Ship Design with a Morphing Evolutionary Algorithm

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***Abstract*— Advancements in digitalisation and cyber-physical automation are opening up new frontiers in the marine industry such as autonomous shipping and smart manufacturing of ships. However, the progress in automating the ship design process which is still very human dependent, is slow. This paper introduces an automated ship design and optimisation concept by Hybridising Evolutionary Algorithm and Morphing (HEAM) to enable a more intelligent and efficient ship design process. It maps the entire ship hull form into a genotype using Non-dominated Sorting Genetic Algorithm II (NSGA-II) and flexible modification through morphing to create efficient designs for the hull form. This new method achieves predictive designs with a performance improvement of 11.67%, while achieving increased efficiency and minimum user dependency.**

Keywords*— *Automated design, evolutionary computation, hull form optimisation, morphing

I. INTRODUCTION

Hull Form Design and Optimisation (HFDO) continues to be an integral part of the ship design process. The hull form accounts for the largest part of a vessel and is increasingly becoming a key consideration in ship design. This is primarily driven by more stringent environmental regulations in the marine industry [1] as well as the commercial push for lower fuel consumption during ship operation [2]. One of the factors that helps to increase fuel efficiency is by reducing ship resistance through effective hull form design process [3]. With digitalization and advances towards Industry 4.0, automated and intelligent systems such as smart manufacturing and autonomous solutions are becoming more prevalent in parts of the marine industry. Nonetheless, relative progress in smart and automated ship design process remains slow. The design of the hull form is an iterative process which includes hull form modification, analysing computational results and refining the design for performance improvements [4]. Traditionally, experience designers used trial-and-error approaches to search for optimal hull forms. This process, which depends heavily on the designers' knowledge and experience, is inefficient, time-consuming and may not lead to optimal designs. Computer-Aided Design (CAD) tools can help speed up the process [5], however it remains labour intensive where a large amount of designer input and guidance are required to improve designs. This is particularly so for new builds where "templating" from existing designs is challenging due to the high level of customisation often required. There is also limited number of readily available hull forms that can be used as "starting points" as most existing designs are proprietary. It is therefore recognised that there is a lack of tools for effective design and optimisation of hull forms with minimal input from the designer, that can (i) automatically explore the design space to "identify" suitable hull forms for customisation and (ii) effectively create new designs from a limited set of existing designs. These are the gaps the methodology presented in this paper aims to fill.

The objectives of the paper are twofold:

(1) To efficiently and automatically explore and size the design space for a set of designs suitable for further customisation to meet bespoke design specifications.

(2) To effectively create new and feasible designs from a small set of initial "generic" designs with minimal user input.

This paper presents a HFDO methodology, which combines an Evolutionary Algorithm (EA) and a novel morphing approach to achieve higher automation by transforming the design problem into an intelligent search process to find optimal designs more efficiently. In doing so, the proposed methodology reduces the dependency on the designer - freeing up their time to focus on the creative tasks and enabling the entire ship design process to be more efficient.

The paper is organised as follows. In Section II, an overview of existing developments in the area of hull form design optimisation is provided. Section III details the proposed methodology - Hybrid Evolutionary Algorithm and Morphing (HEAM) and a novel cross-morph crossover operator. In Section IV, HEAM is applied to an industry design problem to automatically design and optimise the hull form of a container vessel. Section V concludes the paper.

II. EXISTING DEVELOPMENT

Currently, a typical HFDO design process comprises of 3 main components: (A) design exploration, (B) geometry modification and (C) performance evaluation with some of the existing EA applications stated in the design exploration section.

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A. *Design Exploration*

In this process, an optimisation algorithm is used to search for optimal designs. Examples of gradient-based methods applied in HFDO include Sequential Quadratic Programming (SQP) [6-9]. However, even though SQP is a highly efficient search method, it suffers the drawback of searching the optimal solution in local minima [10]. To overcome that, global optimisation approaches such as Genetic Algorithm (GA) [11-17] and Particle Swarm Optimization (PSO) [18-21] are implemented in HFDO. Some of the recent approaches used in hull form design include approximation techniques such as Kriging [22] and Response Surface Methodology [23-26], but these algorithms may be too complex to be applied efficiently when coupled with high fidelity performance evaluation methods such as Computational Fluid Dynamics (CFD).

B. *Geometry Modification*

Geometry modification plays a pivotal role in HFDO by introducing diversity and improvement to the hull form design. This is a complex process as every hull form generated must be smooth and feasible. Modifications can be done using direct methods which set controls point with weightage to define the shape on the hull form such as Basis spline (B-spline) [27-31] and Bézier surface [32, 33]. Other methods used in HFDO are systematic modification such as shifting [34], parametric modification [35-37] and Free-Form Deformation (FFD) [38, 39]. While most of these methods are easy to apply, it depends greatly on the input from the designer.

C. *Performance Evaluation*

In performance evaluation, the hull form design produced from the optimiser are accessed using an objective function, for example, for its hydrodynamic performance. Two main performance evaluation methods used in the HFDO process include empirical and numerical techniques [40]. Some examples of empirical approaches include the Holtrop and Mennon method [41, 42] and ITTC-57 [43, 44], while numerical methods such as Reynolds Averaged Navier-Strokes Equation (RANSE) [45, 46] and potential flow [47] are commonly used to calculate the overall resistance of the ship. While numerical approaches are more accurate than empirical methods, they are more computationally intensive.

These can be incorporated into a CAD tool and function as a standalone component or together in a semi-automatic fashion where the designer provides the "automation" to connect one stage to another. For example, following design exploration, selected designs are manually optimised by the designer where adjustments are made to the hull forms based on their experience and knowledge.

With the increase in the availability and advancement in computational resources and methodologies, it is possible to further simplify the HFDO process, making it more efficient to complement the designer's role and freeing up their time for more creative, non-repetitive tasks. One possibility is to combine the three components of the HFDO process into a single platform for a more automated and streamline tool such as the one illustrated in Fig. 1. Here, automation which was previously carried out by the designer can now be achieved by linking the three components together automatically as represented by the blue arrows. This forms the basis for the proposed methodology in this paper.

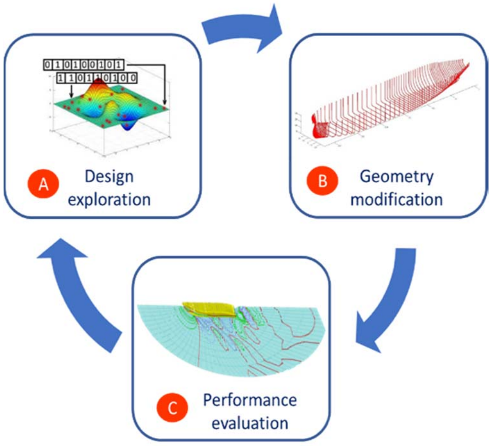


Fig. 1. HFDO process consisting (A) design exploration, (B) geometry modification and (C) performance evaluation [40, 48].

III. Proposed Method: Hybrid Morphing And Evolutionary Computation

In this paper, a Hybrid Evolutionary Algorithm and Morphing (HEAM) method, which combines NSGA-II for the design exploration (objective 1) and morphing for geometry modification for creation of new designs (objective 2), is proposed. The proposed method uses the main operators of the NSGA-II, namely selection, crossover and mutation. All solutions also undergo non-dominated selection and crowding distance measure to form the next generation. The uniqueness of the proposed method lies in the modified crossover and mutation operators where morphing is used to combine (in crossover) and modify (in mutation) the shapes of vessels, creating new solutions. Fig. 2 presents the overview of the proposed HEAM approach.

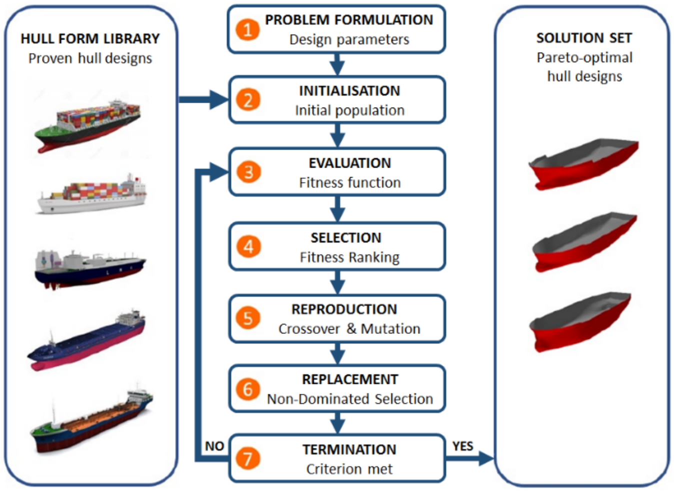
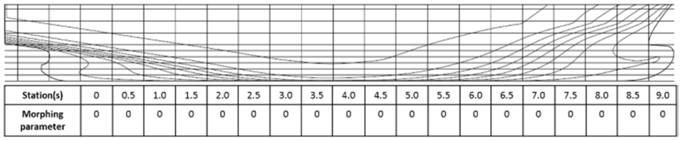


Fig. 2. Proposed Hybrid Evolutionary Algorithm and Morphing (HEAM) approach [40].

During the optimisation process which takes place in the middle block in Fig. 2, the initial population, i.e. starting designs, is obtained from the Hull Form Library where proven hull form designs are used to initialise the search process with the design specifications and optimisation settings. The optimisation process then goes through steps 3 to 7 in an iterative manner until the termination criteria are met and a set of Pareto-optimal solutions is obtained.

Fig. 3 shows the phenotype-genotype representation for a vessel. Each vessel is first divided into a number of different stations, each represented by a real-valued gene. Each gene contains two parameters, namely the station number and a morphing parameter (t). Taken together, the genes form the chromosome representing the entire vessel.



Station(s)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
Morphing parameter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3. Encoding scheme using real value chromosome (morphing parameter, t=0).

Crossover is an important operator used to create more variations in designs. In the proposed methodology, this is where the main geometry modifications take place. It works on a similar basis as the typical "cut and join" approach in conventional EAs where different parent hull forms are split and joined together to form a new child. However, due to the asymmetry in dimension and shape of the hull forms, applying the conventional crossover would result in infeasible structures. This is illustrated in Fig. 4 for two initial parents – a Very Large Crude Carrier (VLCC) and a Pipe laying vessel (PLV) with very different principle dimensions (Table I).

TABLE I. PRINCIPLE DIMENSIONS OF VLCC AND PLV

Dimension(s)	**VLCC (m)**	**PLV (m)**
Length overall (LOA)	327	182
Length between perpendiculars (LPP)	314	168
Breadth (B)	58	46
Height (H)	31	23
Design draft (T)	20	11

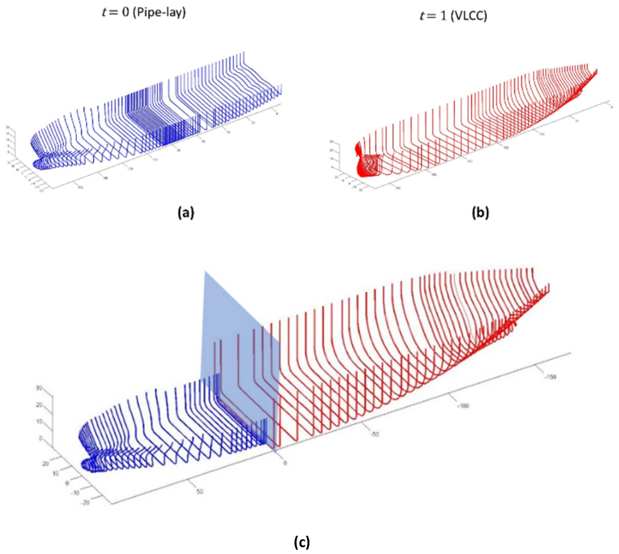


Fig. 4. Wire mesh diagram of two vessels (a) PLV (blue) and (b) VLCC (red). (c) Combination of forward body of the PLV and aft body of the VLCC.

From Fig. 4c, a distinct asymmetrical structure is generated as a result of the irregularities at the "joining junctions" due to the sudden and significant change in dimensions when the two hull forms are combined.

To circumvent this problem, a novel crossover approach, namely cross-morph – crossover using morphing - is developed [40].

The mathematical equation of the morphing is given as follow:

$$M(t) = (1-t) \times R0 + t \times R1 \tag{1}$$

$$\text{for } -0.1 \leqslant t \leqslant 1.1$$

where M is the morphed curve, t is the morphing parameter, $R0$ denotes the source curve and $R1$ denotes the target curve.

Cross-morph works by first splitting the hull forms of two different vessels at a given transverse section and then combining them by morphing their hull lines together depending on the morphing parameter (t). Figure 5 provides an overview of cross-morph when applied to two vessels A and B. First, a 'cut' is applied at a selected point in each vessel, i.e. each vessel is split into two parts as shown in Fig. 5a and 5b. Following this, one part from each vessel is combined with the other to form a new child vessel as shown in Fig. 5c where the aft of Vessel A and forward of Vessel B are combined to form a new hull. Morphing is then applied to the joining junction between the two vessels.

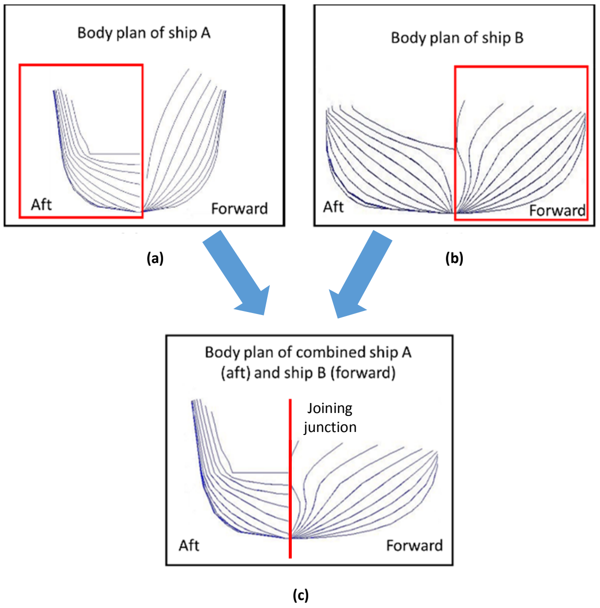


Fig. 5. Cross-morph applied to the aft body of Vessel A and forward body of Vessel B

In the genotype space, the morphing parameter, t is applied to each gene (individual station) around the joining junction, termed the transition frames. The width of the transition frames will vary depending on the difference in sizes between the two vessels. For instance, two vessels of similar dimensions will have a shorter width for the transition frames as compared to two vessels with very different dimensions. As a general guide to ensure that the end products are feasible, the transition frames are set at 10% of a vessel's length for vessels of similar dimensions and 90% for that are very different in size.

Fig. 6 explains the effect of different morphing parameters when applied to a hull line extracted from station 0.5 in each vessel which generate a range of different shapes. Morphing does not only generate new design but also provide smooth transition between the combination different vessels.

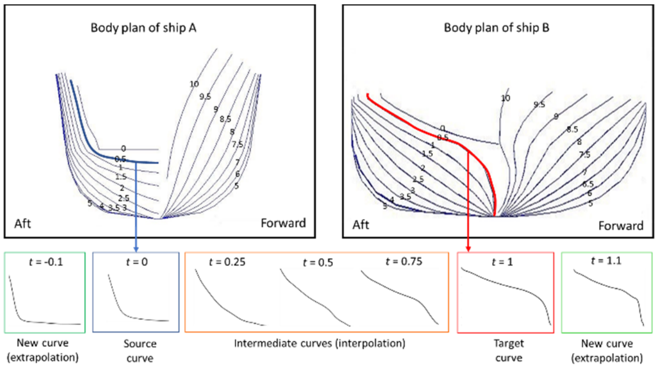
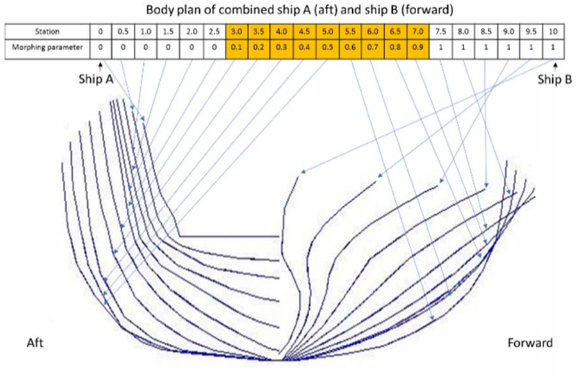


Fig. 6. Intermediate (interpolation) and new hull curves (extrapolation) generated via morphing between ship A and ship B at a station number of 0.5.

Fig. 7 shows the effect of cross-morph when applied to combine the aft and forward of vessels A and B respectively, the transition frames (highlighted in yellow) range from stations 3.0 to 7.0 where stations 3.0 to 4.5 would "resemble" more of Vessel A while stations 5.5 to 7.0 more of Vessel B.


Body plan of combined ship A (aft) and ship B (forward)

Station	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing parameter	0	0	0	0	0	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1	1	1	1	1

Fig. 7. Morphing applied to mid body of combined Vessel A (aft) and Vessel B (forward).

This approach offers flexibility to modify the hull form at any location while maintaining a smooth transition as shown in Fig. 8 for the resultant child vessel produced by cross-morphing the VLCC and PLV in Fig. 4.

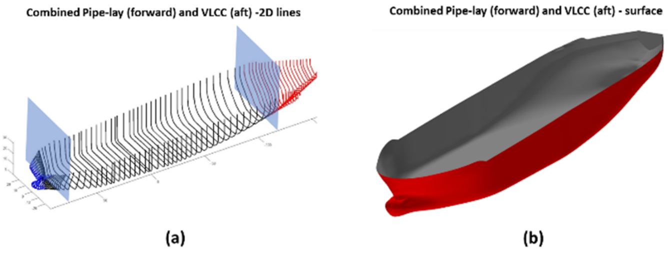


Fig. 8. (a) Wire mesh diagram and (b) 3D surface of the resultant child vessel produced from combining a VLCC and a PLV via cross-morph.

To create greater diversity in the resultant child population, two-point cross-morph can also be applied in the same manner. This will result in the child being formed from a larger variety of parent vessels. This is important because of the limited number of parent vessels available in the initial populations.

Following cross-morph, solutions undergo mutation where 10% of the chromosome in the forward of the vessel is randomly modified, i.e. each station (curve) is extrapolated up to 10% from its initial value. Finally, the performance of every individual solution is evaluated, for example, using the Holtrop and Mennon method [41, 42] to obtain the total resistance of the vessel.

IV. RESULTS AND DISCUSSIONS

This section presents and discusses the results obtained from (A) a case study where HEAM was applied to the design and optimisation of a container vessel, and (B) comparisons between single-point and double-point cross-morph.

A. Case Study: Design Optimisation of a Container Vessel

The objective of this case study is to minimise the total resistance of a container vessel. A total of 36 different combinations were assessed by applying different crossover and mutation rates ranging between 0.5 and 1, in steps of 0.1. The optimal settings for this case study was found to be crossover rate at 1.0 and mutation rate at 0.1.

Principal Dimensions:

- Length between Perpendicular (LPP) = 185m
- Breadth (B) = 32m
- Draft (T) = 9m
- Design Speed (V) = 20 knots
- Displacement Volume (Δ) = $\leqslant$ 34,358.7 tonnes

Optimisation Parameters:

- Initial population = 12 vessels
- Crossover rate = 1.0
- Mutation rate = 0.1
- Total generations = 100

The single-objective optimisation is formulated as follows:

$$\text{Minimise:} \quad f = Rt \tag{2}$$

$$\text{Subject to: LPP} = 185\text{m}, \text{B} = 32\text{m}, \text{T} = 9\text{m}$$

$$\Delta = \leqslant 34{,}358.7 \text{ tonnes}$$

where, Rt is the total resistance to minimise. LPP (Length between Perpendicular), B (Breadth (moulded)), T (Draft) and Δ (Displacement of the vessel in tonnes) are set as constraints for the search.

The initial population is made up of the 12 parent vessels shown in Fig. 9. These vessels were obtained from real-world applications and are used as starting points for the design optimisation. Table II provides the principal dimensions of the vessels.

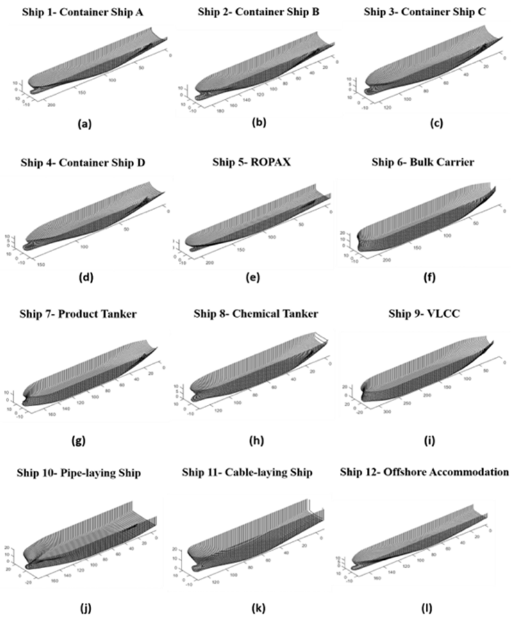


Fig. 9. Body plan of parent vessels in initial population (not drawn to scale).

TABLE II. PRINCIPLE DIMENSIONS OF PARENT VESSELS IN INITIAL POPULATION.

No.	**Vessel type**	**LPP (m)**	**Breadth (m)**	**Depth (m)**
1	Container A	202	32.2	19.1
2	Container B	185	32	19.1
3	Container C	120	23	11.2
4	Container D	145	13.6	13.6
5	Roll-on/ roll-off ship (ROPAX)	210	34	17.1
6	Bulk Carrier	220	36	23.75
7	Product Tanker	171	31	15.6
8	Chemical Tanker	126.5	21.5	10.5
9	Very Large Crude Carrier (VLCC)	314	58	31
10	Pipe-laying Ship	242	45	21.1
11	Cable-laying Ship	121	23	12.5
12	Offshore Accommodation Ship	168	24	13

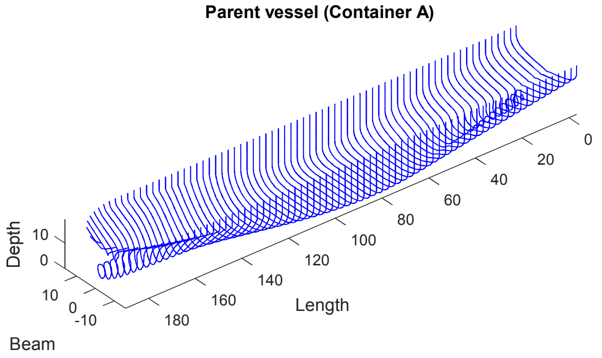
Two-point cross-morph with a crossover rate of 1.0 was used. Mutation rate was set at 0.1. Based on the design criteria, the initial hull forms were first evaluated using the Holtrop method to estimate the total resistance, *Rt*. The best individuals were carried forward to the next generation and the entire optimisation took place over 100 generations.

The results of the optimisation are presented in Table III. The performance of the parent vessels in the initial population and the performance of the best child solution are shown in the first 12 rows and last row respectively. A comparison between the best parent (Container A) and the best child solution (Optimised Hull A) showed that there was an improvement of 11.67% for the resistance *Rt*. This result concurs with the hull forms shown in Fig.10 ((a) – parent vessel, Container A and (b) – child vessel, Optimised Hull A). Comparing the shape of both designs, it can be seen that the bow (forward) and stern (aft) area of the best child vessel is significantly smaller with fuller mid body as compared to the best parent vessel. The result is a more streamlined hull form with lower drag acting on the entire vessel. This is a remarkable achievement considering that the total resistance had reduced significantly (from 944.6 kN to 845.96 kN) despite an increased in displacement (from 32365 tons to 34384 tons).

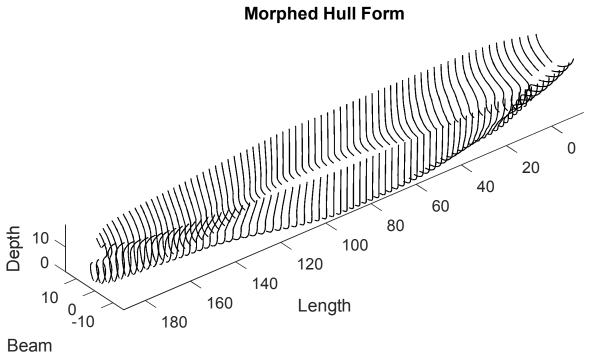
These results demonstrated that the proposed approach is capable of producing design solutions that are both feasible and have good hydrodynamic performances even with a handful of starting points in the initial population. More importantly, it verified the effectiveness of cross-morph as a crossover operator for structures with varying dimensions and forms. This is a key contribution in this paper and is crucial to automating the HFDO process.

TABLE III. PERFORMANCE OF PARENT AND BEST CHILD SOLUTIONS.

Vessels	**Total ship resistance, *Rt*(kN)**	**Displacement, *Δ*(Tons)**
Container A	**944.60**	**32365.18**
Container B	1005.03	34358.73
VLCC	2070.38	45041.05
Bulk Carrier	2445.41	46736.27
Pipe laying vessel	2204.45	45867.3
Ropax	1689.38	40677.06
Container C	1112.38	36658.05
Product tanker	1798.88	46413.78
Chemical/ Product tanker	1695.43	44030.88
Container D	1118.77	35047.05
Cable laying vessel	1572.41	41844.91
Offshore Accommodation vessel	1089.14	37044.81
Optimised Hull A	**845.96**	**34384.59**
Improvement in *Rt* (%)	**11.67**	



(a)



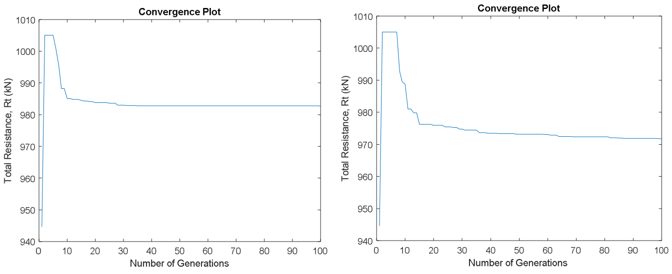
(b)

Fig. 10. Wire mesh diagrams of (a) best parent from initial population - Container A (in blue) and (b) best solution obtained at the end of the optimisation – Optimised Hull A (in black).

B. *Comparison between Single-point and Double-point Cross-morph*

A comparison was conducted to determine if single-point or double-point cross-morph was more effective in exploring the design search space and producing new solutions.

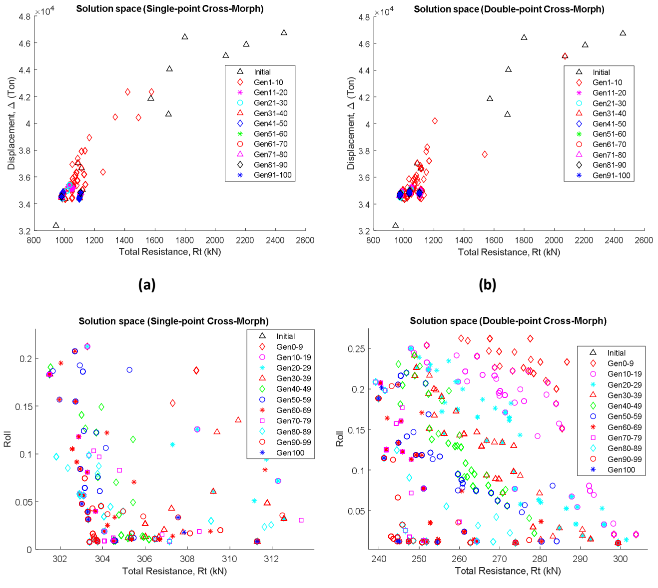
Fig. 11 shows the convergence plots for both types of cross-morph.



(a) (b)

Fig. 11. Convergence plots for (a) single-point cross-morph and (b) double-point cross-morph

In both cases, marked improvements in resistance were observed within the first 15 generations of the search. However, in the case of single-point cross-morph the search started to stagnate around generation 40 whereas the solutions found using double-point cross-morph continue improving even after generation 70 and eventually finding a better solution. This observation also concurred with the solution space plots in Fig 12, which presents the solution space of single point and double point cross-morph. Here, Fig. 12(a)-(b) show the solutions with the best total resistance plotted against displacement. Fig. 12 (c)-(d) show the solution front for 2 conflicting objectives, namely roll and total resistance. From Fig 12(a) and 12(b), it can be seen that double-point cross-morph provided better search space coverage and was able to find better quality solutions as the search evolved. To further illustrate this, resistance was plotted against roll for all solutions found over 100 generations as shown in Fig. 12(c) and 12(d). Fig. 12 (c) and (d) further demonstrate the capabilities of double point cross-morph in terms of diversity and search space coverage as compared to single point cross-morph in the two conflicting objective optimisation. It can be seen that double-point cross-morph had much better search space coverage and solutions found were more superior in comparison to single-point cross-morph. This is likely due to the small number of starting points available in the initial population and hence more crossover is needed to provide more variety in the solutions.



(a) (b)

(c) (d)

Fig. 12. Solution space for resistance vs. displacement (a) single-point cross-morph and (b) double-point cross-morph, and resistance vs. roll (c) single-point cross-morph and (d) double-point cross-morph.

V. CONCLUSION

Hull form design is a highly iterative optimisation process that is so far intensively human dependent. By combining EA and a novel morphing approach, fully automated process can be achieved, with good performance improvements as compared to existing proven vessels. Despite only 12 existing hull form designs were used in the initial population, it is demonstrated that an improvement of 11.67% was achieved. This result proved that HEAM can be used effectively to improve the overall efficiency of hull form design and optimisation.

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