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Evolutionary Computation Automated Design of Ship Hull Forms for the Industry 4.0 Era

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***Abstract*— As the marine industry moves towards the industry 4.0 era, the role of automated smart design is becoming increasingly significant. This offers an ability to produce highly customisable design and to integrate with the product-lifecycle process such as digitalised ship production and ship operations to in an efficient process. Currently, the hull form optimisation process is performed manually using 'trial-and-error' approach, which is not efficient. Focusing on automated smart design, this paper introduces a hybrid evolutionary algorithm and morphing (HEAM). It works by mapping the entire hull form (phenotype) into a chromosome (genotype), which allows global shape modification using a novel 2D morphing method. By combining this 2D morphing and Genetic Algorithm (GA), it enables optimal hull designs to be produced more rapidly with no user intervention.**

***Keywords*— Automated smart design, hull form, 2D curve morphing, evolutionary algorithm**

I. INTRODUCTION

Digitalisation of ships are gaining more attention in the marine industry as ships become eco-friendlier and smarter. With industry 4.0 (I4.0), ship production is now moving towards more intelligent systems or machineries that are highly automated and connected. In the context of ship operation, vessels are also becoming smarter with more automated systems and shifting towards unmanned and autonomous vessel. In comparison, the development of fully automated ship design process has been lacking. Fully digitised product lifecycle refers to a fully automated and connected processes comprising ship design, construction, operation to decommission where information can be shared interchangeably to achieve optimal performance.

With the development of eco-friendlier and more energy-efficient ships, the design and optimisation of hull forms continue to play an important role to help reduce fuel consumption and carbon dioxide emission. Traditional method of ship design and hull form optimisation requires many designer's man-hours using the 'trial-and-error' approach, which is inefficient and does not guarantee optimum designs. While latest simulation-based hull form design and optimisation methods help to automate some of these processes, they still require considerable expert user input and success at end result depends heavily on the designer's experience and knowledge. Another major issue is the extensive computation time when the optimisation algorithm is coupled with solvers such as Computational Fluid Dynamics (CFD) which require high computational resources.

Focusing on achieving a fully automated smart design process, we introduce an innovative concept which aim to address the above issues and achieve the goal of fully digitised product lifecycle by automating the hull form design process with zero user input before, during and after the initial hull form design and optimisation process. This is achieved by combining evolutionary algorithm with efficient geometric transformation approach known as morphing. This hybrid approach is linked to simple evaluation solver based on analytical approach which helps to reduce the computational time significantly and yet provide good indication of improvement for preliminary design stage.

The paper first explores the current simulation-based design methodology and applies it ship hull form designs. With this goal, the paper establishes smart design, detailing how it can be linked to product lifecycle to achieve a fully integrated creation process. A hybrid approach is then developed to optimise the design of the hull form to be fully automated. Finally, results are presented to test and demonstrate the design efficiency and the performance improvement of the proposed approach.

II. CURRENT APPROACHES TO SHIP HULL FORM DESIGN

Traditionally, ships are designed based on ‘trial-and-error’ approach. Designers first produce the new hull form design using hand or computer-aided design (CAD) tools based on their experience and evaluate the results using first principle or model test. This is followed by re-adjusting or modifying the hull form and repeats the process multiple times with the hope to achieve better performance. This method is exhaustive, time consuming and does not guarantee optimal design. Due to stiff competition and shorter design cycle time; such traditional methods are subsequently replaced with faster and more effective computer simulation tools and optimisation methods. In particular, the development of computer simulation and optimisation led to the rise of simulation-based design (SBD) [43], which proved to be very efficient in assisting and guiding the designer in the decision-making process toward the development of more optimal hull form.

As compared to traditional design where a new design is modelled manually by hands or CAD tools and evaluate using model test, SBD utilises computer simulation and optimisation to model, simulate and test in a virtual environment. Currently, SBD had become the main tool for designers to design, simulate and test the digital design using different CAD modelling and simulation tools. More recently, the integration of computer simulation and optimisation allows the process to be integrated and become more automated, although certain user inputs before, during or after the optimisation process are still required. A simple illustration of SBD process is provided in Fig. 1.

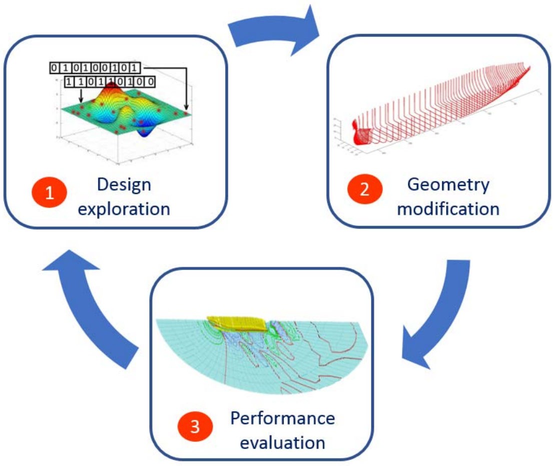

Fig. 1. SBD process consisting (1) design exploration, (2) geometry modification and (3) performance evaluation.

Fig. 1 shows that SBD consists of three key processes- firstly, (1) the hull shape is linked to a design exploration function to systematically search for optimal design. Next, (2) the geometry modification function will change the shape of the hull to create new designs. (3) The performance of the new shape will be evaluated. This process will continue to iterate until the stopping criteria is met.

While the key steps or process are somewhat similar in most Hull Form Design and Optimisation (HFDO) applications [44], there are many different methodologies that are applied in each of the key processes. Design exploration, also known as optimiser, is a parametric optimisation process where key design parameters such as shapes of the hull are modified in an iterative loop through optimisation algorithm to produce a set of optimal hull forms at the end of the optimisation process. Key optimisation algorithms that are widely applied in HFDO can be catergorised under three main types: Gradient-based, derivative free and evolutionary algorithm. Example of Gradient-based algorithm includes conjugate gradient [1,2] and sequential quadratic programming (SQP) method [3,4,5,6,7,8]. Some examples of derivative free algorithm include Hooke and Jeeve method [9, 10] and Nelder and Mead method [11,12]. Examples of evolutionary algorithm include Genetic algorithm (GA) [13,14] and Particle swarm optimisation (PSO) [15,16].

Geometry modification plays an important role in ensuring the hull shape can be easily manipulated to form new shapes in order for the optimiser to investigate and evaluate. There are two main approaches used to modify hull geometry- direct modification and systematic variation. Examples of direct modification includes Beizer curve [11], non-uniform rational basis spline- NURBS [17,18] and T-splines [12]. Some examples of systematic variation methods applied in hull form optimisation include Lackenby shift [19], parametric modification [20,21] and free-form deformation [22].

Performance evaluation assesses each candidate solution produced from the optimiser based on the objective function. There are many hydrodynamic analytical techniques used for performance evaluation, depending on the flow problem and location to be investigated. Each method has its characteristics and suited for different applications. Hydrodynamic performance prediction techniques can be classified into two main types- empirical and numerical based approaches. Example of empirical approach include ITTC 1957 extrapolation line (ITTC-57) [1, 7, 23, 24, 25] and Holtrop method [26] for total resistance evaluation. Examples of numerical (CFD) methods used for resistance evaluation include potential flow [27] and Reynolds Averaged Navier-Strokes Equation- RANSE [28,29].

III. AUTOMATED SMART DESIGN AND THROUGH-LIFE SMART SHIPPING NETWORK

Automated smart designs are relatively new concept and not explored widely in particular ships or hull form design. Automated smart design can be defined as an intelligent design process which is highly automated and able to collaborates closely with smart manufacturing and smart ship or operation throughout the entire lifecycle. I4.0, also known as fourth industrial revolution, aims to merge the real and physical space through cyber-physical system. It provides a platform to transform traditional segregated manufacturing process into fully connected manufacturing system. Basic components and enabling technologies of I4.0 includes internet of things, collaborative robots, cyber security, cloud computing, additive manufacturing and big data analytics. I4.0 or smart factory concept are increasingly adopted and implemented in high tech manufacturing and aviation industry. Some pioneering works on smart design, smart construction and smart ship includes automated hull form design [30], smart ship system design [31,32], smart pipe system [33] and smart ship [34].

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Despite a promising start, advances in smart design are lacking in comparison to smart manufacturing and smart products. This could be attributed to the lack of an integration platform to combine smart design with smart manufacturing and smart product considering the entire product lifecycle. One promising solution is a framework that connects and creates a feedback loop to link up smart manufacturing and smart product to smart design. By connecting up smart design with digital manufacturing and smart operations into a unified digital model, important information can be shared seamlessly across entire product lifecycle of a ship to become a fully integrated through-life smart shipping network in the I4.0 era, as introduced in [35] and illustrated in Fig. 2.

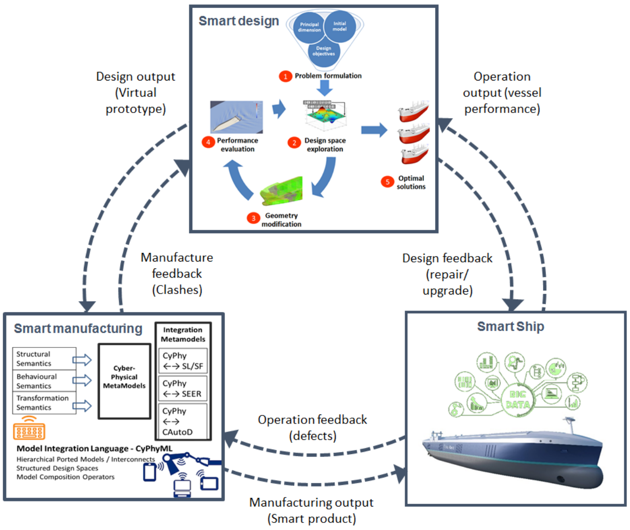


Fig. 2. Through-life smart shipping network

By closing the loop between ship operation and design through smart product, useful through-life data such as ship operating environment and actual performances can be collected, analysed and feedback into smart design process to automatically improve the design performance of future vessels. To achieve this, a hybrid automated smart design approach for HFDO is proposed in this paper.

IV. HYBRID EVOLUTIONARY ALGORITHM AND MORPHING APPROACH

To further automate the hull form design process and elevate toward smart design, a Hybrid Evolutionary Algorithm and Morphing (HEAM) approach was developed by authors in [36, 37] which uses purely on the main operators of GA. The proposed methodology integrates 2D curve morphing and Genetic Algorithm to automate the hull form design optimisation and elevate into smart design. It also includes a smarter process by implementing a non-dominated selection process the further evaluated and select individuals to be carried to the next generation.

Metamorphosis, also known as morphing, is a technique used widely in the animation industry to generate a sequence of images that smoothly transform a source to another target image. It is also applied in computer graphics and industrial design to compute a continuous transformation from a source to another target shape. Morphing can be a very useful tool for the designer to modify, manipulate, transform the shape or geometry of the design in pursuit to improve the design attributes such as performance, quality, aesthetic, etc. Morphing can be catergorised into two main types- two-dimensional (2D) or three dimensional (3D). 2D morphing consist of image morphing and curve morphing and 3D morphing include surface morphing and volume morphing. In ship application, [38] applied morphing using 3D patch model from NAPA to transform a ship hull model into another target model. [39, 40] applied 3D mesh-based surface morphing to generate intermediate hull models between two parent vessels. More recently, [41] applied self-blending method to modify the cross sections of bulbous bow.

In this paper, 2D curve morphing is applied to transform the shape of hull through interpolation and extrapolation between the hull lines of two or more hull forms. Using morphing equation:

$$M(t) = (1 - t) \cdot R_0 + t \cdot R_1 \tag{1}$$

Where $M(t)$ is the morphed shape, t is the morphing parameter, R_0 denotes the source shape and R_1 the target shape. From above equation, we can see when $t = 0$, $M(t)$ is also equal to 0 and hence the morphed shape is equivalent to source shape R_0. Likewise, when $t = 1$, $M(t) = R_1$ which is the target shape.

To illustrate the concept, by using hull lines provided from the body plan of source and target vessels, we can morph and generate large number of intermediate shapes just by changing the morphing parameter (t). Other than interpolating between the source and target vessel, extrapolate beyond the two hull lines to create new 'extended' lines can also be done. As an example, we take one hull line each from vessel A (source) and vessel B (target) at station 2 for both vessels. By applying curve morphing equation, we can generate interpolated and extrapolated curves as illustration in Fig. 3.

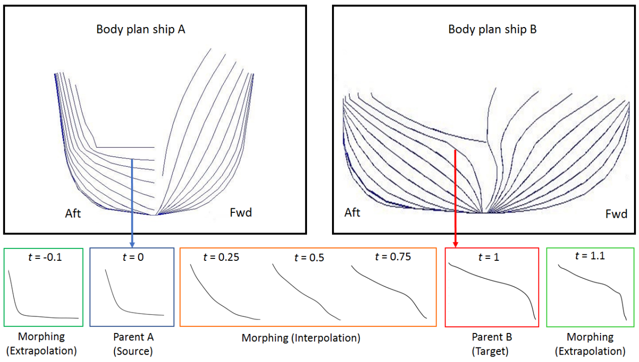


Fig. 3. Curve morphing at station 2

A key feature of 2D curve morphing approach is the ability to capture and easily modify complex shapes such as hull form using minimal design variables, which in this case is represented by morphing parameters (t).

In the proposed approach, 2D curve morphing is combined with a Genetic Algorithm (GA) [42] to automate the hull form design process. Fig. 4 illustrates the working principles of a GA.

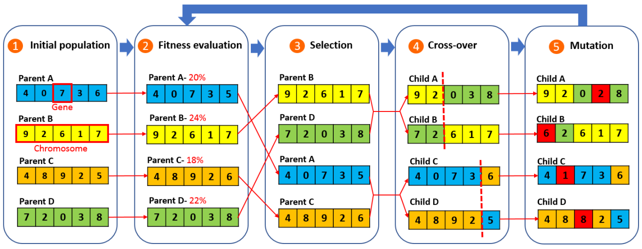


Fig. 4: Genetic algorithm working principle

Through the use of genetic operators namely selection, crossover and mutation, information represented by genes are exchange between these chromosomes over a number of iterations, typically with the fittest solutions replacing the weaker ones and eventually leads to a set of optimal solutions. The key feature of using GA for hull form optimisation is the ability to generate many new hull design combinations, search very huge solution space and subsequently narrow down to a small number of optimal designs.

By combining the advantages of GA- ability to search for best global solution- and that of morphing- ability to generate smooth intermittent shapes from the combination of two or more hull form designs, we can now potentially create a wide range of hull form designs with improved efficiency and thereby finding the most optimal hull form. An overview of the proposed hybrid evolutionary and morphing (HEAM) approach is provided in Fig. 5.

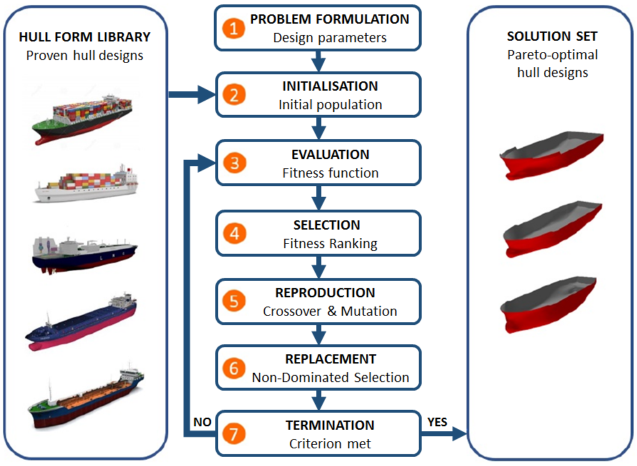


Fig. 5. Proposed Hybrid Evolutionary Algorithm and Morping (HEAM) approach

The proposed HEAM approach comprises the main components of the GA, namely initialisation, selection, crossover, mutation, fitness evaluation and replacement.

At the start of any optimisation process, specifications of the design parameters are vital which include ship type, principle dimensions as well as objective functions. Depending on the number of existing hull designs in hull form library, they can be catergorised by different ship types and selected to form the initial hull designs depending on the design requirements. Principle dimensions such as length between perpendiculars (*Lpp*), beam (*B*), draft (*T*) would need to be specified as per design requirement. Following this, existing vessels from hull form library will go through linear transformation to conform to the desired length, beam and draft.

The next step of HEAM is to create the first pool of individuals by mapping them into unique encoding scheme. In ship design process, this can be obtained from existing hull forms from the hull form library or create from scratch. The advantage of using existing designs is the assurance of their performance which are validated to meet design objective and helps to shorten the design cycle, although the improvements are often incremental. For the proposed HEAM approach, real-value chromosomes (genotype) using morphing parameters (t) which captures the ship's geometry in X and Y planes according to their respective frame or stations across Z planes (phenotype), as illustrated in Fig. 6. This provides a simple yet direct representation of the ship geometry which allows the hull shape to be transformed easily by changing the morphing parameters (t).

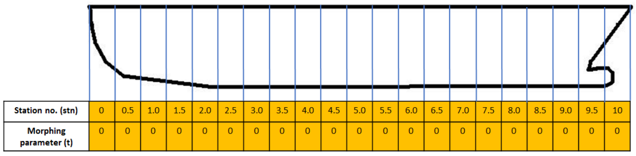


Fig. 6. Encoding scheme using real value chromosome (t=0)

Subject to the number of hull forms available in the library, each vessel will be assigned different morphing parameters - e.g. 1st vessel model (parent A) will be assigned morphing parameter t = 0 and 2nd vessel model (parent B) will be assign t = 1 and so on. This approach allows us to include as many hull forms in order to increase the variety of shapes and hence increasing the search space to achieve more optimal designs. The encoding scheme of the proposed method differs from existing approaches such as Free Form Deformation (FFD) and other ship design applications [45], where it uses binary code or variables to represent and modify the hull geometry.

In the initialisation stage, 2D morphing is extended using full-morph where morphing is applied to the entire hull form using the same morphing parameters within the encoding scheme. In this way, full-morph can be applied to generate a range of 'intermediate' hull forms so as to increase the pool of "parents" in the initial population.

In order to measure the 'fitness' of the parent vessels, the performance of each hull form is evaluated based on the objective function(s). In the proposed approach, candidate design solutions are assessed using semi-empirical methods to provide fast and fairly good estimation which are particularly suited for initial ship design process. Holtrop & Mennen method [26] is used for resistance analysis and strip theory for seakeeping analysis. Depending on the vessel type, objective functions relating to hull form optimisation may include reducing resistance or seakeeping motions. For both objectives, the aim is to minimise the cost function given as follows:

$$\mathit{Minimise}\ f(\chi),\ \chi \in X \qquad (2)$$

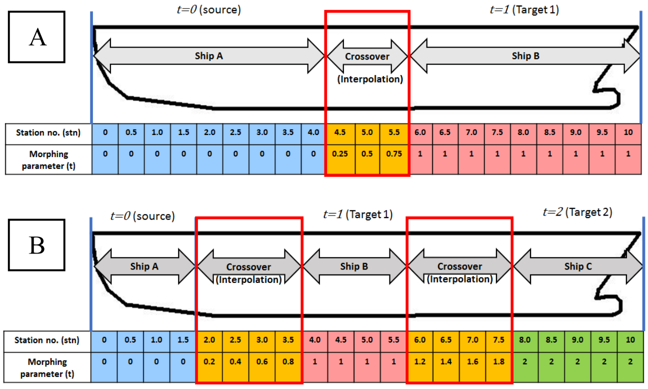
Where f is the vector of design objectives, χ is vector of design variables and X is the feasible design variable space.

The fitness can be evaluated by decoding the chromosomes and genes which consist of the 3D parameter of the entire vessel. Calculations and integration are made throughout the chromosome to obtain the fitness value such as the total resistance of the individual.

Random selection without replacement is used to provide opportunities for every individual to be modified. This will ensure no duplication or similar design produce and hence increasing the diversity.

Crossover

A unique feature of the proposed approach is in the way crossover is carried out which allows two or more hull structures to be seamlessly combined. This is not possible using traditional "cut and joint" crossover operations. In this approach, cross-morph is applied during crossover to 'split' and 'combine' with two or more existing hull form (parents) by applying gradual morphing parameters (*t*) between two different parent models through interpolation to create smooth intermediate curves between the two parents, as illustrated in Fig. 7 below.



Station no. (stn)	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 (t)	0	0	0	0	0	0	0	0	0	0.25	0.5	0.75	1	1	1	1	1	1	1	1	1

Station no. (stn)	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 (t)	0	0	0	0	0.2	0.4	0.6	0.8	1	1	1	1	1.2	1.4	1.6	1.8	2	2	2	2	2

Fig. 7. A-B: Crossover between two different potential vessel designs with linear morphing. (A: Single-point crossover combining Ship A aft and ship B forward body, B: Multi-point crossover combining Ship A aft, ship B mid body and ship C forward body)

Once crossover is completed, the new child hull form then undergoes mutation process where morphing is randomly applied to modify the shape of the hull form. This random modification enables minor changes and thereby granting each child designs to have its own unique features. After completing the modification process, replacement process is done using non-dominated selection method to carry over the fitter individuals into the next generation.

V. CASE STUDY: HULL FORM OPTIMISATION OF CONTAINER VESSEL

To demonstrate the flexibility and benefits of the HEAM, we applied single objective optimisation to optimise the hull form of container vessel based on six existing vessel design. The design objective is to reduce total resistance which will reduce the overall drag acting on the vessel. The design requirements are given as follows: Length between perpendicular (Lpp) = 185m, beam = 32m, draft = 9m, design speed 20 knots, displacement = 32,675 tons. Here, we set the displacement to be equal and not be lower than 32,675 tons. This is to ensure the vessel's capacity are not compromised or reduce while improving the objective function. The single-objective optimisation and GA parameter are formulated as:

$$\text{Minimise} \quad f = Rt \qquad (3)$$

$$\text{Subject to:} \quad \text{displacement} = / > 32{,}675 \text{ tons}$$

Where Rt is the total resistance. The principle dimension for 6 existing parent vessels are given in Table I.

TABLE I. EXISTING VESSEL PRINCIPLE DIMENSIONS

Principle dimension	**Ship 1**	**Ship 2**	**Ship 3**	**Ship 4**	**Ship 5**	**Ship 6**
Length (m)	202	185	314	220	242	210
Breath (m)	32	32	58	36	45	34
Draft (m)	10.5	9	9	10	10.5	10
Displacement (tons)	30641	32675	42840	44727	42363	37376

To determine the optimal crossover and mutation rate, a few test was carried out as shown in Fig. 8 and 9.

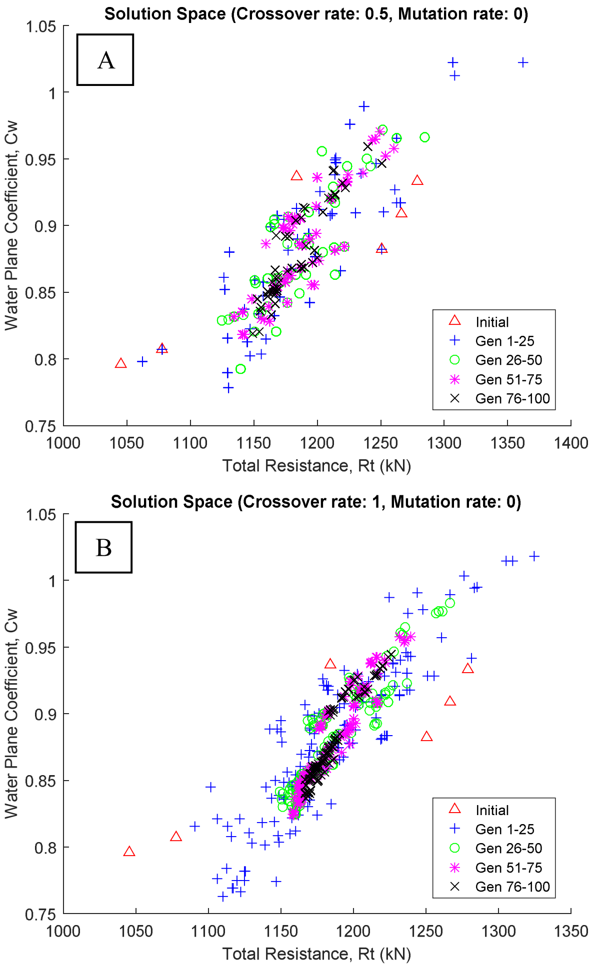


Fig. 8. A-B: Solution Space (A: Cross-rate = 0.5, B: Cross-rate = 1.0)

Firstly, different crossover rates were set in 2 runs of GA as shown in Figure 8A-B. It was found by increasing the crossover rate, it allows more solutions to be created. This diversity is essential to the current case studies as there are only a small number of initial populations. Hence, crossover rate of 1.0 was selected to ensure all individual go through the process to introduce more solutions into the optimisation process. Different mutation rates were then tested with crossover rate = 1 to evaluate the improvement and convergence of solutions. As presented in Fig. 9, mutation rate of 0.8 shows the most improvement and hence selected for this case study.

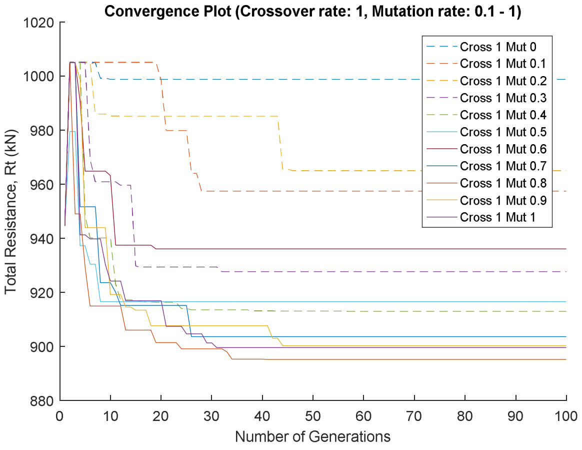


Fig.9. Convergence Plot of different Mutation rate

The GA settings are given as follow:

- Popsize = 6
- Max iteration = 100
- Crossover rate = 1.0
- Mutation rate = 0.8

Based on the design criteria and constraints input, the algorithm will first generate the first set of initial population consisting 10 sets of hull form through interpolation and extrapolation of existing hull forms using full-morph method. The hull forms are then evaluated using Holtrop method to estimate the total resistance for the individuals fitness value. According to [46], waterplane coefficient can approximately indicate the roll amplitude of the vessel and hence the stability. These individuals will undergo a random selection process to allow every individual an equal opportunity to crossover with others. Following which, the initial hull forms are mixed together using the single point cross-morph method to generate new variations of hull forms during crossover. The hull shapes are then further modified randomly in the mutation process. The new design candidates are then carried over to the next generation where the entire processes are repeated until it reaches the stopping criteria of 100 generation. The entire hull form optimisation process was run fully automatically within Matlab and took 318 seconds (5.3 minutes) for 100 generations. The results of the optimisation are presented below in Fig. 10 and 11.

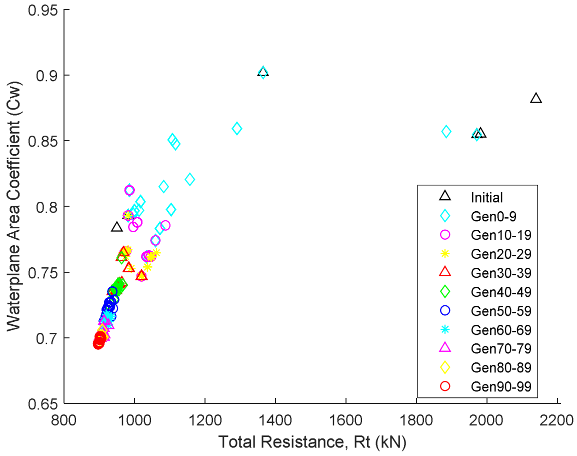


Fig. 10. Solution space (crossover rate of 1.0 and mutation rate of 0.8)

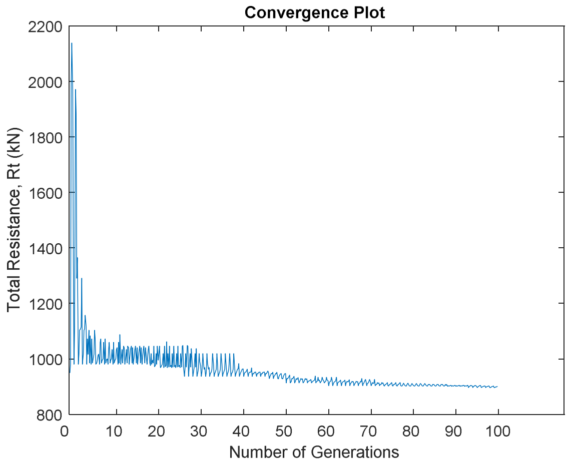


Fig. 11. Convergence plot for 100 generations

From the above solution space diagram and convergence plot, it can be observed that the solutions generated through HEAM approach converges towards the left-bottom corner as the generation increases toward 100. This demonstrated effective reduction of total resistance as well as waterplane coefficient during the optimisation process. The performance of best parent and top five child designs are presented in Table II.

TABLE II. RESULTS OF BEST PARENT AND BEST CHILD DESIGNS

Candidate design	**Displacement (tons)**	**Resistance (kN)**	**Improvement (%)**
Best parent (Ship 1)	32248	949.1	-
Candidate 595	**30804**	**896.2**	**5.58**
Candidate 596	30759	896.5	5.55
Candidate 597	30853	898.9	5.29
Candidate 598	31007	898.8	5.31
Candidate 599	30871	900.2	5.16

From the above results generated, good improvement of 5.58% in overall resistance was achieved for best child design (candidate 595) over best parent design. The shape of best child design (Fig. 12 and 13) are provided as below:

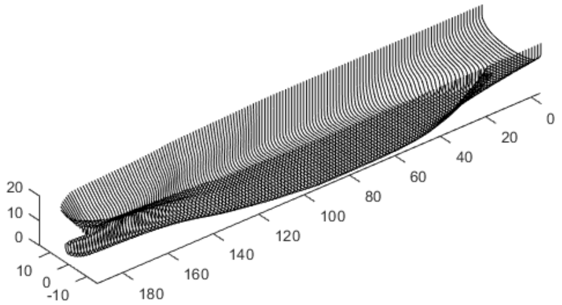


Fig. 12. Wire-mesh diagram of candidate 595 design

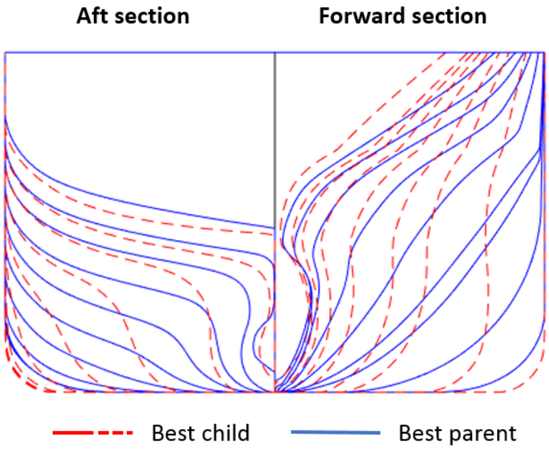


Fig. 13. Body plan comparing best child design (candidate 595) and best parent design (Ship 1)

From above plot of the best child design (candidate 595), it can be seen the hull form generated are still highly smooth and of feasible design- no sudden change in shape or uneven surfaces. This is a significant achievement considering the hull form had went through up to 100 iterations of shape modification fully automatically and with no user inputs.

VI. CONCLUSION

This paper presented an automated smart hull form design approach using HEAM. A unique feature of the proposed approach is the way crossover is performed where two or more hull structures can now be seamlessly combined to produce a new hull form. This is an important contribution in the field of marine design as traditional 'cut and joint' crossover would have resulted in a large number of infeasible designs. The proposed methodology was applied to optimise the hull form of an existing container vessel. Despite the vessel was already optimised and proven, results show that it is capable of further improving the hull design by up to 5.58% reduction in total resistance. This result demonstrated the possibility of a fully automated hull form design and optimisation process, capable of producing optimal hull form with improved hydrodynamic performance. It is envisioned that this approach will help to improve the overall efficiency in hull form design and produces more efficient and smarter ships in the near future.

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