used to obtain the life-cycle cost of the battery with the consideration of battery replacement and depth of discharge. Otherwise, the proposed route cannot be satisfied with the particular design from the optimisation.

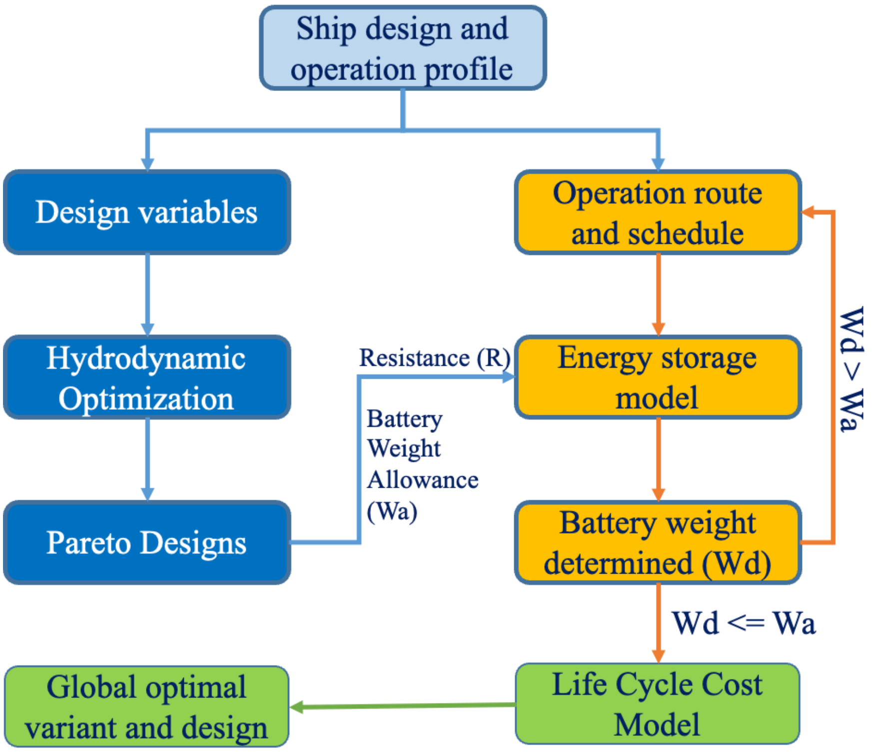

Figure 1 Methodology of this study

1. Optimisation

The ship design optimisation for the short route ferry is set up aiming to select the optimal combinations of the design variables to produce the best overall performance of the vessel. The algorithm utilised is the Non-Dominated Sorting Genetic Algorithm 2 (NSGA2). It is a genetic algorithm that works with a population of solutions and can find multiple Pareto optimal solutions in a single simulation run. The algorithm incorporates innovative features compared to other genetic algorithms; (a) a fast non-dominated sorting procedure, (b) a fast crowded distance estimation procedure and (c) a simple crowded comparison operator, ensuring the preservation of diversity in the produced solutions by monitoring the performance of each design variant, as well as the distance between the solutions within the design space. A non-dominated solution that is in a lesser crowded region is generally preferred(Deb et al. 2002).

The optimisation runs are performed in CAD/CAE software CAESES®. In this optimisation study, the number of generations is set to 100, with each generation having a population of 12 designs. Mutation and crossover probabilities are set to 0.01 and 0.9 respectively.

Objectives

The objectives selected for the global optimisation phase are focused on the hydrodynamic performance of the design. In particular, the minimisation of the calm water resistance at two key operational speeds (12 and 22 knots), along with the minimisation of the maximum wake height produced by the vessel at 22 knots are the objective functions of the study.

Design variables

The design variables selected for the global optimisation phase, along with their limits, are presented in Table 1.

Table 1. Design variables

Design variable	Minimum value	Maximum value
Demihull breadth (max.) [m]	2.150	2.850
Draught (initial) [m]	0.900	1.200
Flat Of Side curve offset factor (of total demihull breadth) (controls the shape of the transverse sections, i.e. U or V) [-]	0.85	1.00
Frame spacing [m]	1.10	1.20
Deadrise angle [deg]	15.0	30.0

Constraints

The constraints set for the global optimisation study are based on the operator's requirements and are presented in Table 2.

Table 2. Design constraints

Constraint	Maximum value
Length overall [m]	40.000
Breadth overall [m]	9.000
Draught [m]	1.200
Air draught [m]	5.000

Multi-criteria decision making

The consideration of more than a single objective in this optimisation study requires a decision-making process, which follows the optimisation run. For this, the utility function theory is utilised, which provides the best compromise solution to the problem (Sen and Yang 1998).

The objective function values corresponding to each feasible design variant are normalised based on the best and worst performers in each objective. The normalised values range between 0 and 1. Then, case scenarios are defined –presented in Table 3 – which determine the weights taken into consideration in the decision-making process. These weights set the significance of each objective in each case scenario. The total of these weights adds up to 100%. The utility function is then calculated for each design variant based on the normalised value and assigned weight factor and the designs are ranked according to their utility function values from best to worst. The maximum score achieved by one design can be 1, whereas the lowest can be 0.

The utility function for this optimisation study is presented in the following equation:

$$\mathrm{U} = \mathrm{w}_{\mathrm{R}_{12}} \cdot \mathrm{u}(\mathrm{R}_{12}) + \mathrm{w}_{\mathrm{R}_{22}} \cdot \mathrm{u}(\mathrm{R}_{22}) + \mathrm{w}_{\mathrm{H}_{\mathrm{W}_{22,\mathrm{max}}}} \cdot \mathrm{u}\left(\mathrm{H}_{\mathrm{W}_{22,\mathrm{max}}}\right)$$

Table 3. Case scenarios

Objective	Scenario 1	Scenario 2	Scenario 3
Calm water resistance (12 knots)	33%	20%	40%
Calm water resistance (22 knots)	33%	40%	40%
Max. wake height (22 knots)	33%	40%	20%

Calm water resistance prediction

The calm water resistance of the hull forms resulting from the parametric surface model in CAESES® is performed using the Slender Body method, which is based on the work of (Couser 1996) and (Tuck et al. 1999). This analytical method computes the energy in the free surface wave pattern generated by the vessel and hence the wave resistance of the vessel. The viscous resistance component is found using the ITTC '57 friction coefficient calculation method and the specified form factor. The sum of the two resistance components (wave and viscous) provides the result. The calculation of the calm water resistance using this method is performed in Bentley® Maxsurf. A software connection is set up with CAESES® to run the simulations for each design variant.

The Slender Body method is a fast and reliable way to predict the calm water resistance in deep water at this stage of the design process, where multiple designs need to be evaluated. Therefore, it is deemed an appropriate evaluation method for the global optimisation study, which is the first step towards the selection of the optimal design for the ferry. Nevertheless, there is uncertainty associated with the results of this approach, compared to those deriving from more advanced methods, such as CFD. Therefore, extensive benchmarking took place before applying the Slender Body method in the global optimisation runs.

To ensure the results of the global optimisation study are reliable, the following steps took place:

- Set up CFD simulations for the ferry in deep water
- Fine-tune the CFD setup to minimise the simulation error
- Run Slender Body calculations and CFD simulations for deep water for several design variants of the ferry (variable displacement and speed)
- Rank the design variants regarding their calm water resistance for each method
- Compare the ranking between the two methods.

The process described above showed an agreement in the ranking between the two methods (Figure 2). Essentially, a design variant that is superior (i.e. characterised by a lower calm water resistance value) to another one using the Slender Body method, is also superior to that design when comparing the calm water resistance results deriving from the CFD simulations. In addition, specific trends are identified between the two approaches; The Slender Body method underestimates the calm water resistance in lower Froude numbers and slightly overestimates it in higher Froude numbers. Hence, it is necessary to further investigate the hydrodynamic performance of the identified optimal designs produced during the global optimisation phase to obtain results of greater accuracy.

Furthermore, an important parameter –the effect of shallow water– must be considered in the optimisation process. Since the Slender Body method cannot capture this effect, the detailed investigation of the selected designs produced in the global optimisation phase will consider this additional factor using advanced CFD tools.

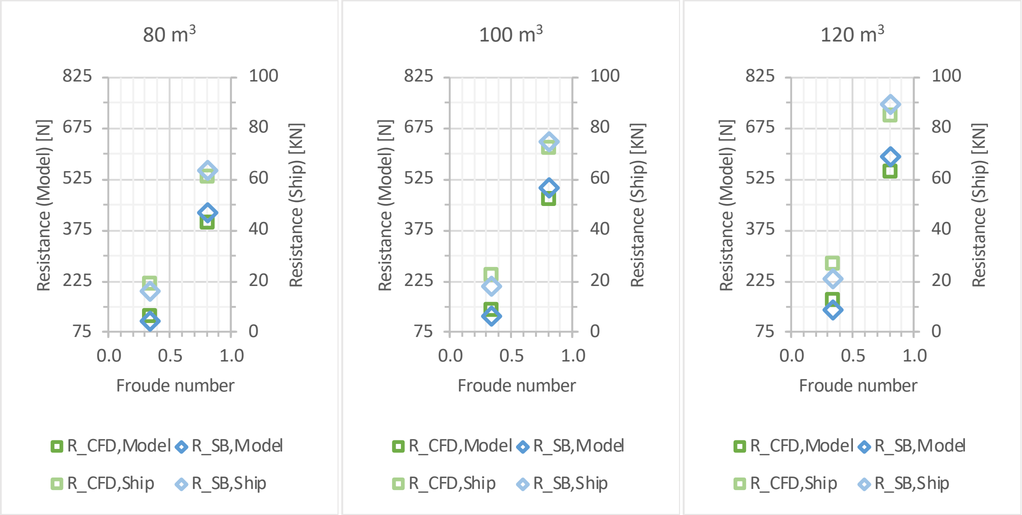

Figure 2. CFD vs. Slender Body method comparison

2. Energy Storage Model

The ESM can estimate the battery weight, size and cost following the approach shown in Figure 3. Firstly, the parametric inputs are defined and developed (Figure 3); the sources of these data are from difference sources and listed in the same table. The estimation of the energy stored in the battery packs should consider the efficiency along the power train. A list of energy loss percentages is provided by the ship operator and shown in Figure 4. Then with the proposed the operational profile and the resistance determined previously, the energy required can be determined. The next step is to take the charging into account. The charging specifications are based on data provided by the vendors including the charging power and energy loss so that the electricity charged into the battery can be derived. Then the depth of discharge of the battery (DOD) is also considered. It significantly affects the numbers of charging cycles and eventually the lifetime of the battery. The relationship between DOD and charging cycles is provided by battery manufacturer and shown in Figure 5. After determining the charging cycles based on the operation profile, the DOD can be looked up and used to finalise the capacity of the battery according to the approach in Figure 6. The last step is to derive the weight, size and cost of the battery packs by combining several battery modules and multiplying the price.

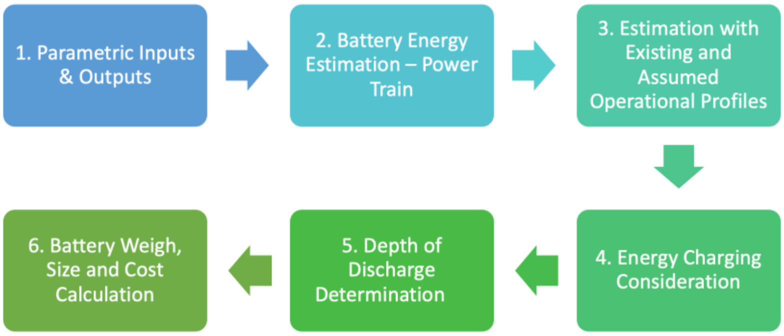

Figure 3. Energy Storage Estimation Approach

Table 1. Parametric inputs of ESM and their sources

Inputs	Source	Inputs	Source
Effective power	Resistance prediction	No. of Accelerations	Operator
Discharge loss (EOL)	Manufacturer	No. of Dockings	Operator
Converter loss	Manufacturer	Charging time in destination	Operator
Motor loss	Shipyard	Charging intervals	Operator
Gear loss	Shipyard	Charging power	Manufacturer
Waterjet loss	Shipyard	Charging connection & disconnection time	Manufacturer
Sea margin	Shipyard & operator	Discharge cycles per day	Operator
Operation hours per round trip	Operator	Usable part of battery	Manufacturer
No. of round trips per day	Operator	Capacity ratio between EOL and BOL	Manufacturer
Operation days per year	Operator	Energy-weight ratio	Manufacturer
Expected battery lifetime	Operator	Battery price	Manufacturer

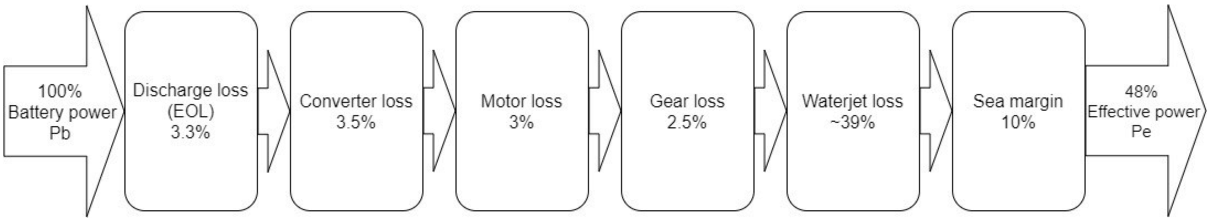

Figure 4. Power train efficiency

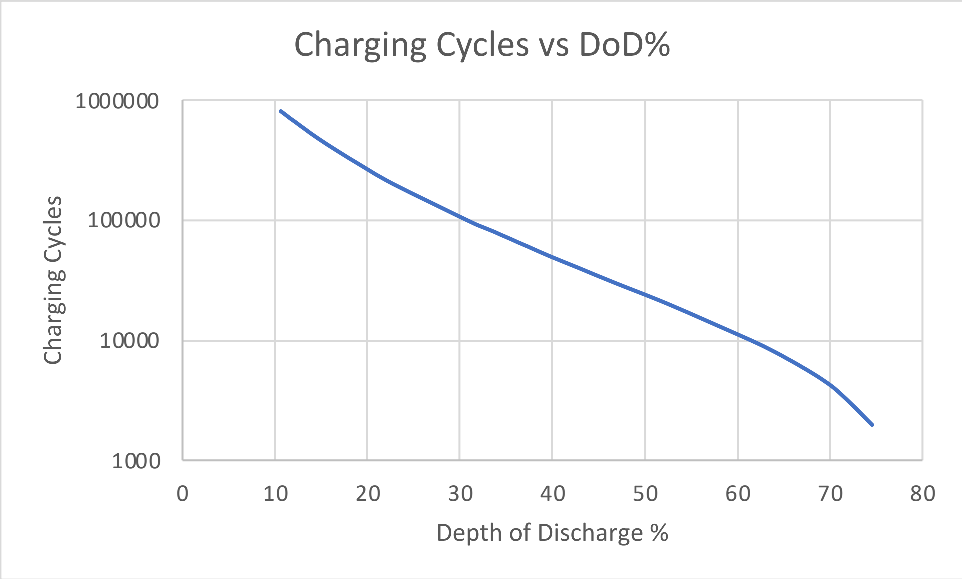

Figure 5 Relationship between Charging Cycles Depth of Discharge

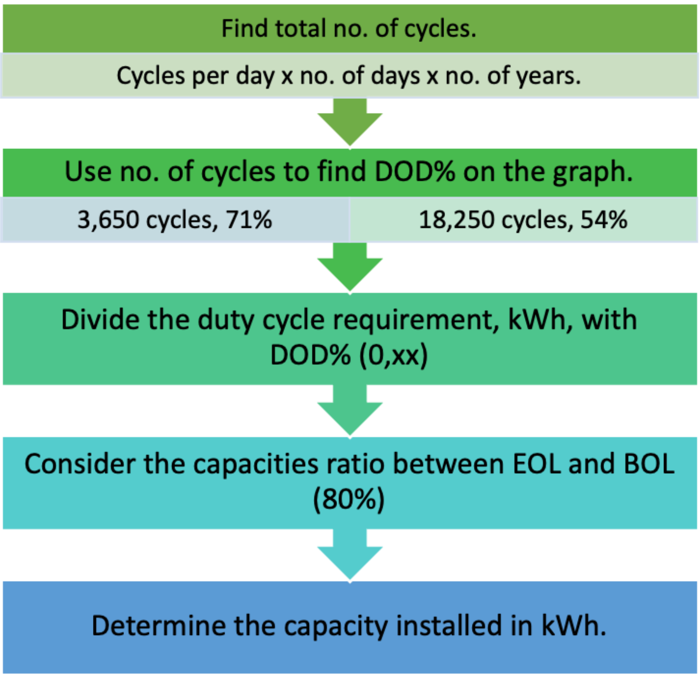

Figure 6 Approach to determine battery capacity with consideration of DOD.

CASE STUDY

Based on the methodology, the analysis to estimate the battery weight and cost are carried out on a selected inland waterways ferry. The details steps are presented in this section.

1. Optimisation

Global hull form optimisation
The optimisation setup described is used to optimise three design variants for the ferry case corresponding to three different design displacements and battery weights (Table 2). The variants can be used for both (passenger and

freight) versions of the ferry. A typical general arrangement of the passenger version is demonstrated in Figure 7. The number of frames and the corresponding compartment length of the battery room changes depending on the design variant to accommodate the selected battery stacks.

Table 2. Design variants

Design variant	Displacement [m^3]	Battery weight [t]
Variant 1	80	10
Variant 2	90	15
Variant 3	100	20

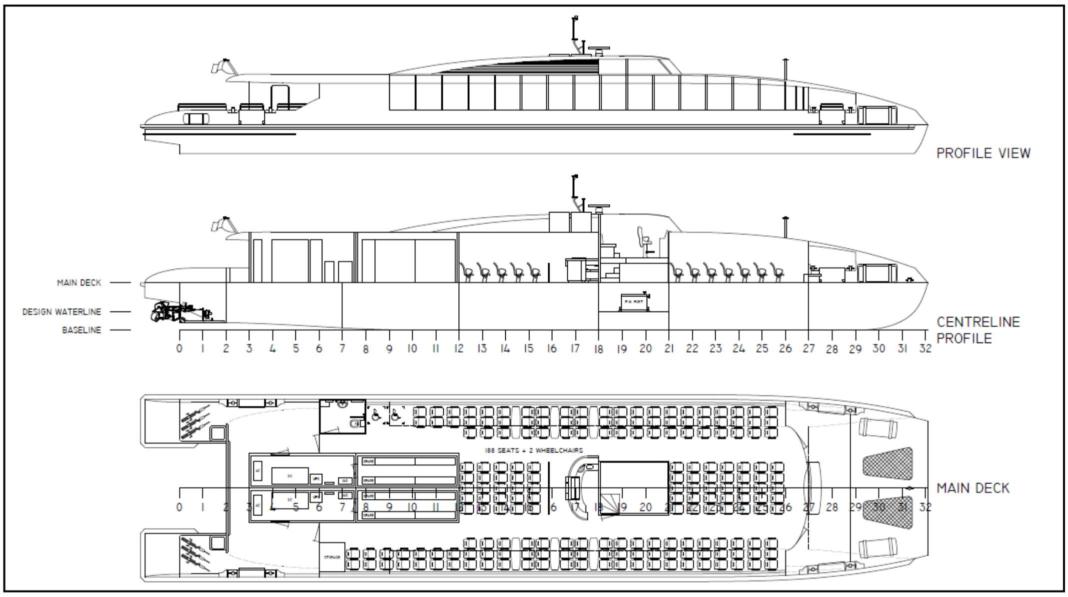

Figure 7. Typical general arrangement of the passenger version of the ferry

Variant 1 (Displacement = 80 m^3)

Out of the 1200 produced designs, 1045 are deemed feasible, while 155 did not meet the constraints set in this study. One optimal design is identified during the decision-making process, named Des0034.

This design ranked first in all three case scenarios (Figure 8). It achieved the best performance regarding the calm water resistance at 22 knots and one of the best performances in the remaining objectives. As far as the design variable values are concerned, the value for the maximum demihull breadth lies on the lower end of the range (2.161 m), whereas the Flat of Side (FOS) curve offset factor, the frame spacing and the deadrise angle are close to the maximum allowed values (0.95, 1.19 m and 16.5 degree respectively). The details of Des0034 are presented in Figure 9, Table 3 and Table 4.

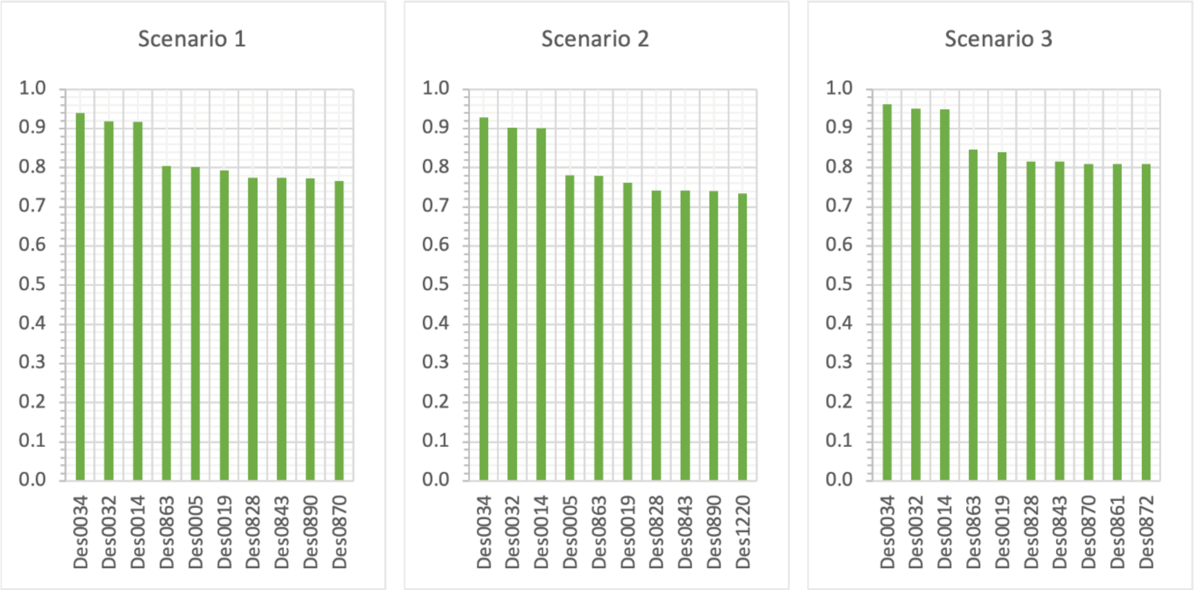

Figure 8. Design ranking for the three case scenarios (80 m^3 variant)

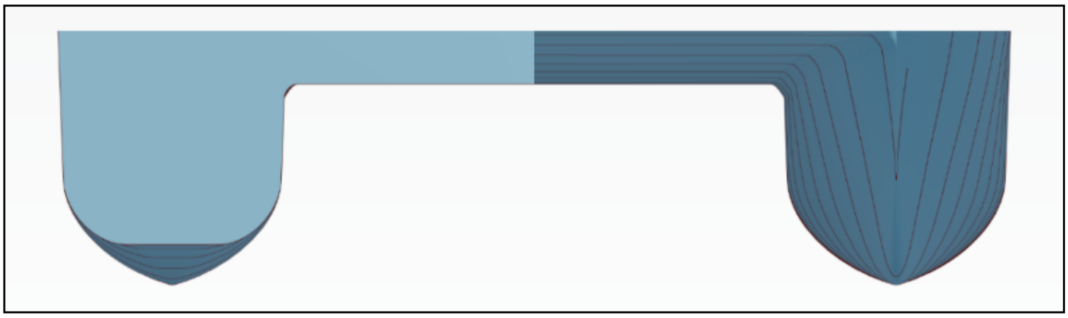

Figure 9. Des0034 bodyplan

Table 3. Design variable values of Des0034

Design variable	Value
Demihull breadth (max.) [m]	2.161
Draught (initial) [m]	0.988
Flat Of Side curve offset factor (of total demihull breadth) (controls the shape of the transverse sections, i.e. U or V) [-]	0.95
Frame spacing [m]	1.19
Deadrise angle [deg]	16.5

Table 4. Main particulars and evaluations of Des0034

Name	Value
Length overall [m]	39.820
Length between perpendiculars [m]	37.375
Breadth overall [m]	9.000
Breadth demihull (at DWL) [m]	2.048
Draught (at DWL) [m]	0.937
Depth [m]	2.388
Displacement [t]	79.9
Displacement [m^3]	80
Demihull separation [m]	6.839
Frame spacing [m]	1.19
Resistance at 12 knots [KN]	13.8
Resistance at 22 knots [KN]	43.0
Wake height at 22 knots (max.) [m]	0.572
Wake height at 22 knots (50% L_{BP} off CL) [m]	0.230
Hull weight [t]	18.6
Superstructure weight [t]	4.6

Variant 2 (Displacement = 90 m^3)

Out of the 1200 produced designs, 1197 are deemed feasible. In this case, two optimal designs are identified during the decision-making process, named Des0034 and Des0042. Des0042 ranked first in two of the case scenarios (scenarios 1 and 3), while Des0034 ranked first in the second case scenario (Figure 10). Des0034 scored the best performance at the calm water resistance at 22 knots, whereas Des0042 achieved the best performance at the calm water resistance at 12 knots. Essentially, Des0034 features the same set of design variables as the optimal design for the 80 m^3 version; however, the position of the design waterline is different to reflect the increased displacement. On the other hand, Des0042 features wider demihulls and a shorter length. The details of Des0034 and Des0042 are presented in Figure 11, Figure 12, Table 5 and Table 6.

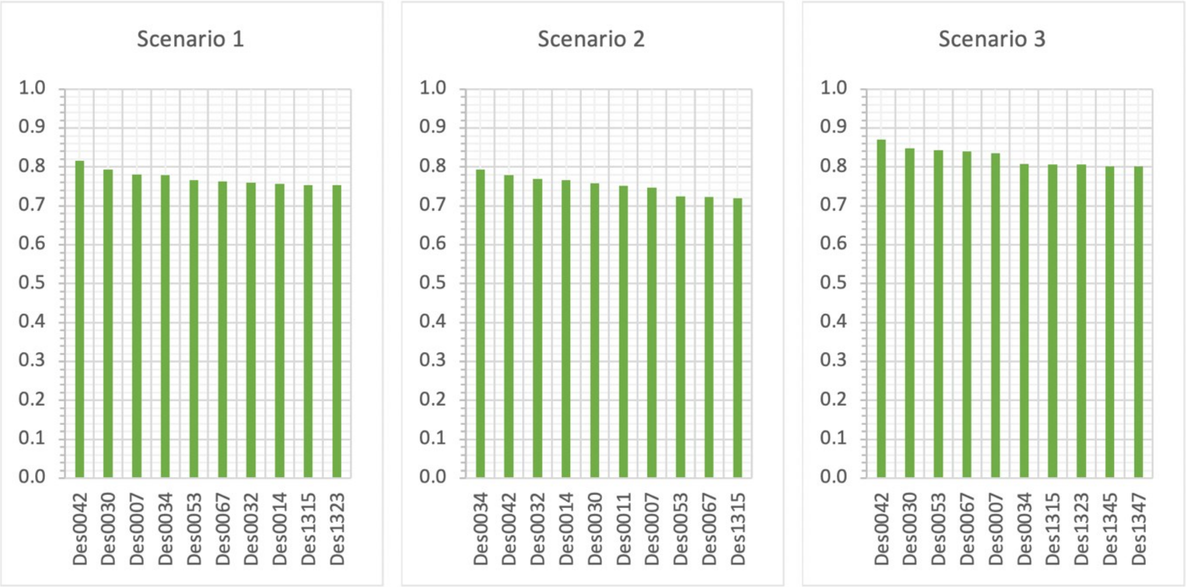

Figure 10. Design ranking for the three case scenarios (90 m^3 variant)

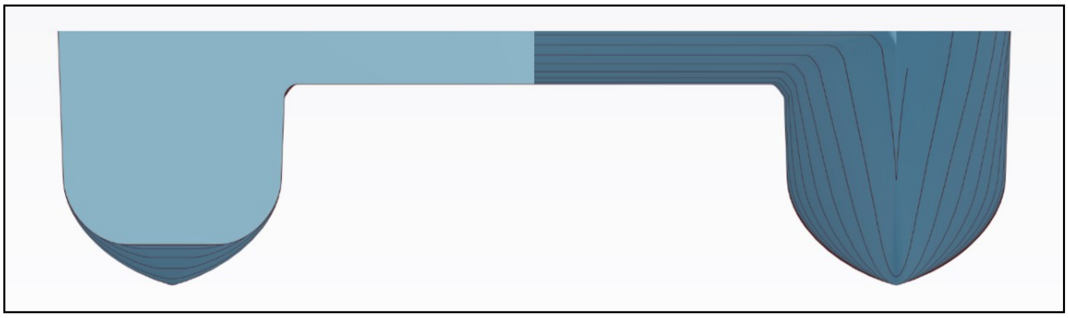

Figure 11. Des0034 bodyplan

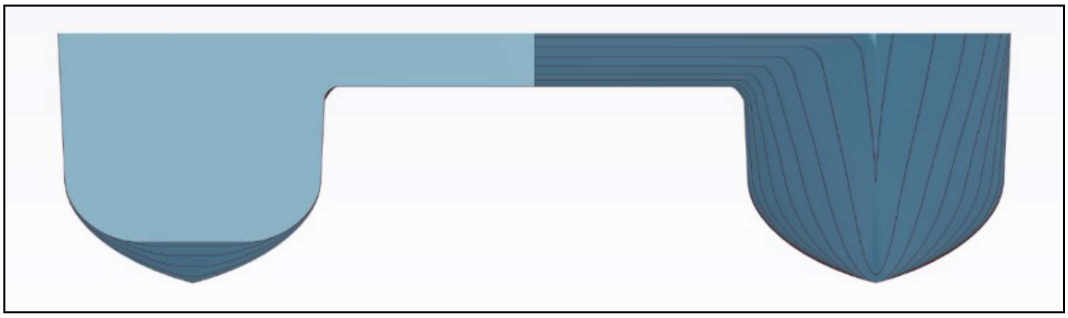

Figure 12. Des0042 bodyplan

Table 5. Design variable values of Des0034 and Des0042

Design variable	Des0034	Des0042
Demihull breadth (max.) [m]	2.161	2.547
Draught (initial) [m]	0.988	0.942
Flat Of Side curve offset factor (of total demihull breadth) (controls the shape of the transverse sections, i.e. U or V) [-]	0.95	0.95
Frame spacing [m]	1.19	1.16
Deadrise angle [deg]	16.5	15.3

Table 6. Main particulars and evaluations of Des0034 and Des0042

Name	Des0034	Des0042
Length overall [m]	39.820	39.280
Length between perpendiculars [m]	37.439	36.863
Breadth overall [m]	9.000	9.000
Breadth demihull (at DWL) [m]	2.062	2.412
Draught (at DWL) [m]	1.012	0.921
Depth [m]	2.388	2.342
Displacement [t]	89.9	89.9
Displacement [m^3]	90	90
Demihull separation [m]	6.839	6.453
Frame spacing [m]	1.19	1.16
Resistance at 12 knots [KN]	16.0	15.0
Resistance at 22 knots [KN]	48.4	48.7

Wake height at 22 knots (max.) [m]	0.673	0.693
Wake height at 22 knots (50% L$_{BP}$ off CL) [m]	0.258	0.269
Hull weight [t]	18.8	18.7
Superstructure weight [t]	4.8	4.8

Variant 3 (Displacement = 100 m^3)

Out of the 1200 produced designs, 1102 met the constraints set in this study. In this case, two optimal designs are identified during the decision-making process, named Des0032 and Des0034. Des0032 ranked first in the third case scenario, whereas Des0034 is considered the best option for scenarios 1 and 2 (Figure 13). Practically, the two designs feature almost identical sets of design variables. Hence, both designs achieved the same resistance values, however, Des0032 marked a better performance regarding the maximum wake height. The details of Des0032 and Des0034 are presented in Figure 14, Figure 15, Table 7 and Table 8.

Figure 13. Design ranking for the three case scenarios (100 m^3 variant)

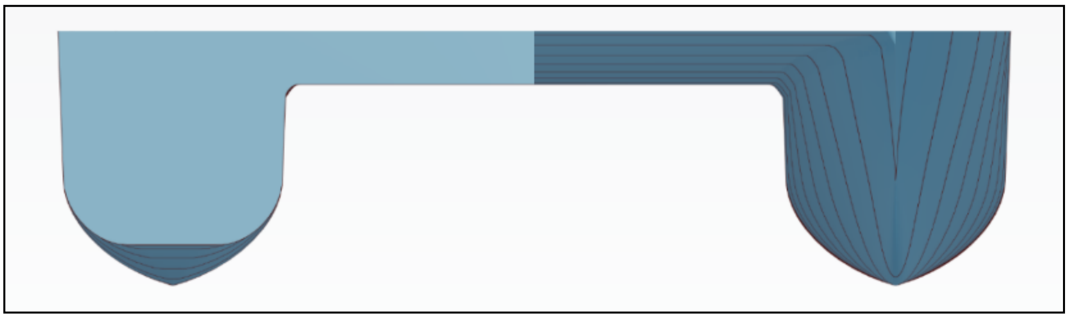

Figure 14. Des0032 bodyplan

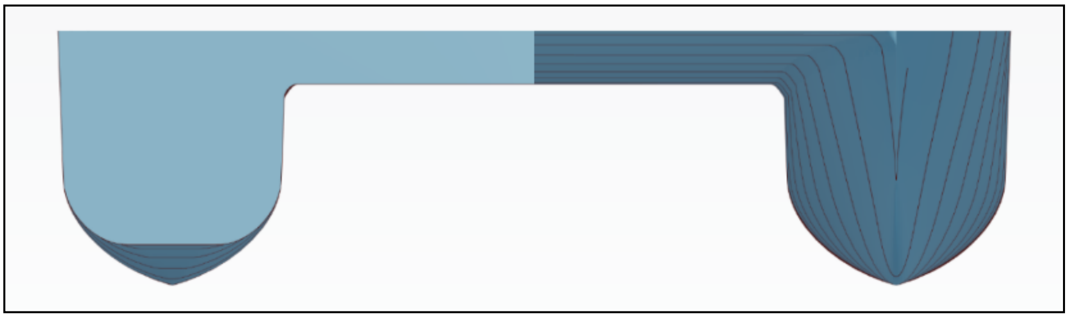

Figure 15. Des0034 bodyplan

Table 7. Design variable values of Des0032 and Des0034

Design variable	Des0032	Des0034
Demihull breadth (max.) [m]	2.171	2.161
Draught (initial) [m]	0.985	0.988
Flat Of Side curve offset factor (of total demihull breadth) (controls the shape of the transverse sections, i.e. U or V) [-]	0.95	0.95
Frame spacing [m]	1.19	1.19
Deadrise angle [deg]	16.5	16.5

Table 8. Main particulars and evaluations of Des0032 and Des0034

Name	Des0032	Des0034
Length overall [m]	39.820	39.820
Length between perpendiculars [m]	37.496	37.496
Breadth overall [m]	2.171	2.161
Breadth demihull (at DWL) [m]	2.078	2.068
Draught (at DWL) [m]	1.082	1.086
Depth [m]	2.385	2.388
Displacement [t]	99.9	99.9
Displacement [m^3]	100	100
Demihull separation [m]	6.829	6.839
Frame spacing [m]	1.19	1.19
Resistance at 12 knots [KN]	17.7	17.7
Resistance at 22 knots [KN]	53.7	53.7
Wake height at 22 knots (max.) [m]	0.745	0.739
Wake height at 22 knots (50% L_{BP} off CL) [m]	0.279	0.285
Hull weight [t]	19.1	19.1
Superstructure weight [t]	5.1	5.1

In all three versions of the ferry, optimal designs are identified, based on the examined objectives. Notably, one combination of design variables is identified as optimal in all three cases: Des0034. Despite having to adjust the design waterline to achieve the respective design displacement (80, 90 and 100 m^3), the specific design variant is considered the best overall and can be applied in all versions of the demonstration case.

2. Energy Storage Model

The ship operator provided 4 pre-set routes for the passenger ferry and 6 for the freight version of ferry. All the conceptual routes for the passenger ferry are presented in the Table 9. The first 3 routes are the original routes for the case study passenger ferry. The last one is a modified route proposed by the ship operator with a reduce full-service speed and with a consideration of charging at the base other than at the starting port. The resultant battery weights from these designed routes are derived for 10 years operation and are shown in Table 10. They compared and checked with the weight allowance originally defined in the optimisation process. Only the fourth route can fulfil the requirement and the others require much larger battery due to too high service speed and too long service route.

Table 9. Conceptual route for passenger ferry

Passenger Ferry Concepts	Full speed (kn)	Slow speed (kn)	Leave/return base	Full speed distance (nm)	Slow speed distance nm)	Charging time (mins)
PF1	28	12	0	8.424	2.376	20
PF2						120
PF3						43
						47
						52
PF4	22	12	5	0.8	2.3	20

Table 10. Comparison of the Resultant battery weight and allowance

Ferry Concepts	Displacement (t)	Wa (t)	Wd(t)	Check
PF1	80	10	81.43	NO
	90	15	90.47	NO
	100	20	102.86	NO
PF2	80	10	25.65	NO
	90	15	28.02	NO
	100	20	31.28	NO
PF3	80	10	25.65	NO
	90	15	28.02	NO
	100	20	31.28	NO
PF4	80	10	8.08	OK
	90	15	8.76	OK
	100	20	9.44	OK

With the extra demands from the operator, a freight version of the ferry is designed which has the similar ship design but different operation routes. There are 6 routes designed for the freight version ferry and shown in Table 11. All the charging time is remained as 20 mins and the battery will be operated for ten years. The resultant battery weights are determined and shown in Table 12 for comparison and check purposes. There are two valid routes, No. 1 and 5. The No.1 route is designed with a low service speed of 15 knots and the length is only 3.54 nm which resulted a very light battery. The No.5 route is 6.6 nm, and the full-service speed is 22 knots, but it has two slow speeds, 12 and 8 knots which led to a light battery too.

Table 11. Routes for freight version ferry

Freight Ferry Concepts	Full speed (kn)	Slow speed (kn)	Slow speed 2 (kn)	Leave/ return base	Full speed distance (nm)	Slow speed distance (nm)	Slow speed 2 distance (nm)

FF1	15	0	0	0	3.5	0	0
FF2	25	12	0	0	4.7	4.7	0
FF3	25	12	0	0	11.7	5.9	0
FF4	28	12	0	0	12.7	6.4	0
FF5	22	12	8	5	3.3	2.9	0.4
FF6	22	12	0	11	16.7	0.5	0

Table 12. Comparison of the resultant battery weight with the allowance (freight ver.)

	Design specifications		Results from ESM	
Ferry Concepts	Displacement (t)	Wa (t)	Wd (t)	Check
FF1	80	10	3.88	OK
	90	15	4.20	OK
	100	20	4.50	OK
FF2	80	10	34.04	NO
	90	15	35.80	NO
	100	20	48.94	NO
FF3	80	10	96.86	NO
	90	15	105.99	NO
	100	20	127.10	NO
FF4	80	10	129.82	NO
	90	15	142.31	NO
	100	20	165.95	NO
FF5	80	10	5.27	OK
	90	15	5.81	OK
	100	20	6.34	OK
FF6	80	10	40.84	NO
	90	15	51.05	NO
	100	20	61.08	NO

With a battery price 137 $/kWh(Statista 2022) and energy density of 125 Wh/kg(Corvus Energy 2022), the cost of the battery during the whole life span of ten years can be determined and shown in Table 13. With a consideration of 30 years ship life, there will be two replacements of battery packs and the total life cycle costs can be derived and they are presented in Table 13.

Table 13 Life Cycle Costing

Ferry Concepts	Battery weight (t)	Cost for 10 years operation ($)	Life cycle costs (30 years)
PF4	8.08	138,370	276,740
	8.76	150,015	300,030
	9.44	161,660	323,320
FF1	3.88	66,445	132,890
	4.2	71,925	143,850
	4.5	77,063	154,125
FF5	5.27	90,249	180,498
	5.81	99,496	198,993

	6.34	108,573	217,145

CONCLUSION

This paper studied a fast catamaran ferry planned for operation in the Thames River powered by battery packs. The battery weight and cost restrictions were analysed using an in-house energy storage model estimating the energy requirement, weight and cost of batteries to match the given operation profile. Due to the low energy density of existing battery technology the operational profile of the planned ferry is modified with the constraint of weight allowance from ship design and optimisation. Among the candidate routes and operational profiles, only three of them are valid for the intense operation:

1. For the passenger version of ferry, the PF4 conceptual route is feasible, and the life cycle cost is estimated and ranged from around 300K USD related to the displacements of the various ship designs.
2. For the freight version of ferry, two candidate routes are feasible: FF1 and FF5; the life cycle costs range from 133K to 217K USD.

The in-house energy storage model can work as a decision-making support tool to provide suggestions and benefits in retrofitting an existing ferry with battery-powered propulsion system. The model will be further validated and updated with data from the ship operators.

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