Lowering Carbon Emissions in Shipping Through Improved Hullform Design for Realistic Operating Conditions

Benjamin Howett[1], Sandy Day[1] and Atilla Incecek[1]

[1] Dpt Of Naval Architecture and Marine Engineering, University of Strathclyde, Glasgow, UK.
Email: benjamin.hobin@strath.ac.uk

Abstract

Efficiency in shipping is of growing concern – both in terms of carbon emissions produced in an increasingly aware society and in terms of reducing operating costs with the ever increasing price of energy. Many current ship designs are optimised to minimise resistance for a particular combination of loading condition and design speed in calm water, without proper consideration of the impact of realistic variations in load and sea state. This study seeks to improve the efficiency of a range of ship types by offering reduced resistance through improved hull form design, and examines incremental improvements through refinements in conventional hull forms. A novel and robust hullform deformation method is used to create a series of potential hullforms, based on an existing design, and a Genetic Algorithm is used to optimise the design for real-life conditions. Improvements in hullform design are assessed for stability and suitability with regards to potential slamming and propeller emergence, and the resistance and powering requirements for both calm water and waves are analyzed for a range of expected weather conditions for a typical route.

Keywords: Low Carbon, Energy Efficiency, Ship Design, Optimisation, Genetic Algorithm, Free Form Deformation

1. Introduction

Naval Architects have been interested for thousands of years in increasing ship performance in terms of either increasing speed or reducing powering requirements. Since the advent of computational techniques for predicting resistance, formal optimisation schemes have been adopted in order to improve hull shape in order to reduce resistance. However in most cases the optimisation is carried out for conditions which do not correctly reflect the environment in which the ship typically operates; traditionally the resistance is minimised for calm water conditions at a design speed and load condition. In reality, the ship will operate in a range of sea states, speeds and loading conditions, and the optimal design for the real-world conditions may well be different from the design optimised for calm water. The present study is designed to explore the benefits which may be gained by optimising ship hull forms for realistic operating conditions.

A software package has been developed which incorporates a series of modules for the analysis of vessel performance, the modification of a basis ships form parameters and the optimisation of these parameters to produce a new, more efficient ship with lower carbon emissions.

The software is primarily written in VBA (Visual Basic for Applications) with Microsoft Excel, and communication with external analysis programs is achieved via the Microsoft COM interface.

The program is constructed in a number of modules. These include analysis modules for the calculation of the resistance of the chosen vessel both for calm water and in waves, as well as vessel stability and motions. Further modules calculate the weight of a vessel, based primarily on its principle dimensions and powering requirements, and describe the environment in which the ship operates in.

In order to explore potential improvements a robust method of generating new hullforms is used. This function must allow a thorough search of the design space and explore new design possibilities while maintaining favourable features and preserving fairness.

A semi-stochastic optimisation technique is used to assess the success of each generation evaluated and evolve future generations using the hullform generation technique.

2. Hull Form Generation

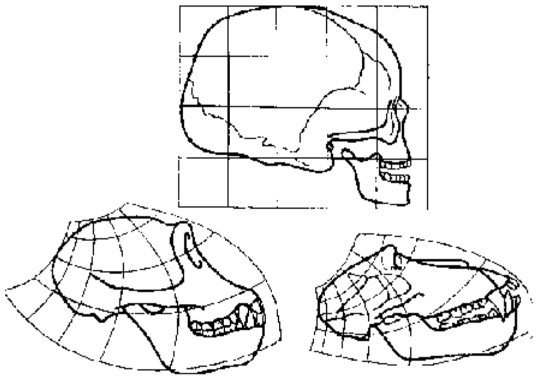
In order to progress through each stage of the optimisation procedure a robust and flexible method of creating hull form variations must be used.

Free form Deformation is a method for transforming and manipulating any shape in a free-form manner. It is widely used in computer assisted design and animation but has only recently been used in the field of design optimisation, pioneered by (Peri & Campana 2005),(Désidéri et al. 2006), and (Duvigneau 2007) The advantage of this method is that it allows a smooth deformation of complex geometries, with only a few variables required

While there are a number of variations on the method, they all have a common aim which is to define a new position for every point within a given region (whether that region is 2D or 3D). It can be thought of as a map, or pathway, from R^3 to R^3.

(Thompson 1917), perhaps without realising demonstrated the first examples of FFD in action when he showed that many evolutionary changes consist of, linear or non-linear, or radial transformations

A further development involves making the transformation hierarchical by embedding localised FFD regions for details like the bulbous bow within the global transformation. This allows further fine control of the shape in key areas while continuing to maintain fairness.



Skulls of a human, a chimpanzee and a baboon and transformations between them

The basis ship hullform is defined as a NURBS surface, which in turn is defined by an array of 3 dimensional control points, or nodes. The x, y, z coordinates for each of the basis ship nodes are read from Maxsurf into an array in Excel. The transformation is then applied to each of these coordinate values and the resultant new coordinates are read from Excel back into Maxsurf to create the new hull form, which is then named according to its generation, version number, and condition and saved to a file for later analysis.

This method has proven to be significantly more robust than the parametric transformation method trailed previously, although at the expense of a slightly increased run time. A significant factor affecting the time taken to complete a transformation is the number of control points used to define the hullform so it is vital to invest some time in preparing the model for analysis in order to minimise time spent later in the optimisation routine.

3. Analysis

3.1 Calm Water Resistance

Calm water resistance analysis is currently performed using *Hullspeed*, developed by Formation Design Systems. The Holtrop and Mennen method is chosen since it has been proven to be sufficiently accurate for a wide range of vessels, with the added advantage of being sufficiently fast and robust to allow large volumes of potential hullforms to be evaluated. Further validation and testing is needed to determine the suitability of the method, and further first principles methods may yet be introduced for more refined analysis, especially for unconventional hullforms, for which regression methods may well be unreliable.

3.2 Added Resistance

Added resistance analysis is performed using *Seakeeper*, developed by Formation Design Systems.

Seakeeper uses the traditional strip theory approach based on the work of Salvesen (Salvesen et al. 1970) to calculate pitch and heave response. Roll response is estimated by assuming the vessel behaves as a simple damped spring/mass system. The Gerritsma & Beukelman II method is used for current version of the model. Alongside the added resistance calculations the ship motions are used to estimate a probability of slamming and propeller emergence.

3.3 Stability

Stability analysis is performed using *Hydromax*, developed by Formation Design Systems. Individual stability requirements for a vessel vary and generally depend on the class society the vessel is registered with. In order to provide a broad overview of the stability of the vessel the main criteria are evaluated from IMO A.749 (18) – Code on Intact Stability, Chapter 3 – Design Criteria applicable to all ships.

3.4 Weight

While in early tests displacement was fixed, in reality this is not a realistic assumption. Steel weight changes with both surface area and structural requirements – generally speaking a longer vessel of the same deadweight will require more substantial structure to resist hogging and sagging than a similar, but less extreme ship, and this translates to a greater mass of steel required. More efficient ships require less power and thus smaller (and lighter) machinery and less fuel. These subtle changes affect not only the displacement but the achievable VCG and therefore must be considered when dealing with major changes to the ship

4. Optimisation

Whilst in the context of this work Optimisation is generally referred to as a modern technique only made possible due the computational power available today, in fact naval architecture, and engineering in general has always been an optimisation process. The classic 'Design Spiral' approach; an Alternating Variable method, describes the process by which a designer moves from an initial design towards the final production design. All the time the designer must balance factors of performance, stability, seakeeping, cost, and so on. Despite this complex problem relatively little work has been completed on developing ship design methodology and techniques. While optimisation studies in the naval architecture field are common; work completed tends to focus of the dominant industry concerns at the time, largely cost and operational factors, and stability and seaworthiness.

An alternative to the traditional ‘single point’ optimisation is a semi stochastic method such as a Genetic Algorithm. Genetic algorithms involve a search of a population of potential solutions rather than looking at a single point. During each iteration of the optimisation process a competitive selection takes place which removes weaker solutions while still allowing the entire design space to be searched without risking converging on local optima.

A typical genetic algorithm follows these steps:

```
Initialise the population
Evaluate this population
Loop until convergence criteria are met {
        Select the next generation
        Apply mutations to generate variety
        Evaluate new population
        }
```

4.1 Population initialisation

In order to fully investigate the design space an initial population is needed that spans the entire range of possible solutions. Given the time required to compute each solution the number of samples must be small and so care must be taken to ensure that the design space is sampled adequately.

It is generally thought that a population size of around 20 is required to provide sufficient variation within the population and prevent the convergence on local minima and maxima. However population sizes significantly larger than this often appear to offer little benefit in terms of the quality of the solution and increase the convergence time.

A population size of 25 has been chosen which seems to be in line with similar studies. Further work is planned in order to establish whether population size has any significant effect on the quality or speed of the solution. Since a random sample with a relatively small population does not guarantee a thorough search of the design space; the features of this initial population are defined according to a latin hypercube (McKay et al. 1979).

4.2 Selection

The aim of a good selection strategy is to allow fitter individuals to have a greater chance of becoming parents for the next generation, whilst maintaining diversity, since even less fit individuals may contain useful genetic material. Initial studies showed that the choice of selection method had little apparent effect in the final result.

Tournament selection was chosen, and involves selecting two samples from the population at random and comparing their fitness. The sample with the highest fitness score is then chosen as a parent for the new generation and both potential candidates returned to the population to allow them to be selected again in future. This process continues until the required number of parents have been selected.

4.3 Recombination

Recombination must achieve 2 things. The child must inherit attributes from each parent, and it must remain a valid member of the population.

This model currently uses a combination of the Line Crossover method where the offspring is generated from a randomly chosen value between chromosome 1 and 2, and the Directional Crossover method which relies on 3 parent chromosomes and biases the offspring towards the most successful parents.

4.4 Mutation

The aim of the mutation operator is to introduce diversity into the population and allow every part of the design space to be explored. Since this GA is real coded the mutation rate chosen is higher than typical for a binary GA and is currently set to a factor of 0.1. A small permutation is then added to any mutating chromosome. This permutation is generated from a normal distribution with a standard deviation of 0.05 times the range of the variable in question, as suggested by (Mason 2010). The previous best solution or 'elite' solution is exempt from this mutation.

4.5 Elitist Selection

The combined effects of recombination and mutation mean that often the best solution from one generation may not be improved upon in the next generation. Elitism combats this by preserving the best solution (or a group of best solutions) from the previous generation. This means that the solution is never allowed to regress and must always be at least as good as the previous generation.

At the end of each optimisation loop the solution is checked for convergence, and if the solution has not converged sufficiently the loop is restarted.

5. Preliminary Results

The following section detail some of the preliminary results obtained as of July 2012. The results presented here are for a 100,000 tonne LNG carrier. The basis ship chosen is an example of a real vessel, currently in operation in the worldwide fleet so as to demonstrate that any savings found are meaningful, and not simply improvements over a theoretical design.

At this stage the model is complete to 'Version 1.0', which is to say that all major functionality is in place, but requires further refinement in order to increase the confidence factor in the results. Along with the refinements, additional functionally is planned following this paper.

The factors which are optimized are the length, breadth at fore, mid, and aft positions, Draft at fore, mid, and aft positions, and flair at fore, mid and aft positions. For each combination of these factors the vessels displacement is calculated and the beam scaled to ensure that the mass and buoyancy of the vessel are in equilibrium. Once this condition is satisfied, which typically takes 4-5 loops of the transformation module, the main resistance analysis can be completed. The model takes into account the added resistance due to the anticipated sea state, based on a weighted average of its anticipated time spent in each condition. From the resistance the anticipated speed can be estimated along with the power required to achieve this speed, and these values are converted into Co2 emissions for the journey.

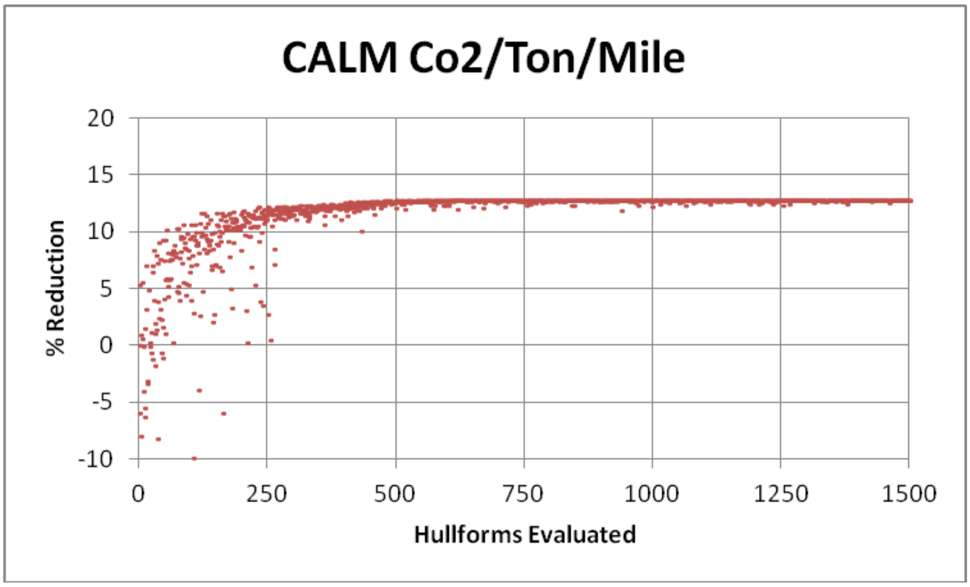
Stability is checked to ensure the vessel is viable and if not a significant penalty is applied to the Co2 emissions in order to discourage unstable vessels in future generations of the optimisation.

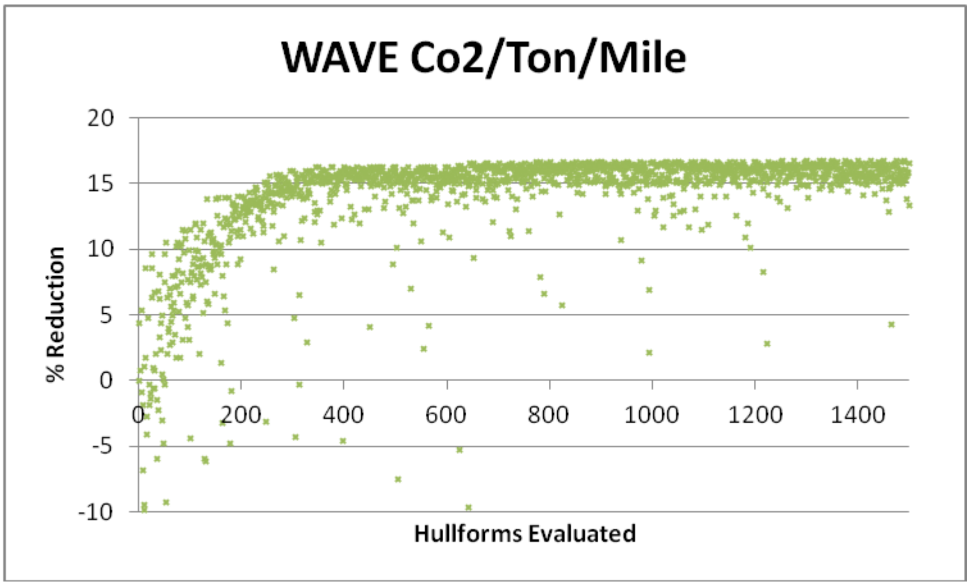
The stability modified Co2 value and the form control variables are then used as inputs for the main optimisation procedure which then outputs suggestions for the next generation of potential designs to be evaluated and the loop is run again until a satisfactory level of convergence in the results is reached.

LWL was allowed to vary by -10% to +25%
Draft Mid was allowed to vary by -20% to +20%
Beam Mid was given no range, since it is governed primarily by displacement
Flair Mid was allowed to vary by -10% to +30%

Draft Fore was allowed to vary by -10% to +20%
Draft Aft was allowed to vary by -10% to +20%
Beam Fore was allowed to vary by -7.5% to +10%
Beam Aft was allowed to vary by -7.5% to +10%
Flair Fore was allowed to vary by -10% to +420%
Flair Aft was allowed to vary by -10% to +40%

The Fore and Aft factors for each transformation are relative to their midpoint value, not absolute. It Additional constraints exist within the draft factors which allow a convex keel profile, and for the keel profile to the angles simulating a change in static trim of the vessel,. A concave keel profile is forbidden.



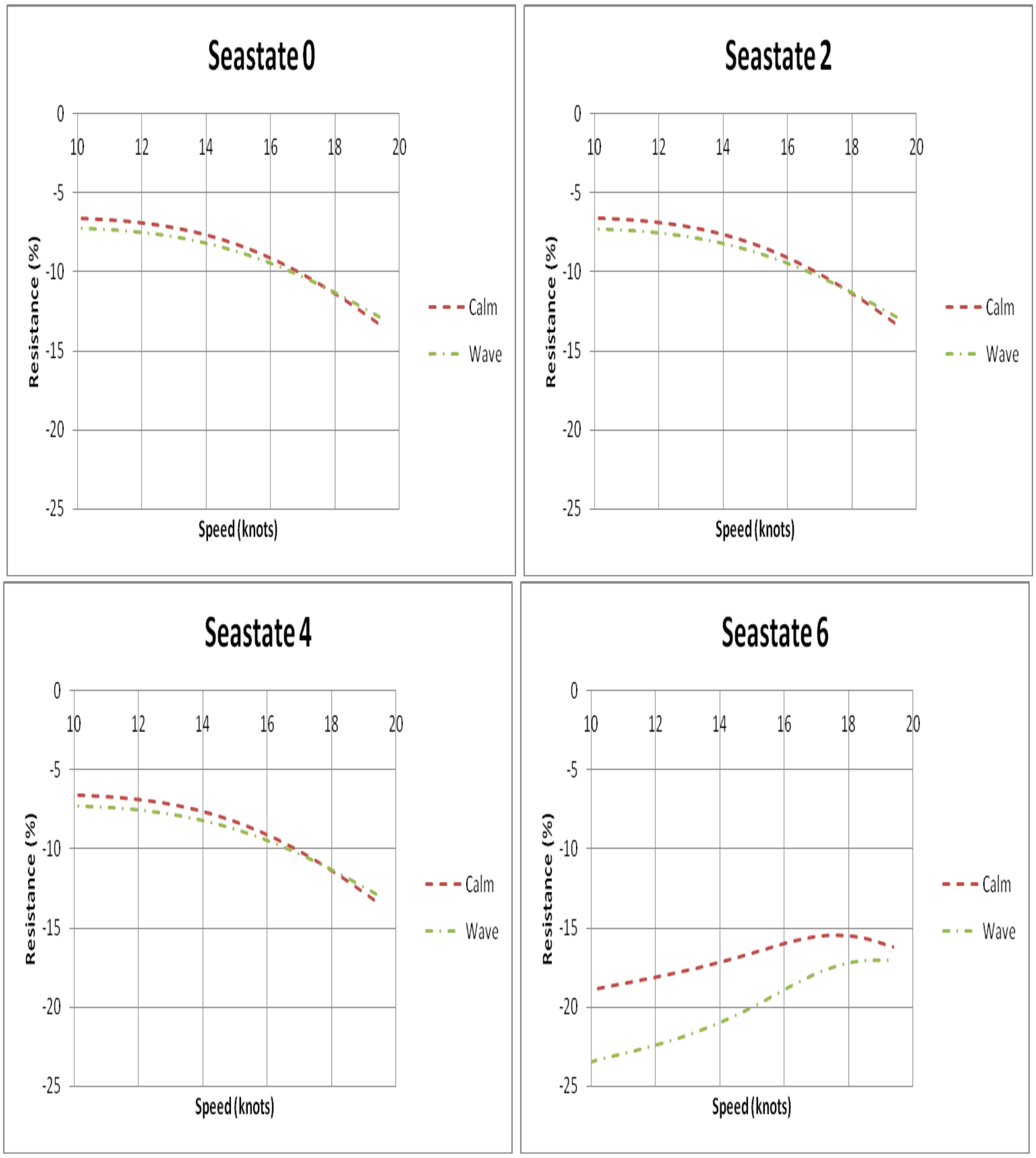


CALM: Co2/g/m reduces by 12.8%
WAVE: Co2/g/m reduces by 16.7%

These results show a significant reduction in Co2 is possible, however in order to achieve these changes a substantial change has taken place in the overall dimensions of the ship. This does mean that these improvements may not be practical when more realistic constraints are imposed, but they are indicative of what may be achieved given a blank canvas.

The Co2 emissions are presented in average Grams per Ton Mile, as opposed to the total emissions for a given voyage. This is to allow for comparisons between ship types, as well as allowing experimentation with different deadweights at a later stage.

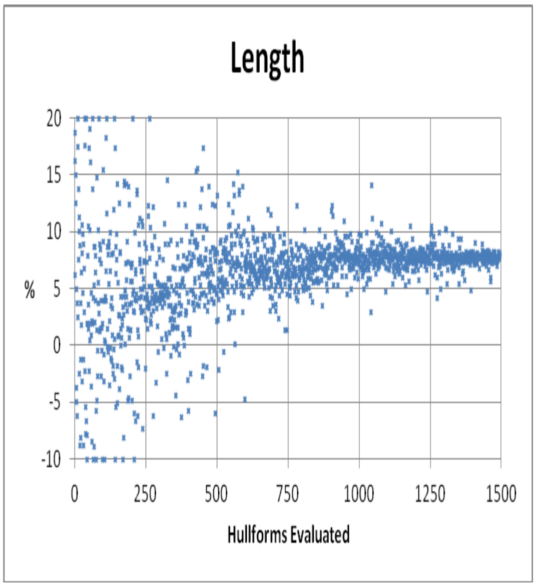
The following results show how the change in resistance for each vessel varies for the sea states analysed.

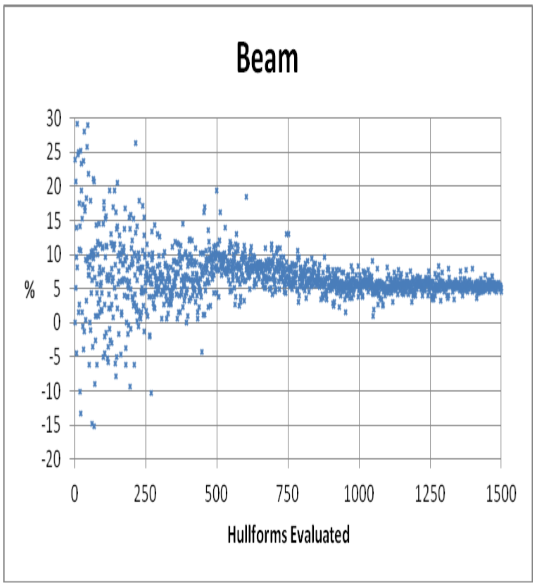


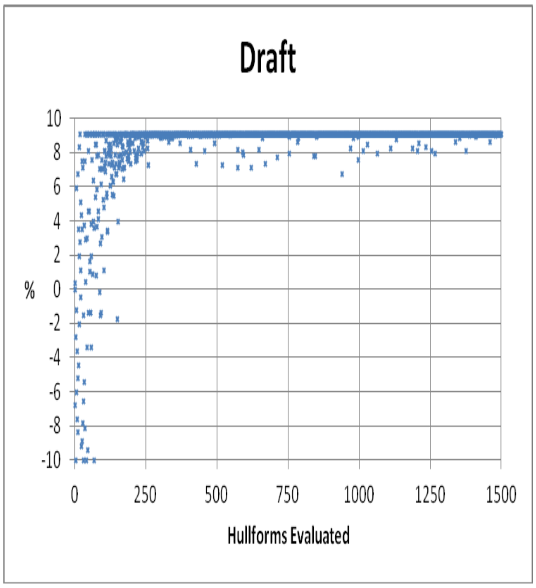
These results show that there is significant value in optimising for added resistance, as well as calm water resistance. While there is little to lose by operating the WAVE optimised vessel in calmer seas, in more extreme seastates, and especially when the vessel may the travelling at slower speeds the gains can be large.

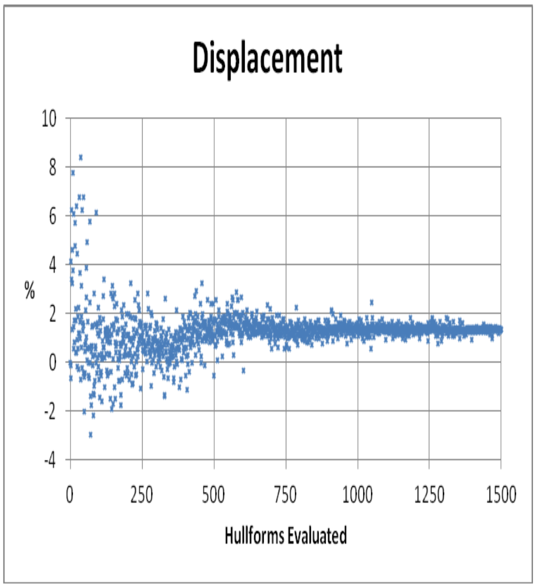
It is also expected that there will be more to gain from optimising directly for performance in waves when further fine changes to the hullform are considered.

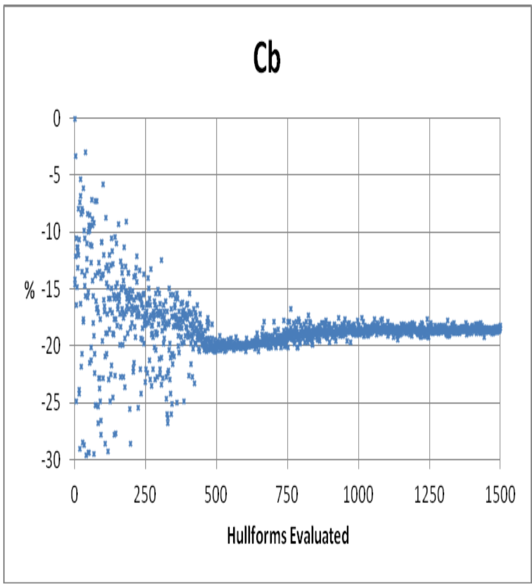
The following figures illustrate how the form parameters for the population change as the optimisation procedure progresses. It is interesting to note that draft rapidly increased within the first few generations and was quickly limited by an artificial depth constraint imposed to simulate typical port depth restrictions for a vessel of that type.

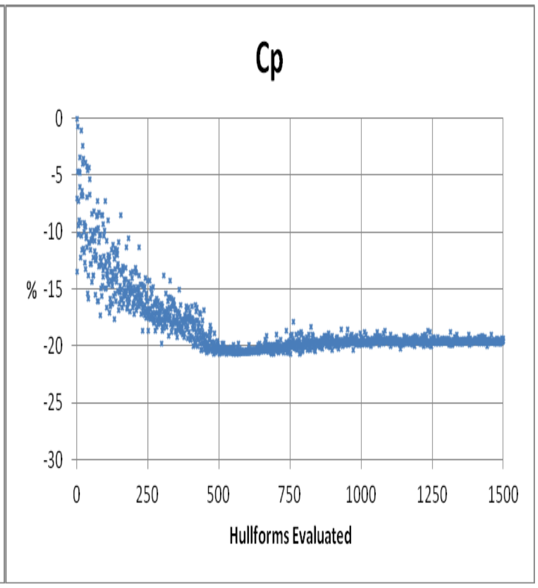

Length
20
15
10
% 5
0
-5
-10
0
250
500
750
1000
1250
1500
Hullforms Evaluated


Beam
30
25
20
15
10
% 5
0
-5
-10
-15
-20
0
250
500
750
1000
1250
1500
Hullforms Evaluated


Draft
10
8
6
4
2
% 0
-2
-4
-6
-8
-10
0
250
500
750
1000
1250
1500
Hullforms Evaluated

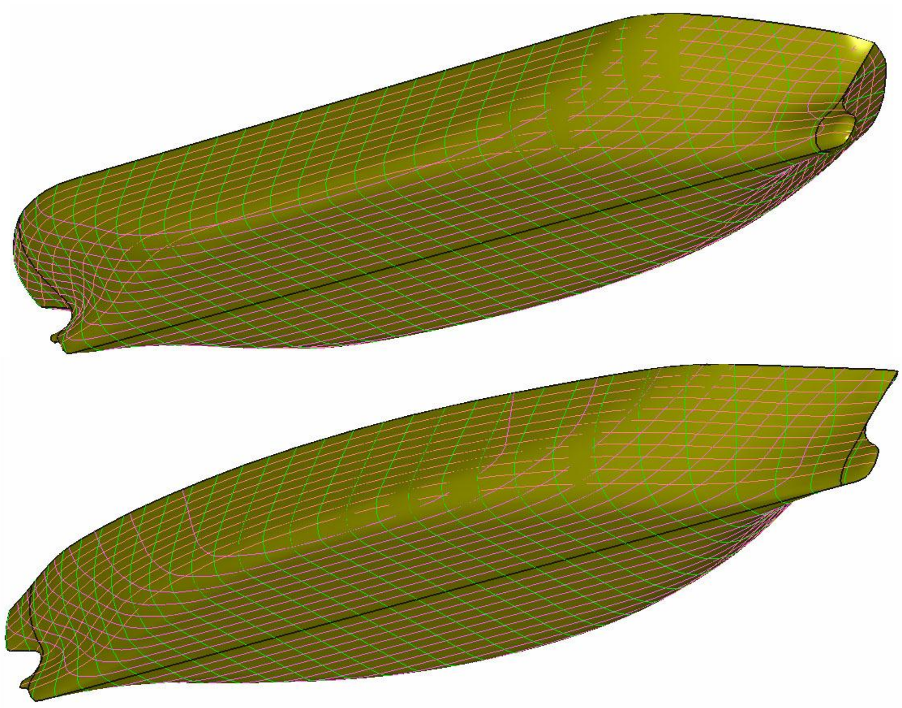

Displacement
10
8
6
4
%
2
0
-2
-4
0
250
500
750
1000
1250
1500
Hullforms Evaluated


Cb
0
-5
-10
% -15
-20
-25
-30
0
250
500
750
1000
1250
1500
Hullforms Evaluated


Cp
0
-5
-10
% -15
-20
-25
-30
0
250
500
750
1000
1250
1500
Hullforms Evaluated

The basis and optimised vessels are presented below. It is apparent from the results how a modest increase in principle dimensions of length, breadth and draft has contributed to redistributing the volume of the ship, allowing for reduced entry and exit angles and smoother waterlines and buttocks.

Further work is ongoing to refine these results – improvements to the analysis methods, an increase in the flexibility of the hullform deformation system, and an expansion to the operational procedures, taking into account more varied loading and trim conditions will be presented in future papers.



6. References

Duvigneau, R., 2007. Aerodynamic Shape Optimization with Uncertain Operating Conditions using Metamodels. *INRIA*, 6143.

Désidéri, J.-A., Duvigneau, R. & Abou El Majd, B., 2006. Algorithms for Efficient Shape Optimization in Aerodynamics and Coupled Disciplines. In *42nd AAAF Congress on Applied Aerodynamics*. Sophia Antipolis, France.

Mason, A.P., 2010. *Stochastic Optimisation Of Americas's Cup Class Yachts*. University of Tasmania.

McKay, M.D., Beckman, R.J. & Conover, W.J., 1979. A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, 21(2), pp.239–245.

Peri, D. & Campana, E.F., 2005. Global Optimization for Safety and Comfort. In *COMPIT 05*. Hamburg.

Salvesen, N., Tuck, E.O. & Faltinsen, O., 1970. Ship Motions and Sea Loads. *SNAME Transactions*, 78, pp.250–287.

Thompson, D., 1917. *On Growth and Form*,