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MULTI-CRITERIA OPTIMIZATION OF HIGH SPEED NAVAL VESSELS: A PARETO APPROACH

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Onur Yurdakul, M.Sc. student of Pîrî Reis University High Performance Ocean Platforms student ID ……………, successfully defended the thesis entitled "MULTI-CRITERIA OPTIMIZATION OF HIGH SPEED NAVAL VESSELS: A PARETO APPROACH" which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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I would like to dedicate my thesis

to my beloved family and my lovely girlfriend, Clio

for their endless supports

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ABBREVIATIONS

AI	Artificial Intelligence
CFD	Computational Fluid Dynamics
CNR-INSEAN	National Research Council-Marine Technology Research Institute
DE	Differential Evolution
DP	Dynamic Programming
DTMB	David Taylor Model Basin
EA	Evolutionary Algorithm
ECN	Ecole Centrale de Nantes
EEDI	Energy Efficiency Design Index
ES	Evolutionary Strategy
GA	Genetic Algorithm
ITTC	International Towing Tank Conference
ITU	Istanbul Technical University
LCB	Longutudional Center of Buoyancy
LFC	Load-Frequency Control
LP	Linear Programming
MAUA	Multi-Attribute Utility Analysis
NGSA-II	Nondominated Sorting Genetic Algorithm II
NLP	Non-Linear Programming
NTUA	National Technical University of Athens
PS	Pareto Search
PSO	Particle Swarm Optimization
RANS	Reynolds-Averaged Navier-Stokes
RS	Random Search
RSO	Response Surface Optimization
SA	Stochastic Approximation
SO	Stochastic Optimization
TEU	Twenty-Foot Equivalent Unit

UI	The University of Iowa
VCG	Vertical Center of Gravity

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NOMENCLATURE

$\ddot{\eta}_3$	instantaneous heave acceleration
$\dot{\eta}_3$	instantaneous heave velocity
$\ddot{\eta}_5$	instantaneous pitch acceleration
$\dot{\eta}_5$	instantaneous pitch velocity
∇^2	Laplace operator
h_3	sectional Diffraction force
A_{33}	added mass coefficient for heave due to heave
A_{35}	added mass coefficient for heave due to pitch
A_{53}	added mass coefficient for pitch due to heave
A_{55}	added mass coefficient for pitch due to pitch
B_{33}	damping coefficient for heave due to heave
B_{35}	damping coefficient for heave due to pitch
B_{53}	damping coefficient for pitch due to heave
B_{55}	damping coefficient for pitch due to pitch
C_{1-10}	constants in Fung method
C_{33}	hydrostatic restoring coefficient for heave due to heave
C_{35}	hydrostatic restoring coefficient for heave due to pitch
C_{53}	hydrostatic restoring coefficient for pitch due to heave
C_{55}	hydrostatic restoring coefficient for pitch due to pitch
C_p	prismatic coefficient
C_w	waterline coefficient
C_x	maximum midship coefficient
F_3	heave exciting force
F_5	pitch exciting force
I_5	moment of inertia for pitch
$U_0(t)$	time dependent velocity of translation
Z_3	heave response
Z_5	pitch response

a_{1-17}	regression coefficient in Fung method
a_{33}	section added mass
a_{33}^{A}	added mass of transom section
b_{33}	section damping
b_{33}^{A}	damping of transom section
f_3	sectional Froude-Krilov force
m_i	odd integer in the range of 0<m_i<1
v_i	binary fraction direction numbers
v_{ij}	jth bit following the binary point in the expansion of v_i
$\bar{x}$	Pareto design vector
x^A	x ordinate of transom (from center of gravity, negative aft)
x^i	a series with low inconsistency over the unit interval
$\hat{y}, \hat{z}$	outward normal unit vector of the section
ζ^*	efficient wave amplitude
η_3	instantaneous heave displacement
η_5	instantaneous pitch displacement
ω_0	wave frequency
ω_e	wave enconter circular frequency
ϕ_{30}	amplitude of the two dimensional velocity potential of the section in heave
$\emptyset(x, y, z; t)$	perturbation potential
Δ	displacement tonnage
∇	displacement volume
B	beam
b	section beam
B/T	beam-draft ratio
C_s,dl	section contour and element of arc along the section
D	depth
e	Euler's number
FP	fore peak
g	acceleration due to gravity

i	the square root of -1
ie	angle of entrance
kn	knot
kN	kilo Newton
L	length
L/B	length-beam ratio
m	meter
M	mass of the vessel
P	primitive polynomial
s	second
T	draft
U	vessel forward velocity
V/L	velocity-length ratio
x,y,z	longitudinal, transverse and vertical position of the section
$\Phi(x, y, z; t)$	velocity potential
ζ	wave amplitude
μ	wave heading angle
ξ	longitudinal distance from LCB
ρ	fluid density

ABSTRACT

MULTI-CRITERIA OPTIMIZATION OF HIGH SPEED NAVAL VESSELS: A PARETO APPROACH

In a ship design process, determining the main dimensions is one of the most fundamental work packages which seems quite underestimated when considered its continuous effects on the whole design. It could be a time-sink to turn the design cycle more than usual and specify these dimensions again and again because of encountered problems which might be predictable at first. In this study, a preliminary design process of a high speed naval combatant will be discussed to overcome mentioned situations by using Pareto Analysis. Pareto fronts can be obtained from at least two conflicting parameters which are relatively more important than the other parameters for ship's purpose/mission and these parameters are completely depend on the designer's call. Once the Pareto front is obtained for this ship type, oncoming similar ship designs could take less time and be more accurate.

Keywords: preliminary ship design, main dimensions, Pareto analysis, Sobol set, multi-criteria optimization

ÖZET

YÜKSEK HIZLI GEMİLERİN ÇOK KRİTERLİ OPTİMİZASYONU: PARETO YAKLAŞIMI

Gemi tasarım sürecinde ana boyutları belirlemek en önemli, ancak genel olarak düşünüldüğünde etkisi tüm süreci etkileyecek olmasına rağmen oldukça hafife alınan iş paketlerinden biridir. Tasarımcının görevi en kısa sürede, istenilen özellikleri karşılayan en uygun yani optimum tasarımı ortaya çıkarmaktır. Bu da en uygun ana boyutlardan yola çıkarak mümkündür. Geminin misyonuna bağlı olarak önceden tahmin edilip önüne geçilebilecek durumlardan ötürü dizayn spiralini defalarca dönüp ana boyutları tekrar belirlemek ciddi zaman kaybı oluşturabilir. Ayrıca regresyon analizi vb. yöntemlerle belirlenen ölçülerin en iyi değerler olduğunu söylemek de güçtür. Bu çalışmada yüksek hızlı bir askeri geminin ana boyutlarının belirlenmesinde Pareto analizi uygulanacaktır. Pareto sınırı, birbiriyle çelişen ve diğer parametrelere göre daha önemli sayılabilecek en az iki tasarım parametresinden elde edilebilir. Pareto sınırı bir kez elde edildi mi benzer tasarımların ana boyutları daha kısa sürede ve daha yüksek doğruluk hassasiyetiyle oluşturulabilir.

Anahtar Kelimeler: Gemi tasarımı, ana boyutlar, Pareto analizi, Sobol set, çok kriterli optimizasyon

1. INTRODUCTION

Pareto analysis, also called 80/20 rule is an optimization method mostly used in economics and simply says that %80 of outcomes can be attributed to %20 of the causes for a given event. Pareto analysis took its name from Vilfredo Federico Damaso Pareto who was an Italian engineer and economist [1]. He observed that the income distribution in Italy was not equal. In 1986, he showed that around %80 of the territory in Italy owned by only %20 of the population. Then he realized that this proportion is valid for many daily life cases. Later on it started to find its place in problem solving techniques and it was used frequently especially in economics.

In a ship design process, determining the main dimensions is one of the most fundamental work packages which seems quite underestimated when considered its continuous effects on the whole design. It could be a time-sink to turn the design cycle more than usual and specify these dimensions again and again because of encountered problems which might be predictable at first.

In this study, Pareto analysis is applied to a ship design process to obtain its optimum main dimensions.

%80 of outcomes can be attributed to %20 of the causes for a given event.

It can be considered as:

Given event ➔ Ship Design

Causes ➔ Design Parameters

Outcomes ➔ Ship Performance

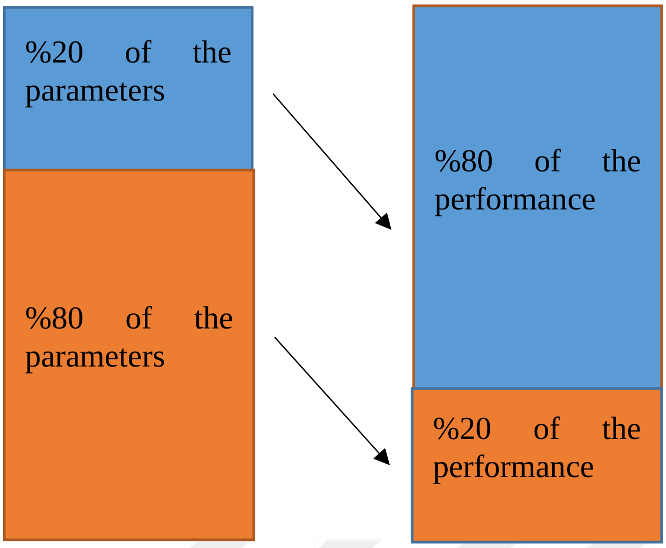


Figure 1.1 Pareto Principle in Ship Design

So it can be more efficient to optimize %20 of the design parameters thus %80 of the ship performance in less time than spending much more time for preliminary design phase.

1.1 Aim of the Project

Optimization is one of the most important things in every aspect of engineering. A well-known fact is multi-objective optimization occurs between conflicting criteria. That means while one of them is improving, the others are going to worsen. Many methods have been developed from past to nowadays. A brief history of optimization is presented in the next section to see this development process and understand its necessity.

A ship design is a complex process which includes many conflicting parameters from the beginning to the end. The facilities for designing ships in the past were very few compared to today and even today, doing experiments and analysis is expensive and time-consuming. After having owner's requirements, the first step of a ship design process is called concept design. In that phase, expectation from the designer is turning the ship design cycle (Figure 1.2) once and to draft the design roughly. Main dimensions are determined here first and changing them causes lots of re-work and wasted time. To begin with optimum dimensions provides quicker and more accurate design.

In this study, Pareto analysis is applied to a naval combatant (DTMB 5415) which is a fictitious vessel broadly used in resistance benchmark analysis and optimization studies and etc. The DTMB 5415 hull is already optimized for resistance (Single Objective Optimization). The point is to see if any better main dimensions on an existing and most probably well-optimized vessel could be obtained by using this method for more than one objective. In other words, the challenge is set to be the achievement of additional design objectives conflicting with each other, without compromising from the main design objective. If so, this might prove that Pareto analysis can be a valuable tool in ship conceptual design.

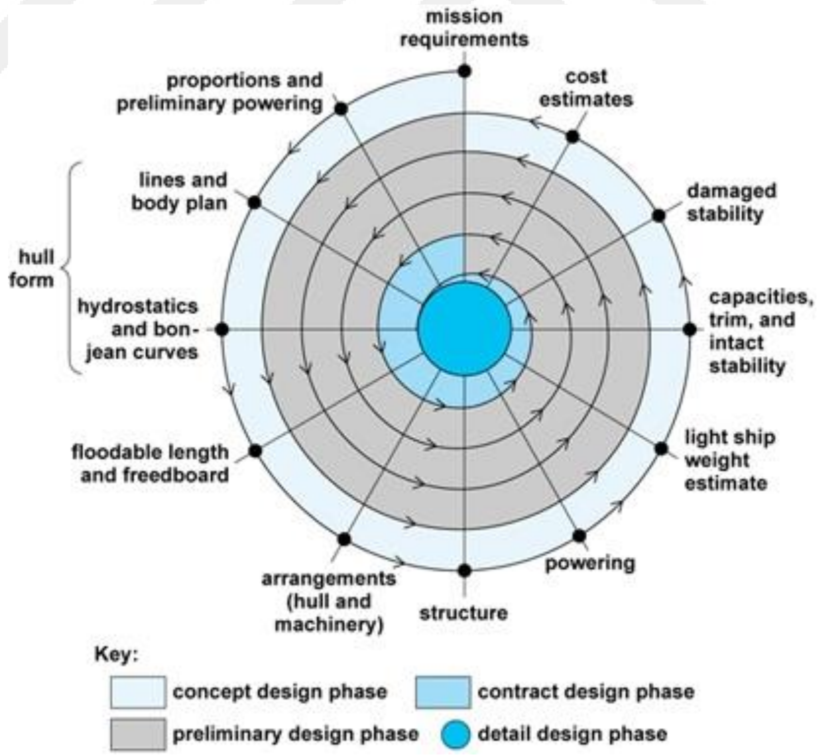


Figure 1.2 Ship Design Spiral [2]

1.2 Overview of Calculus and Optimization Techniques

In the simplest way, Optimization is a mathematical branch that has relation with finding of the maximum or minimum values of a system. The earlier mathematicians and philosophers forged its foundations by defining the optimum with different ways on several domains such as numbers, shapes, optics, astronomy etc…[3].

The birth of Cartesian geometry which is found by the French mathematicians René Descartes and Pierre De Fermat can be considered as one of the most important advancement in optimization. Descartes and Fermat also found analytic geometry at the same time, but separately. Descartes introduces the systematic use of the coordinated axes, which in our time are called "Cartesian axes", which allow us to give a representation of the points with pairs or triads of numbers and the geometric relations between the points with mathematical relations. Universalizing the principle, Descartes argues that an equation with two unknowns always identifies a line that is a straight line, if the equation is of the first degree ($ax + by + c = 0$); it is a conic if the equation is of the second degree (for example a circumference $x^2 + y^2 + ax + by + c = 0$, or a parabola $y = ax^2 + bx + c = 0$, etc.); and it is finally a more complex curve if the equation is of a higher degree ($y = x^3$). Among the most important results achieved by Descartes, the general determination of the normal to any plane algebraic curve in any point, and the consequent determination of the tangent, is worthy of great consideration.

Also Pierre de Fermat solved the tangent line problem, finding the derivative and thereafter obtaining the optimal point where the slope is zero ($df(x)/dx = 0$).

But the two most recognized discovers of calculus are Isaac Newton and Gottfried Wilhelm Leibniz.

Leibniz's calculus symbols are largely adopted by the mathematics community, and thank to this calculus Newton was able to find the substential physics laws that are adequate in macro scale to define many physical phenomena in nature.

The Bernoulli brothers, Jacob and Johann continued the evolution of the calculus, applying separation of variables in the solution of a first-order nonlinear differential equation.

Jacob definitively resolved the problem of the catenary in 1691, using the methods of the infinitesimal calculus, and other optimization problems, such as the isoperimetric problem and curves of fastest descent.

Johann and Jacob founded the calculus of variations together and Johann developed the exponential calculus.

Leonhard Euler suggested the symbol ‘e’ for the base of natural logs and in 1777 ‘i’ for the square root of -1. With the formula $e^{ix} = \cos x + i\sin x$ he unifies the trigonometric and exponential functions. The calculus of variations was named and created by Euler and through several works he made fundamental discoveries. The first studies in calculus of variations was made in *Methodus inveniendi lineas curvas* written in 1740.

The first optimization algorithms were developed during the nineteenth century, thanks to these pioneers' works. Important contributions were made by different mathematicians. In 1847 Augustin-Louis Cauchy explained steepest descent (gradient descent) method. This method could be considerable as one of the most fundamental derivative-based iterative methodology to be used in such problems like minimization of a differentiable function.

Another important optimization method is the least-square approximation. This method makes possible to obtain an approximate solution for a set of equations where there are more equations than unknowns. In 1795, Gauss formulated a solution to this problem, but it was first made known by Lagrange in 1806. Fundementaly, the sum of the squares of the residual errors get minimized by this method.

In the twentieth century, there were discovered several optimization techniques by mathematicians like Oskar Bolza and Gilbert Bliss. The first book on optimization with the title *Maxima and Minima* was written in 1917 by Harris Hancock. The Linear Programming (LP) was developed and established by the Russian mathematician Leonid Vitaliyevich Kantorovich in 1939, but became famous only with the publication of the *Simplex* method, published by the American mathematician George Bernard Dantzig. LP or linear optimization provides us a solution to determine optimum outcome in a given system related to a list of needings which are defined by linear relationships.

The theory of duality was developed and applied in the game theory by John Von Neumann as a LP solution. Besides, he proved the minimax theorem in the game theory.

William Karush developed nonlinear programming (NLP) in 1939. NLP is a substantial tool in control theory since control problems are in functional spaces, while NLP considers optimization problems in Euclidean spaces.

Richard Bellman was the first who introduced the dynamic programming (DP) in 1952. This method is widely used in complicated optmisation problems by dividing them into simpler structures.

All methods mentioned above are deterministic approaches which are applied on known differentiable functions. On the other hand, stochastic approximation (SA) finds the minimum or maximum points of an unknown function with unknown derivatives. Herbert Ellis Robbins and Sutton Monro were the first who introduced the stochastic approximation in 1951.

Evolutionary algorithms are stochastic optimization methods inspired by biological phenomena of natural evolution. The first proposals in this direction date back to the 1960s, when in the United States John Holland introduced the Genetic Algorithms and Lawrence Fogel the Evolutionary Programming, while in Europe, simultaneously and independently, Ingo Rechenberg and Hans-Paul Schwefel began their work on Evolutionary Strategies. Their pioneering efforts gave rise over time to a class of methods suitable for dealing with complex problems where little is known of the underlying research space. An evolutionary algorithm simulates the evolution of a population of candidate solutions for the object problem by applying iteratively a set of stochastic operators, of which the most important are mutation, recombination, reproduction and selection. The mutation randomly perturbs a candidate solution; the recombination decomposes two distinct solutions and produces a new one by randomly reassembling their parts; reproduction replicates with greater probability the best solutions in the population and the selection eliminates the poor ones. The resulting process tends to find globally optimal solutions for the object problem in a way very similar to how in Nature populations of organisms adapt to the environment that surrounds them.

Rainer Storn and Kenneth Price in 1995 developed differential evolution (DE), that also can be used on optimization problems.

Also the Particle Swarm Optimization (PSO), developed by Russel C. Eberhart and James Kennedy in 1995 was used to be performing optimization [3].

1.3 Literature Review

The optimization studies are performed locally or globally. The ship design studies requires considering ship structure, fluid dynamics, hydrodynamics, ship seakeeping performance, resistance and other disciplines. Solving optimization problems needs a lot of techniques for each steps. Modelling of ships, creating design space and obtaining optimum design has changed throughout the optimization studies. A ship structure study is performed to represent the efficient techniques of optimization to obtain optimum design [4]. Model generation is achieved by random number generations. Random Search (RS) method, Evolutionary Strategy (ES) and Pareto search (PS) are comprised an the result shows that the ES method cannot search global optimum points in most cases, RS methods are able to search global points and PS method the best searching method. In terms of accuracy the difference percentages are 0.56% for PS, 0.77 for RS and 3.56 for ES. At the end, the success percentages are 15% for ES, 90% for PS and 70% for RS. That shows the Pareto Strategy is the most efficient method for ship design [5] [6].

Optimization of ship structures is also studied [7]. Plate thickness, web height and thickness, flange width, spacing are the design variables and the cost of raw materials, the labour cost and the overhead costs are the design objectives. This study aims minimum cost and minimum weight while minimum required strength is acquired.

DTMB 5415 hydrodynamic multi-objective optimization is studied by tree different university, and the results for each university is comprised [8].The overall idea of the project is the methods based on the Simulation-based Design Optimization methods and improving the resistance and seakeeping. Provide hull variants and optimization of each variants' hydrodynamic performance, combining low and high-fidelity solvers, design modification tools and multi-objective optimization algorithms. Low-fidelity is the first step and the high-fidelity is the second step of project. ITU, INSEAN/UI, and NTUA are studied on low-fidelity and ECN/CNSR is studied on high fidelity. The methods and results shows that the average improvements for low-fidelity as 10.35% for ITU, 6.75% for INSEAN/UI, 14.6%

for NTU. For the high-fidelity, the optimal hull of INSEAN/UI is used. ISIS-CFD is a flow solver that is available for the Reynolds-averaged Navier Stokes equation (RANS). The results shows that the average improvement can be determined as 0.2 reduction.

There is also a study about 6500 TEU container ship concept design optimization [9]. The aim of this study is demonstrate the modern ship design optimization techniques in the shipbuilding industry and represent minimization of capacity ratio, required freight rate, EEDI, ship resistance and maximization of stowage ratio. Ships hulls modeling with CAESES/Frıendship-Dramework. The techniques are Sobol sequence for hull generation and genetic algorithm with Pareto front for optimization. The improvement is about 7.5%.

The propeller optimization is studied to advance ship propulsion efficiency [10]. The propeller is simulated by using different numerical models in CFD. Three types of mesh grid, coarse, medium and fine, are used, then the most reasonable result belongs to fine mesh. Sobol Sequence is performed for generation of variant ships in design space. The method for optimization is the Tangent Search Method. For all parametric modelling, an optimization phase study is conducted with CEASES modeler. It is denoted that the most efficient design has %1.3 increasing in open water efficiency.

Another study is about ship propeller-hull optimization [11]. Thrust, torque, open water efficiency and skewness ratio are the design parameters. NGSA-II, an evolutionary algorithm, is employed to optimize parameters, thus can find the Pareto front. The results conclude that the LFC and the cost have been minimized efficiently.

The other example study is about the sailboat design study by response surface optimization is performed [12]. The study is interested in enhancing the upwind performance. The steps of the study is given as the improvement of the forms in the design space which are generated from base design, apply performance measurement for each design, built a mathematical relation between performance measurements and the design parameters, and find the best design and calculate the corresponding geometry and parameters. The parametric of 946 hull design from base hull is generated with FRIENDSHIP-Modeler by coupled with Sobol Sequence the minimum or maximum value of the function provides to search the best design by computing with optimization solver. The multi-dimensional function is called as surface or response subsurface by considering the input or output relation. It’s named as Response Surface Optimization (RSO) for optimization with the response surface function. The optimization is proceed by using Generalized Reduced Gradient for this study. In conclusion the best designs are obtained as shown in the. The optimization percentage is maximum 2.8%.

1.4 Methodology

In this section, the content of the study is going to be presented chapter by chapter.

Chapter 2 is focusing on the algorithm behind the Pareto analysis and it will be examined in detail. Two separated MATLAB codes, one for 2-objectives and one for 3-objectives, which apply this algorithm are going to be generated according to it.

Chapter 3 represents the definition of design space. The parameters which are going to be optimized will be evaluated. The ship and its variations will be modeled as 3-D and Sobol algorithm which is a quasi-random low-discrepancy sequence is going to be used to determine variation of length and breadth. Resistance and ship motions calculations. Fung method will be used for resistance calculations and then these results are going to be validated by a potential code and experimental results. Motion calculations will be done by Maxsurf Motions with strip theory-based methods.

Chapter 4 represents applying Pareto method to obtained data and finding Pareto front and therefore optimum design. Results and discussions will be in this chapter.

Chapter 5 represents conclusion, further studies and suggestions.

2. PARETO ANALYSIS

It can be considered to evaluate Pareto approach when multi objective optimization is the case. First and most of its application area is in economy. Pareto approach can also be considered as a trade-off strategy which is utilized most of the design problems in engineering. There are two principal challenges in Pareto approach. First one is populating the Pareto set and the second one is choosing among the potential Pareto optimum points. The challenge is similar to the challenges of decision-based process. A design vector $\bar{x}$ is a Pareto optimum if the below statement is achieved [13].

$$f_j(x) \leq f_j(\bar{x}), j = 1, \ldots, m; j \neq i => f_i(x) \geq f_i(\bar{x}) \tag{2.1}$$

Above equation is the fundamental of Pareto analysis.

There are several techniques to determine Pareto optimum design among others. The simplest method is to select a design according to the objective's values and compare how well they coupled with the willed values. This technique is used in (Nelson, *et al*. 1999) when dealing with more than one Pareto optimum design sets. Das (1999) introduced the notion of 'order of efficiency'. According to Hazelrigg (1996) a 'meta-objective' of maximizing profit should lead the selection solutions from a set. Horn, *et al*. (1994) use MAUA (Multi-Attribute Utility Analysis) to choose the 'optimum' solution among the Pareto optimum design set. Eschenauer, *et al.* (1990) established L_p norms as the most commonly used technique. This method minimizes the distance from the Pareto optimum design set to a most-preferred solution (utopia point) to find the Pareto optimum based on the below formulation:

$$minimize\left(\sum_{i=1}^{m}(f_i(x) - f_i^*)^p\right)^{\frac{1}{p}} \tag{2.2}$$

In this study, we utilize the L_2 norm, which means p is equal to 2, to find the optimal design from the Pareto optimum design set for two and three-criteria optimizations.

Pareto method takes part in the design space. Design space is the zone which is constituted by taking the design objectives into consideration as coordinate axes. On these axes the parameter values of each design is plotted. Generally speaking, the outcomes' plot seems like a region in the design space [13].

The steps are briefly,

1. Creating a design space which consists of potential optimum solutions
2. Choosing an Pareto optimum solution among the design space

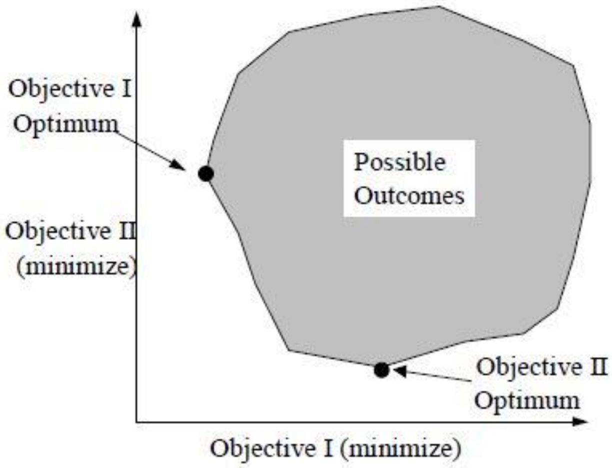


Figure 2.1 A Sample of Design Space [13]

Since it is a trade-off strategy, it is impossible to optimize all the criteria together. A point should be chosen to satisfy all of them according to their importance. In this study, all the criteria are equally weighted which is actually why L_2 norm is going to be utilized.

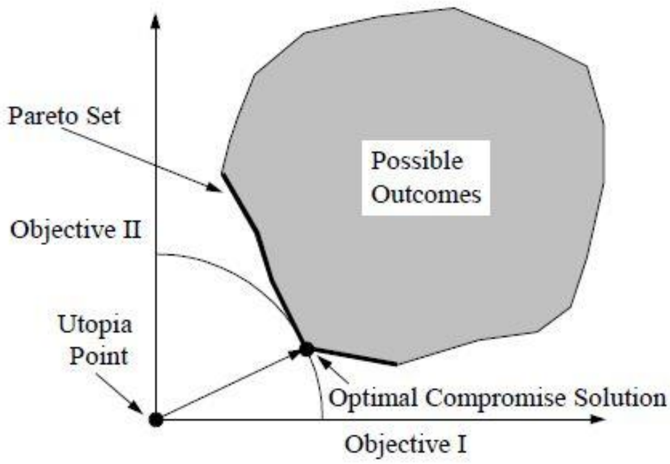


Figure 2.2 Pareto Optimum Solution (Using L_2 Norm) [13]

Utopia point is where all the criteria are satisfied together at the same time, which is impossible in real life as can be understood from the 'Utopia' expression. But the closer the solution gets to utopia point, more 'optimum' it would be for equally-weighed criteria problems.

Two separated MATLAB code which apply Pareto algorithm are generated. Since it is a numerical approach, one of the most important part is to do discretization of design space correctly. If the step size of the discretization is too high, most possible you can't catch the Pareto optimum solution accurately. If it is too small, you can get entire design space as the Pareto optimum solutions. The codes offer several step size options and it is up to user to select which one might be more suitable on the case.

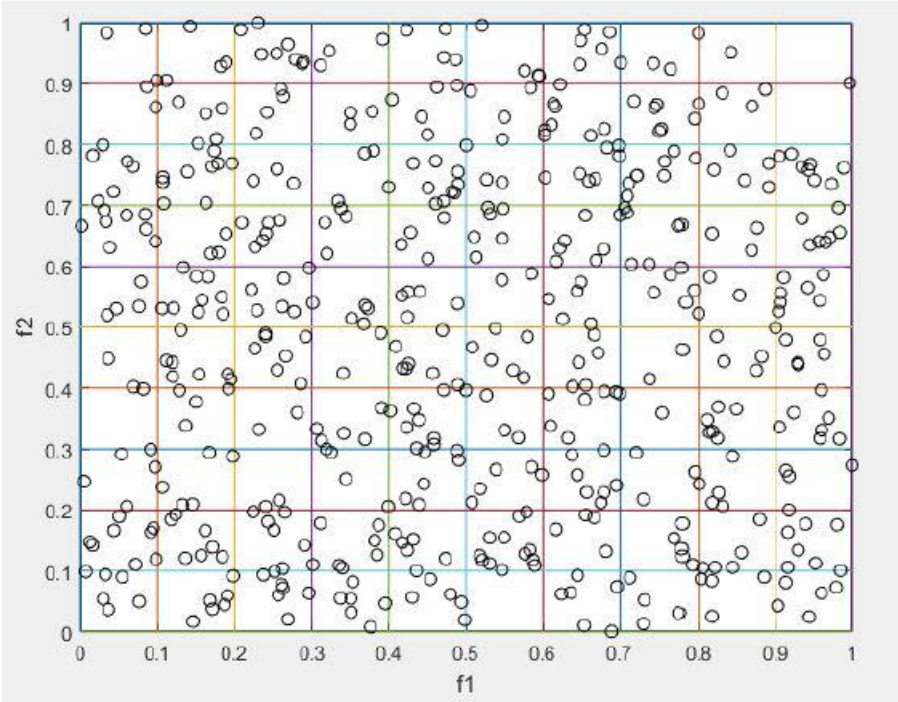
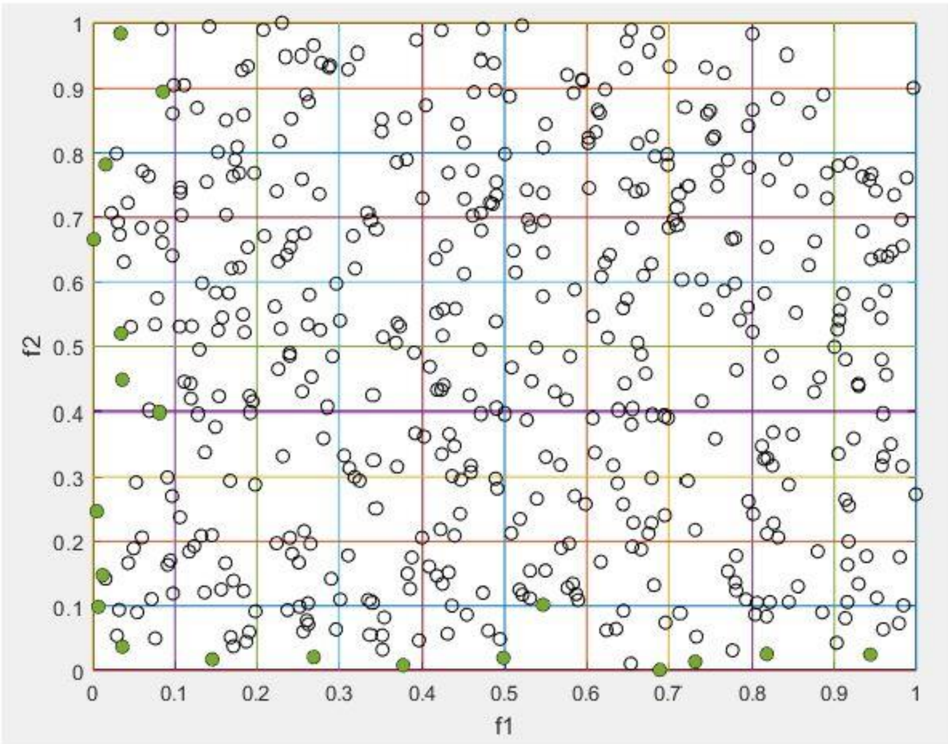


Figure 2.3 An Example of Random Design Space (Step Size: 0.1)

After discretization, the codes search the meshes one by one to find minimum points for each axes.



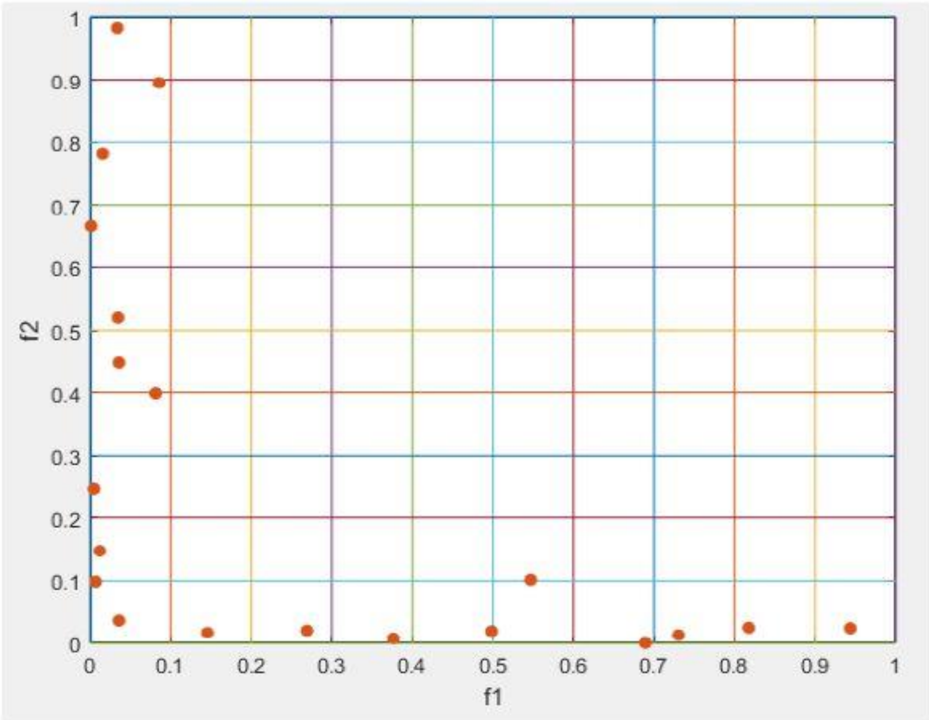


Figure 2.4 Pareto Optimum Solutions

At this stage, there is a need of another filter to get Pareto optimum solutions. Because the codes find the minimum points in each mesh. But we need a general perspective. Added filter eliminates y points (x and y are design points) if;

$$f1(x) < f1(y)$$
$$f2(x) < f2(y)$$

(2.3)

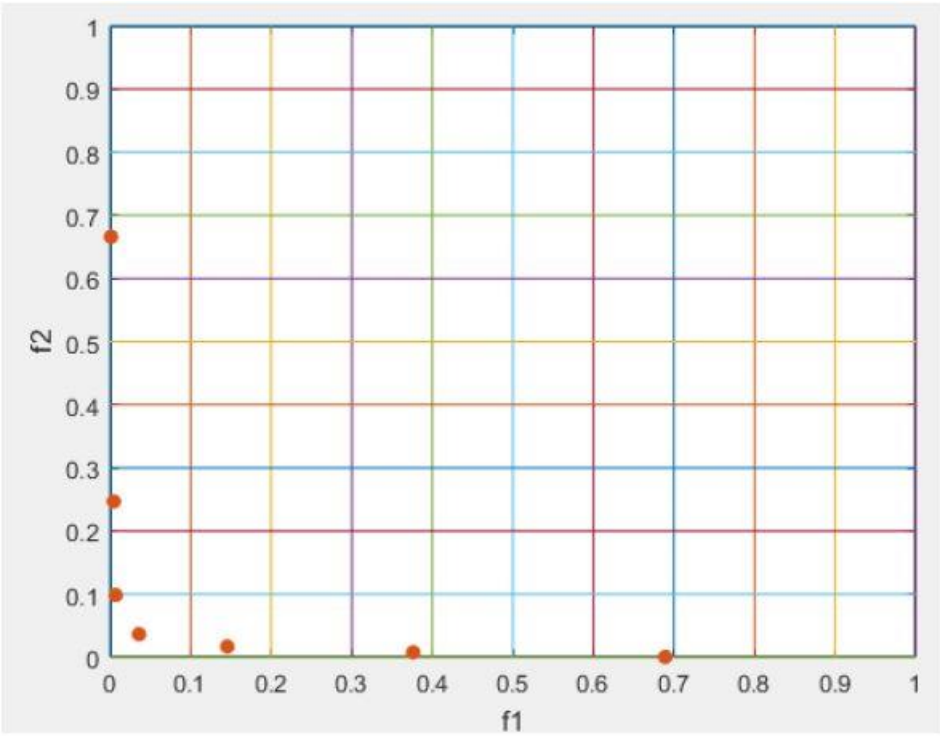


Figure 2.5 Pareto Optimum Solutions (Pareto Front)

After applying this filter, the points which form Pareto front appear as seen in Figure 2.5.

3. DESIGN SPACE DEFINITION AND ANALYSIS

In this chapter, DTMB 5415 (Arleigh Burke Class Frigate) and its variations are going to be modeled in 3-D. Before that, a test matrix should be created for length and beam variations to define design space. There are several approaches to achieve it.

One of them is random distribution within the range of design constraints. This method gives us a completely random design space. Therefore it could be difficult to obtain an even distribution. Even distribution is important because the workforce is limited. Hence the goal is to cover entire domain with the least possible combinations. An example of random distribution is;

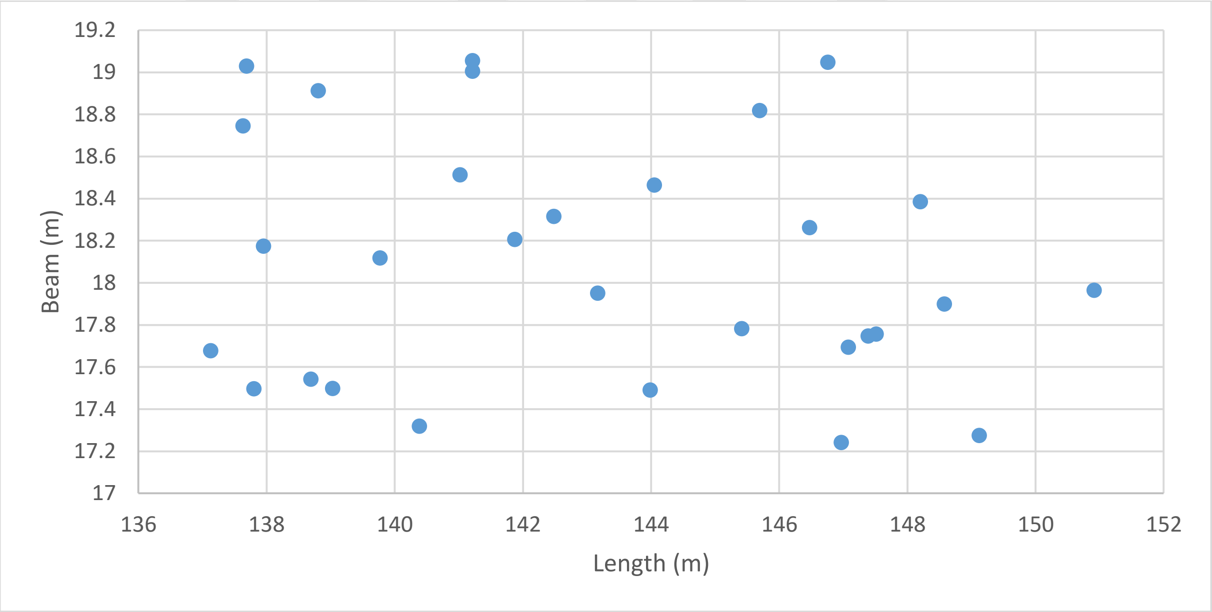


Figure 3.1 Random Distribution

As seen in the graph, top-right part is empty so the design space does not cover the domain properly. This method can be usable but it is not recommended.

The other approach is parametric spacing. Defining constant spacing values for both length and beam within the range of design constraints gives us a design space which covers whole domain. An example is given below.

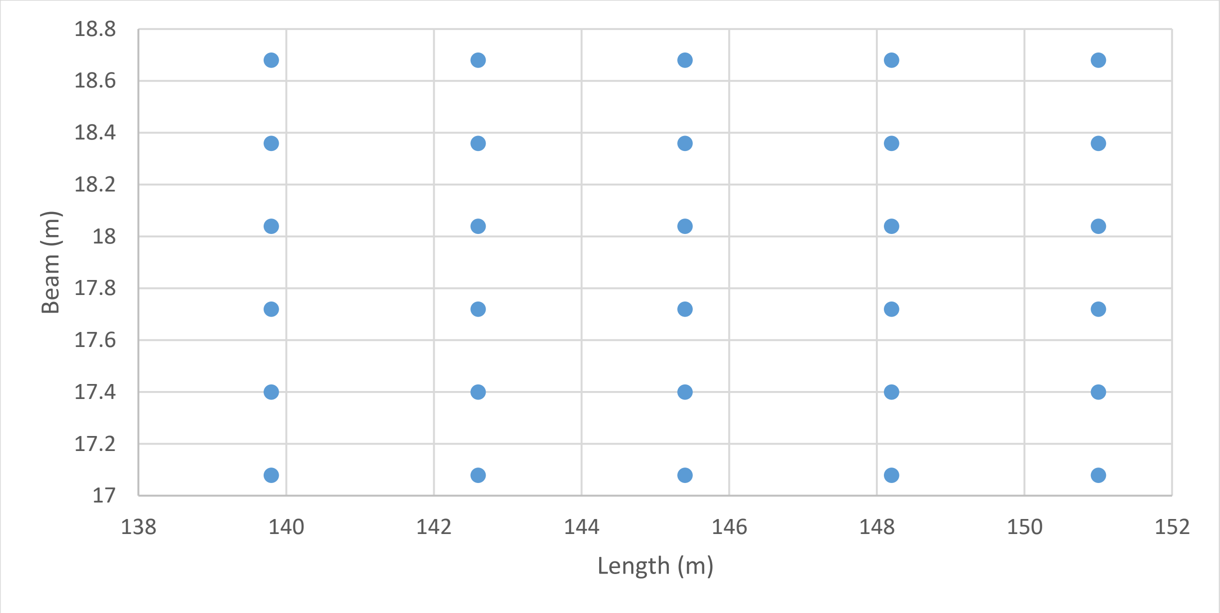


Figure 3.2 Parametric Spacing

This approach is also valid and usable but 30-ship set can be obtained from only 5 different length and 6 different beam values. So we have total of 11 length-beam variations but 30 ships. That may cause the differences between characteristics of variations quite similar and somehow something can get out of sight.

Another approach is using Sobol set which is a quasi-random low discrepancy sequence. Quasi-random sequences are more suitable than the others above. The reason is that they seem like completely random (but they are not) and their distributions over the domain are even. They are used in simulation, optimization and numerical integration. Quasi-random sequences other than Sobol can be listed as van der Corput sequence, Halton sequence, Hammersley set and Poisson disc sampling.

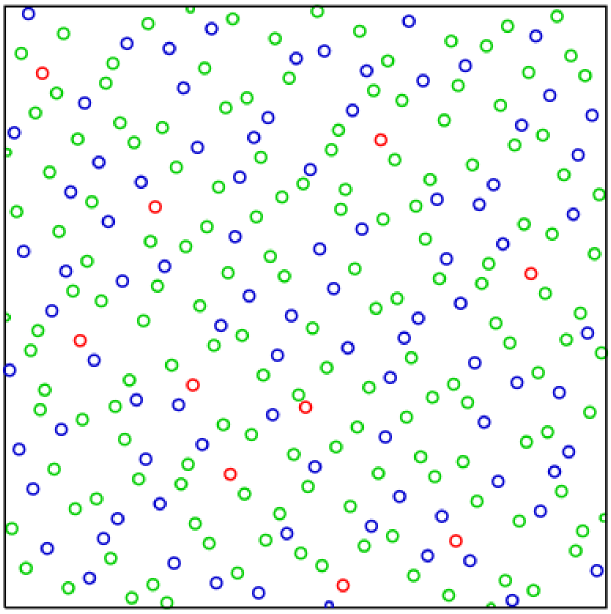


Figure 3.3 Halton Sequence of 256 Points

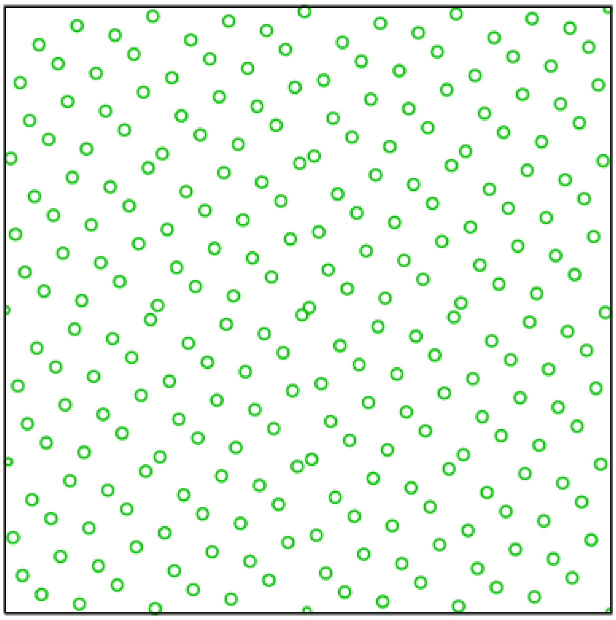


Figure 3.4 2D Hammersley Set of 256 Points

In this study Sobol sequence is utilized to define design space.

3.1 Sobol Sequence

Sobel or Sobol sequence is a type of quasi-random low-discrepancy sequences. Basically this sequence provides the random numbers mapped onto uniform distribution. Sobel sequence is introduced by Russian mathematician Ilya M. Sobol. When it is applied on creating design space, Sobol sequence creates uniform design space. In the beginning it looks like random but as the number of design increases, the uniform distribution is most-likely going to appear. In comparison to random distribution, this method avoids to produce clusters or voids. This smart space samples and uniform distribution makes the sequence more efficient for the optimization [10] . The Sobol sequence also avoids to generate grid lines, this provides stable basis for following steps as optimization [12].

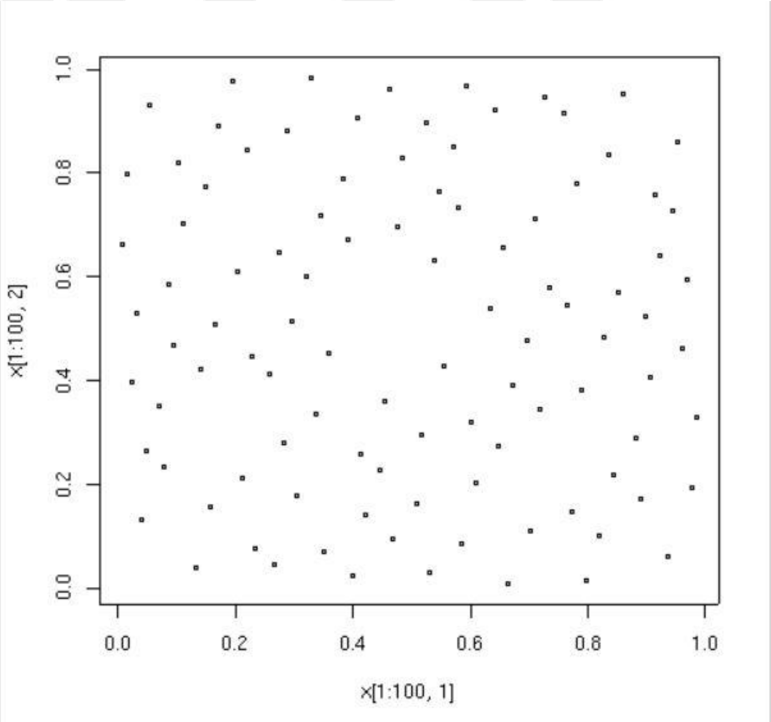


Figure 3.5 Sobol Sequence (First 100 Points)

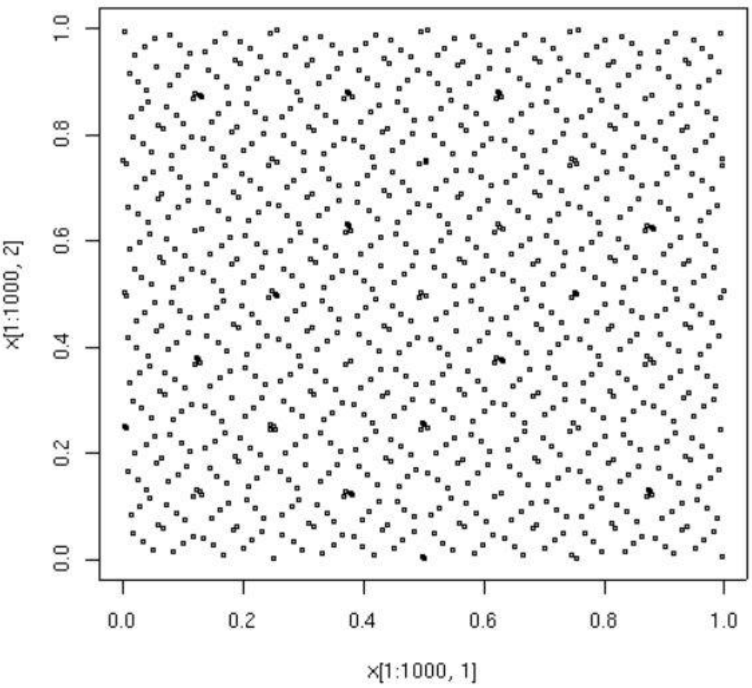


Figure 3.6 Sobol Sequence (First 1000 Points)

The numbers are generated in an interval of 0 to 1 which is also called as unit interval. It progresses by arranging the coordinates in each dimension. The series generate the numbers as binary fraction from a set. The aim is to form a series of values $x^1, x^2, \dots, 0 < x^i < 1$ with low inconsistency over the unit interval. Firstly, a set of direction numbers $v_1, v_2, \dots, v_i$ need to be specified. Each v_i is a binary fraction.

$$v_i = 0.v_{i1}v_{i2}v_{i3} \dots \tag{3.1}$$

Where v_{ij} is the jth bit following the binary point in the expansion of v_i. It can be shown instead;

$$v_i = \frac{m_i}{2^i} \tag{3.2}$$

Where m_i is an odd integer in the range of $0 < m_i < 1$.

To obtain v_i, a polynomial with coefficients selected from {0,1} should be decided.

$$P \equiv x^d + a_1 x^{d-1} + \cdots + a_{d-1} x + 1 \tag{3.3}$$

When we have selected a primitive polynomial we use its coefficients to calculate v_i ;

$$m_i = 2a_1 v_{i-1} \oplus 2^2 a_2 m_{i-2} \oplus \ldots \oplus 2^{d-1} a_{d-1} m_{i-d+1} \oplus 2^d m_{i-d} \oplus m_{i-d} \tag{3.4}$$

In the end, to create the sequence $x^1, x^2 \ldots, x^n$ below equation can be used.

$$x^n = b_1 v_1 \oplus b_2 v_2 \oplus \ldots \oplus b_n v_n \tag{3.5}$$

Where …,$b_3 b_2 b_1$ is the binary representation of n [14].

3.2 Hull Design

DTMB 5415 is the initial hull form and the other variations will be generated according to it. It can also be called as base model and parent ship. The modeling process has been completed by Maxsurf Modeler Advanced.

Table 3.1 DTMB 5415 Main Particulars

Waterline Length	142.18	m
Beam	19.08	m
Depth	16	m
Draft	6.15	m
Cp	0.607	-
LCB	51%	From FP
Displacement	8513	tons

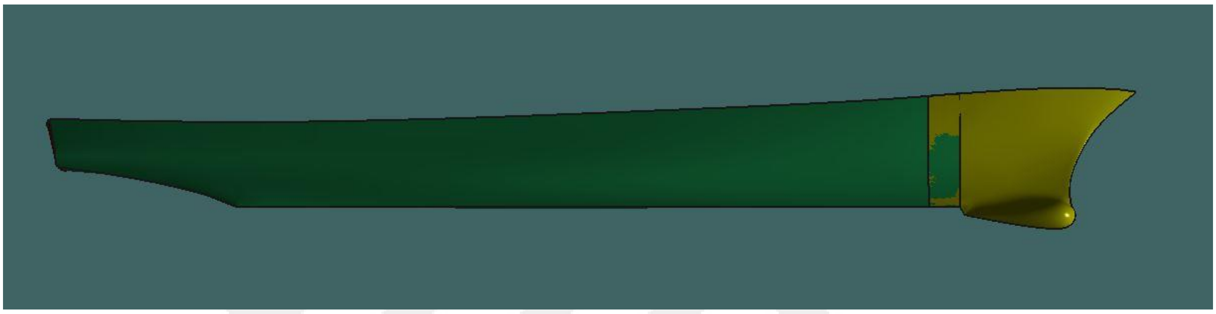


Figure 3.7 Profile Plan of Base Model

Length and beam variations are obtained by using Sobol sequence in MATLAB in the range of $\pm$%5 of original dimensions. First 30 values, so 30 ships, are retained from the set.

Table 3.2 L-B Variations by Using Sobol Sequence

L (m)	B (m)
135.07	18.13
135.54	19.17
136.02	19.97
136.49	19.05
136.97	19.36
137.44	18.43
137.91	18.74
138.39	19.79
138.86	19.60
139.34	18.68
139.81	18.50
140.28	19.54
140.76	18.86

141.23	19.91
141.71	19.23
142.65	19.11
143.13	18.19
143.60	18.99
144.08	20.03
144.55	18.37
145.02	19.42
145.50	19.73
145.97	18.80
146.45	18.62
146.92	19.66
147.39	19.48
147.87	18.56
148.34	19.85
148.82	18.93
149.29	18.25

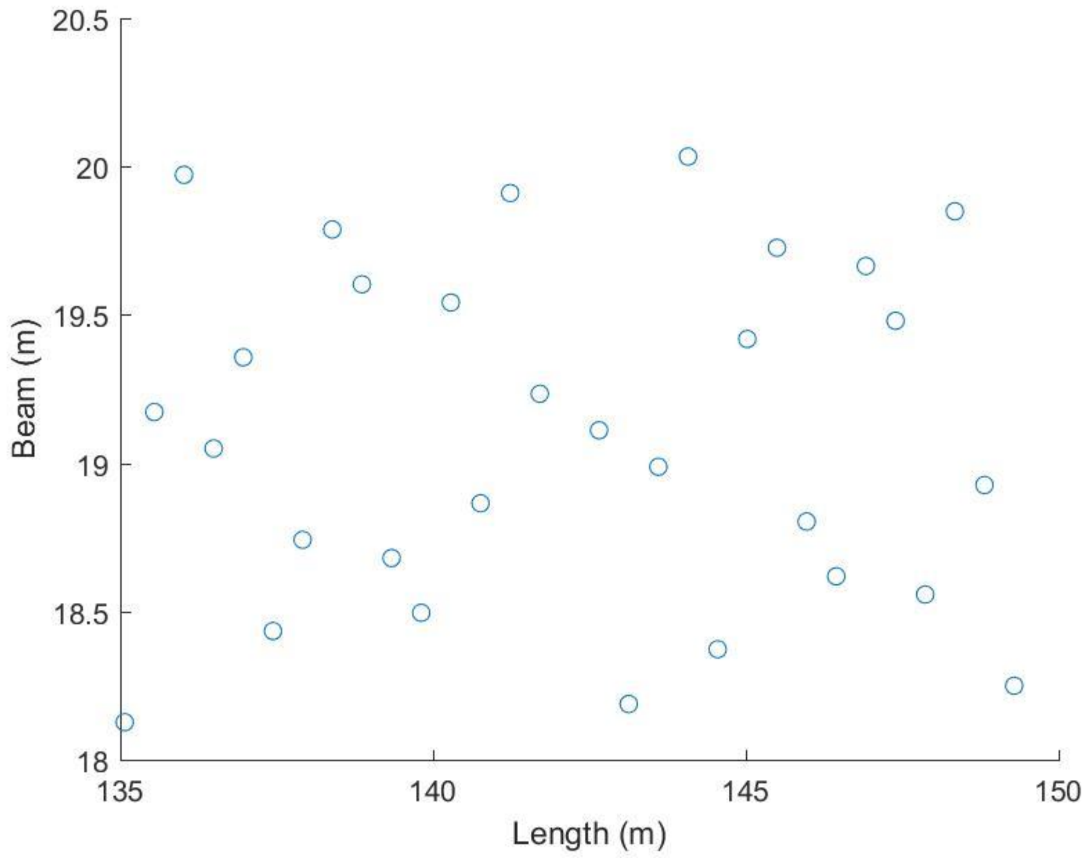


Figure 3.8 Even Distribution of Design Space

For each ship among these 30, there are 3 different C_p and 3 different LCB combinations. So the design space is populated from 30 to 270 ships. Changing length, beam, C_p and even LCB should change also the displacement and draft values relatively. A simple algorithm is applied to determine the displacement values of the design space with an assumption of payload of all ships will remain constant and the payload is equal to %40 of the displacement value of the original ship.

Table 3.3 Design Constraints

Payload	Constant	3405	tons
Length	Variable	135.07 < L < 149.29	m
Beam	Variable	18.13 < B < 20.03	m
C_p	Variable	0.59 – 0.607 – 0.624	-
LCB	Variable	%50 - %51 - %52	From FP

Main dimensions, displacement, C_p and LCB are needs for modeling of the design space. The Sobol sequence has given the length and the beam of the hulls. Depth has been calculated by proportion to the length of the parent ship.

Table 3.4 Design Space

Lwl (m)	B (m)	D (m)	Displacement (tons)	CP range	LCB range
142.18	19.08	16.00	8513	0,590-0,607-0,624	50%-51%-52%
135.07	18.13	15.20	7785	0,590-0,607-0,624	50%-51%-52%
135.54	19.17	15.25	8070	0,590-0,607-0,624	50%-51%-52%
136.02	19.97	15.31	8299	0,590-0,607-0,624	50%-51%-52%
136.49	19.05	15.36	8105	0,590-0,607-0,624	50%-51%-52%
136.97	19.36	15.41	8214	0,590-0,607-0,624	50%-51%-52%
137.44	18.43	15.47	8016	0,590-0,607-0,624	50%-51%-52%
137.91	18.74	15.52	8126	0,590-0,607-0,624	50%-51%-52%
138.39	19.79	15.57	8424	0,590-0,607-0,624	50%-51%-52%
138.86	19.60	15.63	8411	0,590-0,607-0,624	50%-51%-52%
139.34	18.68	15.68	8208	0,590-0,607-0,624	50%-51%-52%
139.81	18.50	15.73	8193	0,590-0,607-0,624	50%-51%-52%
140.28	19.54	15.79	8498	0,590-0,607-0,624	50%-51%-52%
140.76	18.86	15.84	8355	0,590-0,607-0,624	50%-51%-52%
141.23	19.91	15.89	8665	0,590-0,607-0,624	50%-51%-52%
141.71	19.23	15.95	8520	0,590-0,607-0,624	50%-51%-52%
142.65	19.11	16.05	8555	0,590-0,607-0,624	50%-51%-52%
143.13	18.19	16.11	8339	0,590-0,607-0,624	50%-51%-52%
143.60	18.99	16.16	8590	0,590-0,607-0,624	50%-51%-52%
144.08	20.03	16.21	8912	0,590-0,607-0,624	50%-51%-52%
144.55	18.37	16.27	8489	0,590-0,607-0,624	50%-51%-52%
145.02	19.42	16.32	8814	0,590-0,607-0,624	50%-51%-52%
145.50	19.73	16.37	8935	0,590-0,607-0,624	50%-51%-52%
145.97	18.80	16.43	8711	0,590-0,607-0,624	50%-51%-52%
146.45	18.62	16.48	8693	0,590-0,607-0,624	50%-51%-52%
146.92	19.66	16.53	9026	0,590-0,607-0,624	50%-51%-52%
147.39	19.48	16.59	9010	0,590-0,607-0,624	50%-51%-52%
147.87	18.56	16.64	8778	0,590-0,607-0,624	50%-51%-52%
148.34	19.85	16.69	9189	0,590-0,607-0,624	50%-51%-52%
148.82	18.93	16.75	8956	0,590-0,607-0,624	50%-51%-52%
149.29	18.25	16.80	8791	0,590-0,607-0,624	50%-51%-52%

3.3 Resistance Calculations

Resistance calculations can be carried out by several methods. Low fidelity empirical formulas such as Holtrop-Mennen, Compton, Fung etc. which is suitable for the current ship might be used during this process to obtain initial resistance values quicker. Another way is using potential code due to its efficiency and giving fairly good estimations. As the viscosity effects are often limited to small boundary layer, potential flow models are particularly useful for free surface flow such as flow around the ship hull. The fluid is assumed inviscid, irrotational and incompressible flow. The total velocity potential could be expressed as below [15]:

$$\Phi(x, y, z; t) = U_0(t)x + \phi(x, y, z; t) \tag{3.6}$$

Subject to Laplace Equation:

$$\nabla^2\Phi = 0 \tag{3.7}$$

Where $\phi(x, y, z; t)$ is the perturbation potential, $U_0(t)$ is the time-dependent velocity of translation.

Using Reynolds-Averaged Navier-Stokes methods (RANS) most probably gives us the most accurate results but when taking into account the ships in the design space, using this method in the first place won't be efficient.

In this study, Fung resistance method is utilized to calculate bare hull resistance values by using Maxsurf Resistance.

3.3.1 Fung Resistance Method

Fung (1991) developed a mathematical model for resistance and power prediction of transom stern hulls to support NAVSEA ship synthesis design programs during early ship design phases. The range of application of this mathematical model is given at below table [16].

Table 3.5 Range of Application (Fung's Method)

$L/\nabla^{1/3}$	4.567 – 10.598
B/T	2.2 – 5.2
L/B	3 - 18
C_w	0.67 – 0.84
C_p	0.52 – 0.7
C_X	0.62 - 1
ie	3° - 20°

The mathematical model for residuary resistance coefficient was developed using multiple step-wise regression analysis for 18 different V/L (speed-length) ratios. The equation ignores the hull form parameters' interaction's effect and thus has in it no cross-coupling terms. The equation comprises reciprocal, quadratic and linear terms as follows.

$$Cr_1 = C_1 + a_1 * \left(\frac{\triangle}{L^3} * 28571\right) + a_2 / \left(\frac{\triangle}{L^3} * 28571\right) \tag{3.8}$$

$$Cr_2 = C_2 + a_3 * \left(\frac{B_x}{T_x}\right) + a_4 / \left(\frac{B_x}{T_x}\right) \tag{3.9}$$

$$Cr_3 = C_3 + a_5 * C_p + \frac{a_6}{C_p} \tag{3.10}$$

$$Cr_4 = C_4 + a_7 * C_x + \frac{a_8}{C_x}$$

(3.11)

$$Cr_5 = C_5 + a_9 * ie + \frac{a_{10}}{ie}$$

(3.12)

$$Cr_6 = C_6 + a_{11} * \left(\frac{A_{20}}{A_x}\right) + a_{12} * \left(\frac{A_{20}}{A_x}\right)^2$$

(3.13)

$$Cr_7 = C_7 + a_{13} * \left(\frac{B_{20}}{B_x}\right) + a_{14} * \left(\frac{B_{20}}{B_x}\right)^2$$

(3.14)

$$Cr_8 = C_8 + a_{15} * \left(\frac{T_{20}}{T_x}\right)$$

(3.15)

$$Cr_9 = C_9 + a_{16} * \left(\frac{A_0}{A_x}\right)$$

(3.16)

$$Cr_{10} = C_{10} + a_{17} * \frac{S}{(L * D)^{0.5}}$$

(3.17)

Where a_{1-17} are regression coefficients and C_{1-10} constants that when summed equal zero. Residuary resistance coefficient is obtained by summing the terms,

$$C_R = Cr_1 + Cr_2 + Cr_3 + Cr_4 + Cr_5 + Cr_6 + Cr_7 + Cr_8 + Cr_9 + Cr_{10}$$

(3.18)

Frictional resistance is then calculated by using the ITTC 1957 regulations. To clarify hull roughness, a standard value of 0.0004 is added to the fiction coefficient. Values for the regression coefficients and constants were not published, instead Fung provided tables of the residuary resistance components for each function of hull form over Froude number 0.18 to 0.68.

Equations for estimating T_{20}/T_x (transom-depth) ratio, wetted surface area and half angle of entrance at the early phases of the design are given.

Table 3.6 Range of Application (Fung Method) vs Design Space

	Fung Method Range	Design Space
$L/\nabla^{1/3}$	4.567 – 10.598	6.815 – 7.233
B/T	2.2 – 5.2	2.78 – 3.44
L/B	3 - 18	6.81 – 8.18
C_p	0.52 – 0.7	0.59 – 0.624

Resistance values of first 30 ships are given below. For the rest Appendix A might be checked.

Table 3.7 Resistance Values for First 30 Ships (18 knots)

	Fung Resistance [kN]	Nondimensionalized Resistance
Hull_000	363.3	0.919
Hull_001	351.3	0.888
Hull_002	353.4	0.894
Hull_003	348.1	0.880
Hull_004	340.6	0.861
Hull_005	344.4	0.871
Hull_006	343.2	0.868
Hull_007	358	0.905
Hull_008	357.4	0.904
Hull_009	359.5	0.909
Hull_010	363	0.918
Hull_011	363.4	0.919
Hull_012	362.8	0.917
Hull_013	353.9	0.895
Hull_014	357.3	0.903
Hull_015	356.8	0.902
Hull_016	374.3	0.946
Hull_017	374.1	0.946
Hull_018	375.3	0.949
Hull_019	376.4	0.952
Hull_020	373.2	0.944
Hull_021	375.5	0.949
Hull_022	365	0.923
Hull_023	368.7	0.932
Hull_024	369.2	0.934
Hull_025	387.9	0.981
Hull_026	388.8	0.983
Hull_027	377.3	0.954
Hull_028	363.8	0.920
Hull_029	362.1	0.916
Hull_030	361.1	0.913

Hull_000 indicates the base model and non-dimensionalization has been done according to maximum resistance value among all values.

Fung resistance values and experimental results are compared to each other for base model.

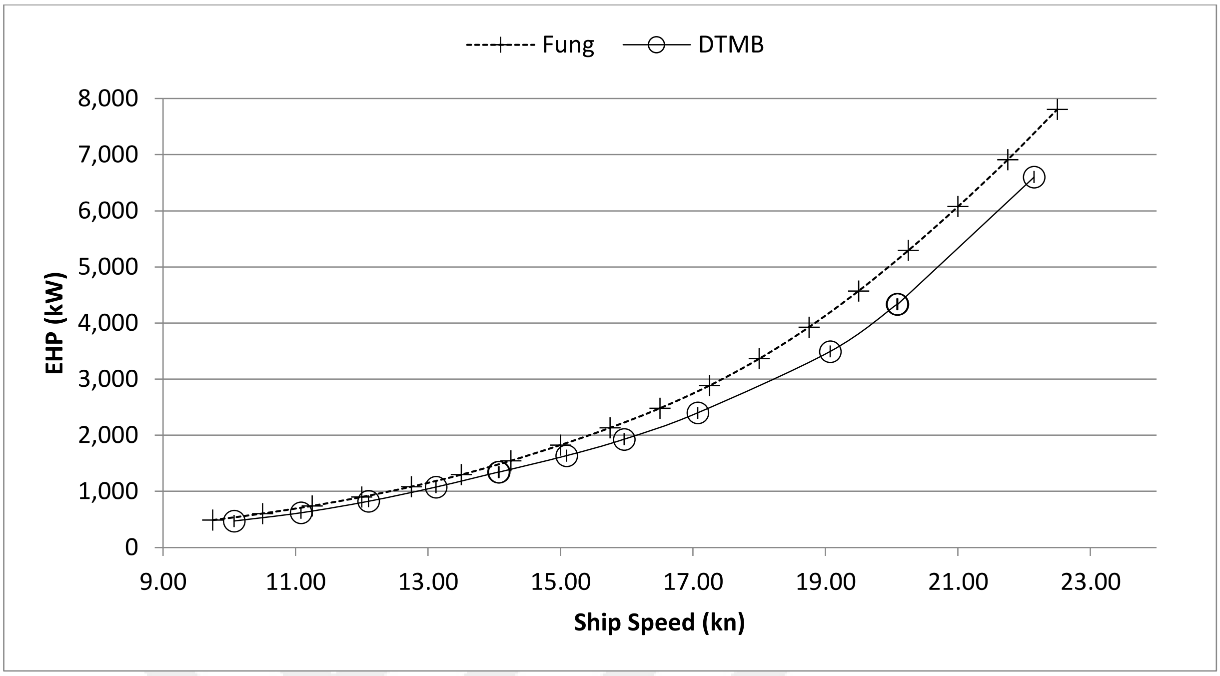


Figure 3.9 Model Experimental Results vs Fung Method

Fung method gives fairly good estimations for this ship type as seen in Figure 3.9.

3.4 Seakeeping Calculations

The seakeeping calculations required for this study are performed by strip theory based Maxsurf Motions. Given information below is mostly acquired from its user's manual [17].

Heave, pitch and roll motions are oscillating motions by reason of the restoring force. The motions of a ship could be thought as a forced damped-spring-mass system. The two related equations of pitch and heave motions are given below;

For heave:

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{35}\ddot{\eta}_5 + B_{35}\dot{\eta}_5 + C_{35}\eta_5 = F_3 e^{i\omega_e t} \tag{3.19}$$

And for pitch:

$$(I_5 + A_{55})\ddot{\eta_5} + B_{55}\dot{\eta_5} + C_{55}\eta_5 + A_{53}\ddot{\eta}_3 + B_{53}\dot{\eta}_3 + C_{53}\eta_3 = F_5 e^{i\omega_e t}$$

(3.20)

Where:

M mass of the vessel

I_5 moment of inertia for pitch

A_{33} added mass coefficient for heave due to heave

A_{55} added mass coefficient for pitch due to pitch

A_{53} added mass coefficient for pitch due to heave

A_{35} added mass coefficient for heave due to pitch

B_{33} damping coefficient for heave due to heave

B_{55} damping coefficient for pitch due to pitch

B_{53} damping coefficient for pitch due to heave

B_{35} damping coefficient for heave due to pitch

C_{33} hydrostatic restoring coefficient for heave due to heave

C_{55} hydrostatic restoring coefficient for pitch due to pitch

C_{53} hydrostatic restoring coefficient for pitch due to heave

C_{35} hydrostatic restoring coefficient for heave due to pitch

F_3 heave exciting force

F_5 pitch exciting force

η_3 instantaneous heave displacement

$\dot{\eta}_3$ instantaneous heave velocity

$\ddot{\eta}_3$ instantaneous heave acceleration

η_5 instantaneous pitch displacement

$\dot{\eta}_5$ instantaneous pitch velocity

$\ddot{\eta}_5$ instantaneous pitch acceleration

In order to figure out these equations it is a requirement to get excitation force-moment and the coefficients.

The coupled heave and pitch motions are solved by using the following method established by Bhattacharyya (1978):

$$P = C_{33} - (m + A_{33})\omega_e^2 + iB_{33}\omega_e \tag{3.21}$$

$$Q = C_{35} - A_{35}\omega_e^2 + iB_{35}\omega_e \tag{3.22}$$

$$R = C_{53} - A_{53}\omega_e^2 + iB_{53}\omega_e \tag{3.23}$$

$$S = C_{55} - (I_{55} + A_{55})\omega_e^2 + iB_{55}\omega_e \tag{3.24}$$

And heave response:

$$Z_3 = \frac{F_5 Q - F_3 S}{QR - PS} = Z_{30} e^{i\varepsilon_3} \tag{3.25}$$

Pitch response:

$$Z_5 = \frac{F_3 R - F_5 P}{QR - PS} = Z_{50} e^{i\varepsilon_5} \tag{3.26}$$

The pitch and heave motions are calculated by dividing the vessel into a number of cross sections and then taking into account the forces on each section. Therefore the two dimensional added mass, restoring force and damping coefficients are obtained for each section and later on the related global coefficients are calculated by integrating them throughout the hull length. The assumption is that the oscillation amplitude is adequately small to keep the vessel’s response linearly proportional to the wave amplitude.

The global damping and added mass are computed based on the method established by Salvesen (1970). The first formulation neglects the transom terms, while they are included in the second formulation. The coefficients are summarized below for both forms:

$$A_{33} = \int a_{33}\, d\xi \tag{3.27}$$

$$B_{33} = \int b_{33}\, d\xi \tag{3.28}$$

$$C_{33} = \rho g \int b\, d\xi \tag{3.29}$$

$$A_{35} = -\int \xi a_{33} d\xi - \frac{U}{\omega_e^2} B_{33} \tag{3.30}$$

$$B_{35} = -\int \xi b_{33} d\xi + U A_{33} \tag{3.31}$$

$$C_{35} = C_{53} = -\rho g \int \xi b d\xi \tag{3.32}$$

$$A_{53} = -\int \xi a_{33}\, d\xi + \frac{U}{\omega_e^2} B_{33} \tag{3.33}$$

$$B_{53} = -\int \xi b_{33} d\xi - U A_{33} \tag{3.34}$$

$$A_{55} = \int \xi^2 a_{33} d\xi + \frac{U^2}{\omega_e^2} A_{33}$$

(3.35)

$$B_{55} = \int \xi^2 b_{33} d\xi + \frac{U^2}{\omega_e^2} B_{33}$$

(3.36)

$$C_{55} = \rho g \int \xi^2 b d\xi$$

(3.37)

For the transom, the following terms are combined together with the coefficients given afore:

$$A_{33Trans} = -\frac{U}{\omega_e^2} b_{33}^A$$

(3.38)

$$B_{33Trans} = +U a_{33}^A$$

(3.39)

$$A_{35Trans} = +\frac{U}{\omega_e^2} x^A b_{33}^A - \frac{U^2}{\omega_e^2} a_{33}^A$$

(3.40)

$$B_{35Trans} = -U x^A a_{33}^A - \frac{U^2}{\omega_e^2} b_{33}^A$$

(3.41)

$$A_{53Trans} = +\frac{U}{\omega_e^2} x^A b_{33}^A$$

(3.42)

$$B_{53Trans} = -Ux^A a_{33}^A$$

(3.43)

$$A_{55Trans} = -\frac{U}{\omega_e^2}(x^A)^2 b_{33}^A + \frac{U^2}{\omega_e^2} x^A a_{33}^A$$

(3.44)

$$B_{55Trans} = +U(x^A)^2 a_{33}^A + \frac{U^2}{\omega_e^2} x^A b_{33}^A$$

(3.45)

Where the variables are defined as follows:

a_{33}	section added mass
a_{33}^A	added mass of transom section
b_{33}	section damping
b_{33}^A	damping of transom section
b	section beam
g	acceleration due to gravity
U	vessel forward velocity
x^A	x ordinate of transom (from center of gravity, negative aft)
ρ	fluid density
ω_e	wave enconter circular frequency
ξ	longitudinal distance from LCB

The wave excitation force and moment govern the vessel's motion. If the global force and moment are known, the coupled pitch and heave motions could be solved; yet, the forces have to be broken down into the sectional Froude-Krilov and diffraction forces to find out the wave induced shear force and bending moment. Several assumptions could be done to simplify these equations. Three methods are available today to evaluate the global wave excitation force and moment, which are:

- Arbitrary wave heading
- Head seas approximation
- Salvesen (1970)

Arbitrary wave heading approximation is evaluated in this study and only this method is explained below.

Arbitrary wave heading method is evaluated to calculate the forces (Froude-Krilov and Diffraction) for arbitrary wave angles.

The wave depth decrement term is calculated as:

$$wave\ depth\ attenuation = 1 - k \int \frac{y(z)}{y(0)} e^{-kz} dz$$

(3.46)

And the effective wave amplitude is given below:

$$\zeta^* = \zeta \left[1 - k \int \frac{y(z)}{y(0)} e^{-kz} dz \right]$$

(3.47)

It should be noted that $y(0)$ is the waterline half beam.

Added resistance is calculated by Salvesen method, according to below equation:

$$R_{AW} = \frac{ik}{2}\left(\eta_3 \widehat{F_3} + \eta_5 \widehat{F_5}\right) + R_7$$

(3.48)

Where

$$\widehat{F_3} = \zeta \int_L e^{-ik\xi} e^{-kz} \left[c(\xi) - \omega_0(\omega_e a_{33}(\xi) - ib_{33}(\xi))\right] d\xi$$

(3.49)

$$\widehat{F_5} = -\zeta \int_L e^{-ik\xi} e^{-kz} \left[c(\xi) - \omega_0 \left(\xi + \frac{iU}{\omega_e}\right)(\omega_e a_{33}(\xi) - ib_{33}(\xi))\right] d\xi$$

(3.50)

$$R_7 = \frac{\zeta^2 k \omega_0^2}{2\omega_e} \int_L e^{-2kz} b_{33}(\xi) d\xi$$

(3.51)

Note that η_3 and η_5 are the complex heave and pitch amplitudes.

Pierson Moskowitz sea spectrum with 24 knots wind speed has been selected during the analysis to define wave characteristics. More information about setup of the analysis is given in the below table.

Table 3.8 Seakeeping Calculation Parameters [8]

Sea Spectra	Pierson-Moskowitz
Heading Angle (for pitch motion)	180°
Heading Angle (for roll motion)	90°
Added Resistance Calculation Method	Salvesen
Wave Force Calculation Method	Arbitrary Wave Heading
VCG	7.54 m
Roll Gyradius	%40 Boa
Pitch Gyradius	%25 Loa
Yaw Gyradius	%25 Loa

The pitch and roll motions are evaluated during this process.

The analysis results are given for first 30 ships and base model below table. For rest of the results see APPENDIX B.

Table 3.9 Pitch and Roll Motion Results (First 30 Ships)

Pitch Acc. (rad/s^2)	Roll Acc. (rad/s^2)
0.02617	0.0654
0.03112	0.04646
0.03164	0.04498
0.03037	0.04876
0.0303	0.04531
0.0326	0.0437
0.03076	0.04798
0.03005	0.0481
0.03044	0.04444
0.02957	0.05357
0.02961	0.06824
0.02922	0.06368
0.02864	0.06978
0.02884	0.06527
0.03104	0.06239
0.02946	0.06834
0.02819	0.0703
0.02907	0.06829
0.02798	0.07578
0.0284	0.08889
0.02787	0.08556
0.02753	0.09049
0.02793	0.08552
0.02975	0.08332
0.02839	0.086
0.02739	0.09149
0.02785	0.08957
0.02796	0.06761
0.02958	0.06443
0.02878	0.0611
0.0284	0.06728
0.02865	0.06157

4. RESULTS AND DISCUSSION

After collecting all the data two-parameter and three-parameter optimizations are implemented. Pitch acceleration and resistance parameters are selected according to ship's characteristics for 2-paramater optimization. DTMB 5415 has a sonar at bow and the sonar should be stand still to function properly. So pitch motion should be minimized, first parameter for the optimization. Resistance can be selected as second parameter for most of the cases regardless the ship type and mission since minimizing it means either low fuel consumption or much more speed.

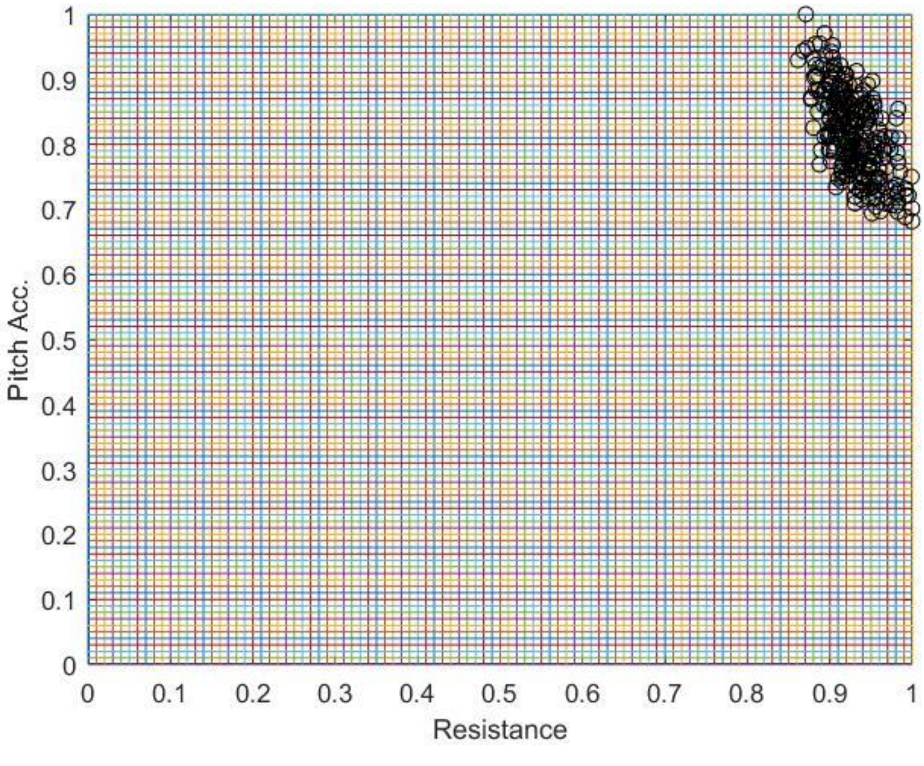


Figure 4.1 2-D Domain (Mesh Size: 0.01)

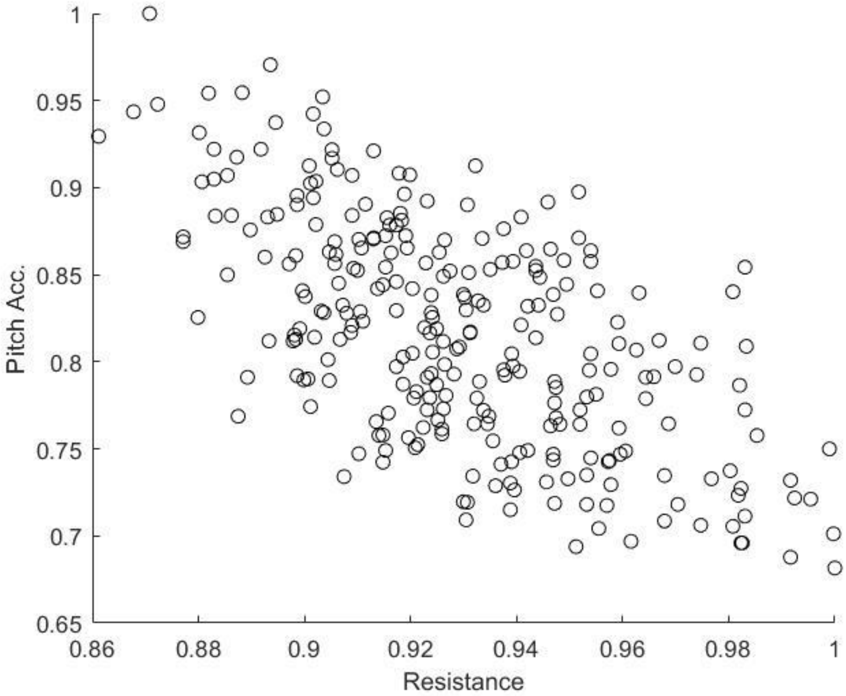


Figure 4.2 2-D Domain (Zoomed)

After applying the Pareto code which is generated before;

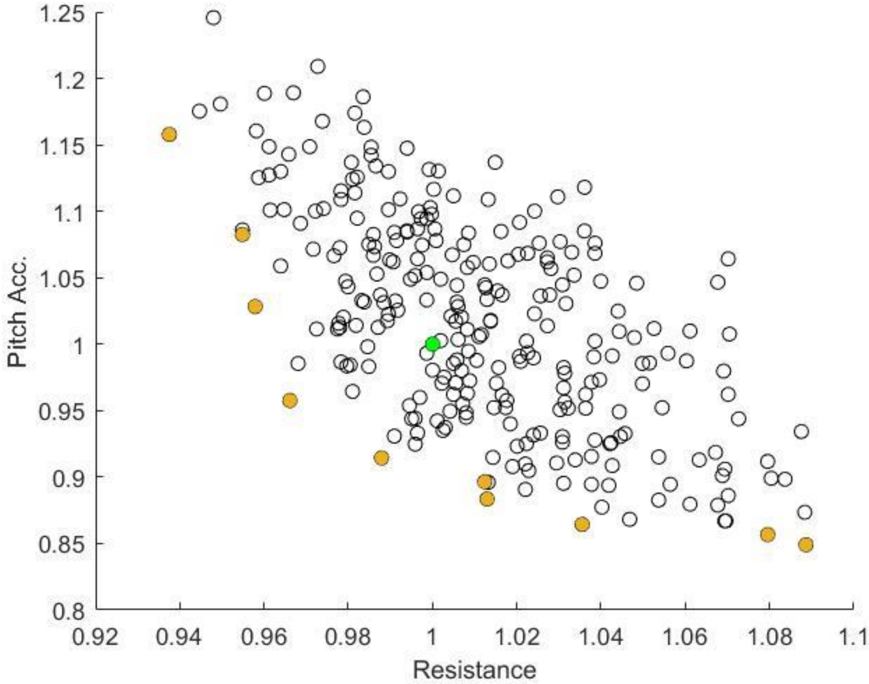


Figure 4.3 Pareto Front and Base Ship

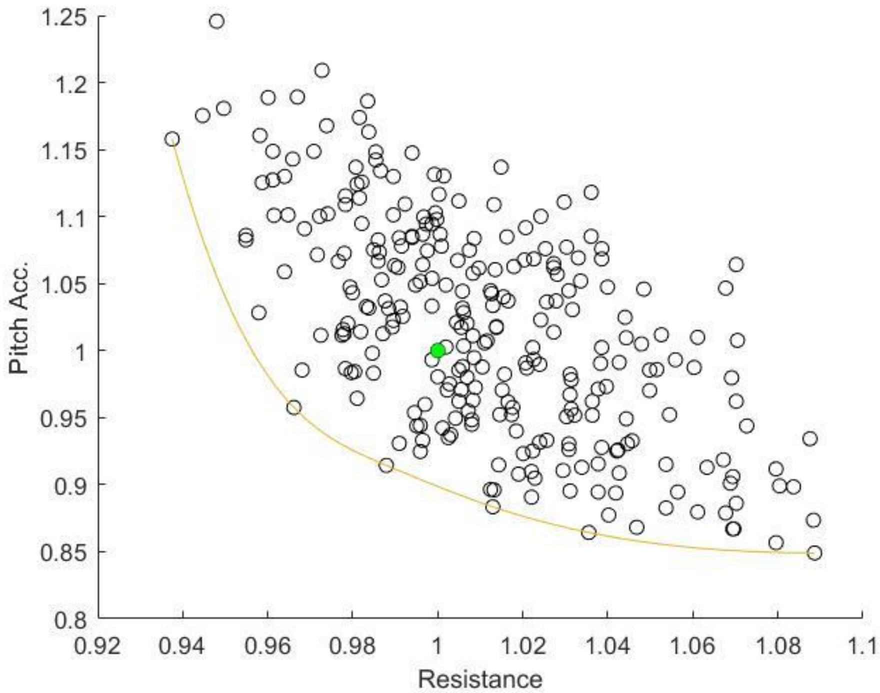


Figure 4.4 Pareto Front Curve

To populate the data at front can be provided by Adapted Weighted Sum or Normal Boundary Interaction methods to obtain a smoother front.

The green point indicates the base hull and hull numbers 4, 96, 177, 250, 252, 255, 261, 264, 267 and 270 form the 2-D Pareto front. Main particulars and details are shown in the below table.

Table 4.1 Pareto Front Ships (Two-parameter)

	L (m)	B (m)	D (m)	Cp	LCB	Resistance Improvement	Pitch Acc. Improvement
Hull_000	142.18	19.08	16.00	0.607	0.510	0	0
Hull_004	135.07	18.13	15.20	0.590	0.510	%6.2	-%15.8
Hull_096	139.81	18.50	15.73	0.590	0.500	%4.5	-%8.2
Hull_177	144.55	18.37	16.27	0.590	0.500	%4.2	-%2.8
Hull_250	148.34	19.85	16.69	0.624	0.510	-%8	%14.3
Hull_252	148.34	19.85	16.69	0.624	0.500	-%8.9	%15.1
Hull_255	148.82	18.93	16.75	0.607	0.500	-%1.2	%10.4
Hull_261	148.82	18.93	16.75	0.624	0.500	-%3.5	%13.6
Hull_264	149.29	18.25	16.80	0.607	0.500	%1.2	%8.6
Hull_267	149.29	18.25	16.80	0.590	0.500	%3.4	%4.2
Hull_270	149.29	18.25	16.80	0.624	0.500	-%1.3	%11.7

If it is considered that both parameters are equally weighted, then hull number 264 is the Pareto optimum design among 270 models for resistance and pitch acceleration values. It has %1.2 less resistance and %8.6 less pitch acceleration which could be considered as a great deal in shipbuilding industry.

When it comes to three-parameter optimization roll acceleration is added as the third parameter beside the first two. It is not a mandatory selection, any parameter other than roll acceleration can also be selected.

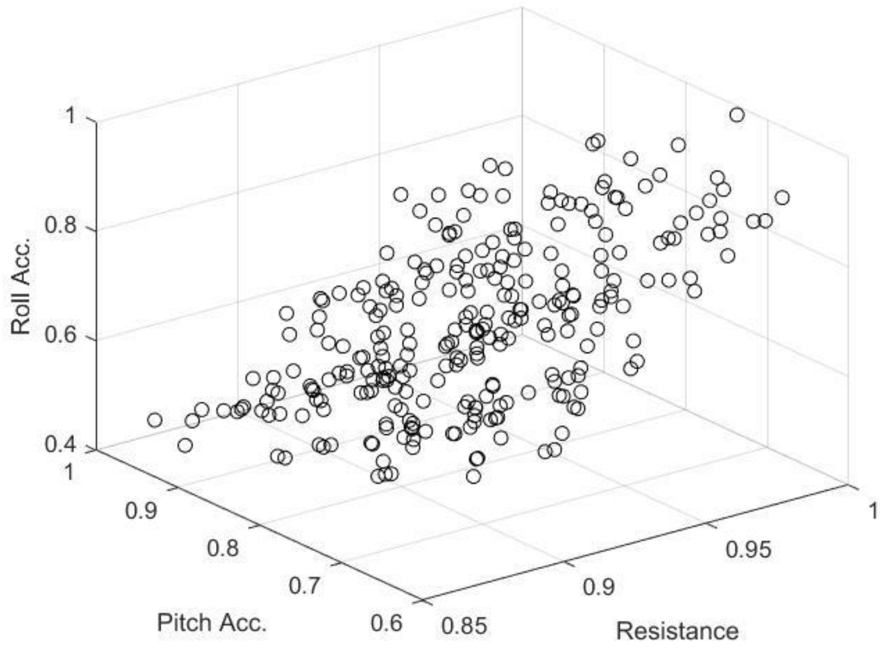


Figure 4.5 3-D Domain (Mesh Size: 0.01)

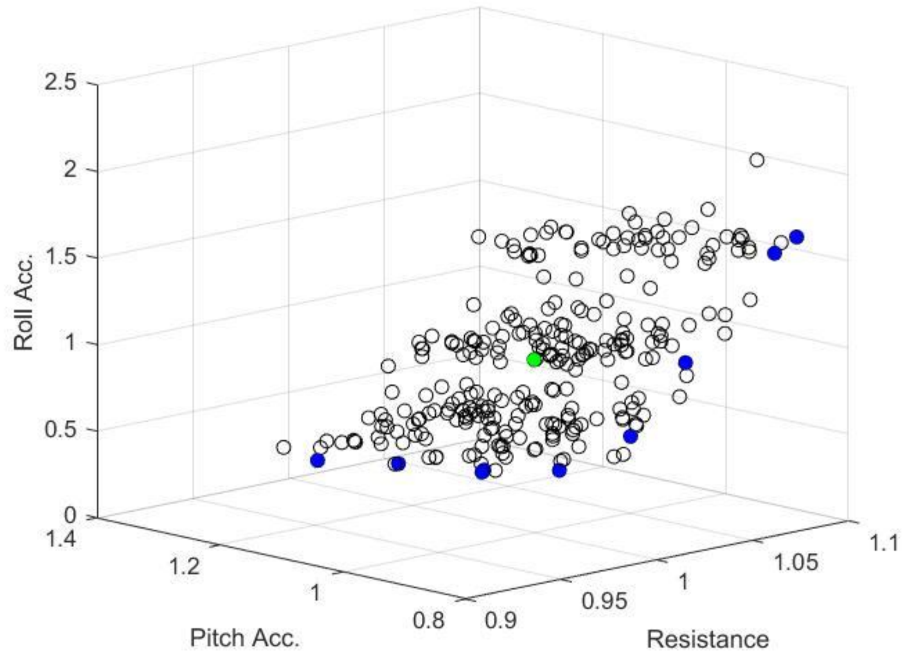


Figure 4.6 3-D Pareto Front and Base Model

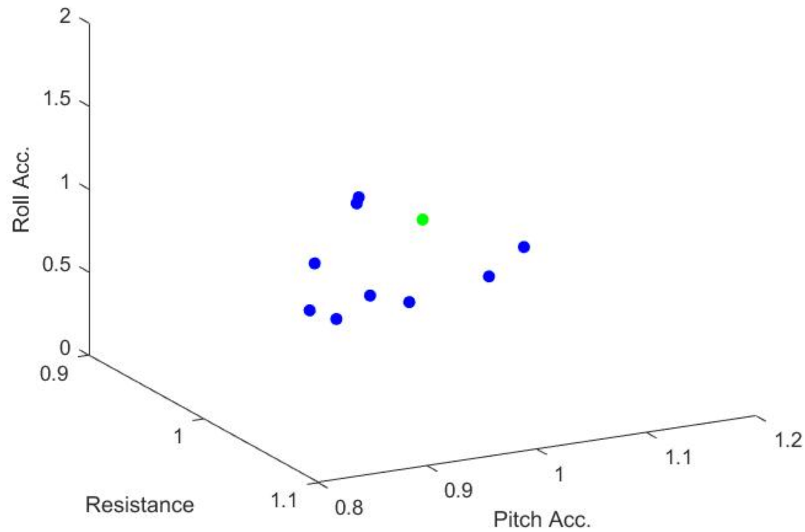


Figure 4.7 3-D Pareto Front and Base Model (Rest of the Domain Filtered)

In three-parameter optimization, Pareto front is expected to be a surface. In this case, surface generation with available data didn't give a good result. The reason behind that is being considered due to lack of design space data. With more models, this can be avoided.

According to results, hull numbers 4, 149, 250, 252, 261, 263, 265, 266 and 270 form the 3-D Pareto front. Some of them is also Pareto optimum for two-parameter, but not all. With the added parameter Pareto optimum ships are changed. Details are given in the below table.

Table 4.2 Pareto Front Ships (Three-parameter)

	L (m)	B (m)	D (m)	Cp	LCB	Resistance Improvement	Pitch Acc. Improvement	Roll Motion Improvement (Degrees)
Hull_000	142.18	19.08	16.00	0.607	0.510	0	0	0
Hull_004	135.07	18.13	15.20	0.590	0.510	%6.2	-%15.8	3.25
Hull_149	143.13	18.19	16.11	0.590	0.520	%4.5	-%8.2	3.41
Hull_250	148.34	19.85	16.69	0.624	0.510	-%8.0	%14.3	-3.15
Hull_252	148.34	19.85	16.69	0.624	0.500	-%8.9	%15.1	-3.61
Hull_261	148.82	18.93	16.75	0.624	0.500	-%3.5	%13.6	-0.05
Hull_263	149.29	18.25	16.80	0.607	0.520	-%3.5	%13.6	3.25
Hull_265	149.29	18.25	16.80	0.590	0.510	%1.2	%8.6	3.26
Hull_266	149.29	18.25	16.80	0.590	0.520	%3.4	%4.2	3.43
Hull_270	149.29	18.25	16.80	0.624	0.500	-%1.3	%11.7	2.19

Again, all three parameters are equally weighted and the hull number 265 is the Pareto optimum design among all. It has %1.2 less resistance, %8.6 less pitch motion acceleration and %56.6 less degrees of roll motion.

As a result of the both optimization processes, hull numbers 264 and 265 are obtained as Pareto optimum models. The comparison between each other is given at below table.

Table 4.3 Comparison between Main Particulars of Hull Number 264-265 and Base Model

	Hull_000	**Hull_264**	**Hull_265**
Length (m)	142.18	149.29	149.29
Beam (m)	19.08	18.25	18.25
Depth (m)	16	16.80	16.80
Draft (m)	6.15	6.33	6.49
C_p	0.607	0.607	0.59
LCB	%51	50%	51%
Δ (t)	8513	8791	8791

These two processes propose similar ships with little differences. Without roll motion parameter, hull number 264 is obtained as the Pareto optimum design and with added roll motion parameter, hull number 265 took its place. Hull number 264 has also %48.1 improvement on roll motion but 265 has a higher improvement.

5. CONCLUSION

Multi-criteria global optimization of a high speed naval vessel, DTMB 5415, by Pareto approach has been outlined in this study. The optimum main dimensions of this fictitious ship has been obtained by separately 2-parameter and 3-parameter optimization processes. A 270-ship design space is populated from a base model by Sobol set under some design constraints. Resistance and seakeeping analysis has been carried out and the data set which can be seen in APPENDIX A and APPENDIX B has been obtained. Since this is a minimization process, the location of utopia point has been determined as (0,0) in Cartesian coordinate plane. A MATLAB code which applies Pareto algorithm has been generated and optimization has been successfully done according to it.

For 2-parameter optimization, resistance and pitch acceleration values have been evaluated. As a result, Hull Number 264 has been obtained as the Pareto optimum design. Resistance value has decreased by %1.2 and pitch motion acceleration has improved by %8.6 compared to base model.

For 3-parameter optimization, roll motion has been introduced as the third parameter and this time a different model, Hull Number 265, has been obtained as the Pareto optimum design. This design has almost the same improvement for resistance and pitch motion if the results are rounded upwards to 3 decimal places. But Hull Number 265 has %56.6 less degrees of roll motion whereas Hull Number 264 has %48.1.

With regression analysis which can be considered as a traditional way to find main dimensions it is not likely possible to find optimum dimensions. These all show that Pareto approach can be a useful tool to use in preliminary ship design for beginning the design with the possible optimum main dimensions.

To uplift this study there are several additions can be implemented.

First of all, the design space might be populated even further. To do so, all the programs needed must be working in batch mode. Otherwise this causes significantly rise of potential human error and a loss of time.

Another addition might be changing parameter weights. In this study, all the parameters are thought to be equally weighted. This addition helps the designer to find the Pareto optimum main dimensions more specifically and gives more control to designer in optimization processes.

Pareto front generation process may involve Adapted Weighted Sum method or Normal Boundary Interaction method to obtain smoother and more populated front. But for this, all the programs have to work in batch mode as mentioned before.

Once Pareto front is obtained, GA might be applied and front data can be populated with crossing each other over to find even more optimized main dimensions.

The resistance and even seakeeping calculations might be carried out by higher fidelity solvers than Fung method and Maxsurf Motions module.

As a consequence, this study managed to find different optimum main dimensions for each single-objective, 2-objective and 3-objective optimization cases.

Further studies on this topic are going to be in progress with considering above additions and suggestions.

REFERENCES

[1] Wikipedia contributors. (2018, May 2). Pareto principle. In *Wikipedia, The Free Encyclopedia*. Retrieved 08:22, May 8, 2018, from https://en.wikipedia.org/w/index.php?title=Pareto_principle&oldid=839300274

[2] 'Ship design process', available in MarineWiki at URL: http://www.marinewiki.org/index.php/SHIP_DESIGN_PROCESS, accessed 20 July 2015.

[3] Kiranyaz, S.; Ince, T.; Gabbouj, M., Multi Dimensional Particle Swarm Optimization for Machine Learning and Pattern Recognition, 2014

[4] Na, S.-S., & Karr, D. (2016). Development of Pareto strategy multi-objective function method for the optimum design of ship structures. South Korea: Elsevier

[5] Augusto, O. B., Bennis, F., & Caro, S. (2012). Approach, Multiobjective Engineering Desig Optimzation Problems a Sensitivity Analysis. Pesquisa Operational, 575-596.

[6] Çalışal, S. (n.d.). Fuel or Acceleration a Pareto Design Procedures for Ships. Turkey, Canada.

[7] Rigo,Ph., Caprace, J-D, Optimization of Ship Structures

[8] Diez, M., Serani , A., Campana, E., Gören , Ö., Danışman , D., Grigoropulus, G., et al. (2015). Multi-objective hydrodynamic optimization of the DTMB 5415 for resistance and seakeeping.

[9] Prifitis, A., Papanikolaou, A., & Plessas, T. (2016). Parametric Deisgn & Multi-Objective Optimization of Containerships. Jornal of Ship Production and Design.

[10] Turan, O., Mizzi, K., Demirel, Y. K., Banks, C., Atlar , M., & Kaklis , P. (2016). Design Optimization of Propeller Boss Cap Fins for Enhanced Propeller Performance. Glasgow, UK.

[11] Esmailian , E., Ghassemi, H., & Zakerdoost, H. (2017). Systematic Probabilistic Design Methodology for Simultaneously Optimizing the Ship Hull-Propeller System. International Journal of Naval Architecture and Ocean Engineering, 9, 246-255.

[12] Fassardi , C. D., & Hochkirch, K. (February, 2006). Sailboat Design by Response Surface Optimzation. 2nd High Perfomance Yacht Design Cpnference. Auckland.

[13] Kasprzak, E.M.,& Lewis, K.E., Pareto Analysis in Multi Objective Optimization Using the Colinearity Theorem and Scaling Method.

[14] Bratley, P.,& Fox, B.L., Algorithm 659 Implementing Sobol's Quasirandom Sequence Generator.

[15] R. BECK, A.R., 'Modern seakeeping computations for ships', 23rd Symposium on Naval Hydrodynamics, 2001.

[16] Moody, R.D. (November,1996), Preliminary Power Prediction During Early Design Stages of a Ship.

[17] Bentley Systems (2013), Maxsurf Motions User Manual, Windows Version 20

APPENDICES

APPENDIX A: DESIGN SPACE

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
0	142,18	19,08	16,00	8513	0,607	51%	6,150
1	135,07	18,13	15,20	7785	0,607	51%	6,278
2	135,07	18,13	15,20	7785	0,607	52%	6,234
3	135,07	18,13	15,20	7785	0,607	50%	6,235
4	135,07	18,13	15,20	7785	0,59	51%	6,414
5	135,07	18,13	15,20	7785	0,59	52%	6,340
6	135,07	18,13	15,20	7785	0,59	50%	6,327
7	135,07	18,13	15,20	7785	0,624	51%	6,065
8	135,07	18,13	15,20	7785	0,624	52%	6,000
9	135,07	18,13	15,20	7785	0,624	50%	6,098
10	135,54	19,17	15,25	8070	0,607	51%	6,086
11	135,54	19,17	15,25	8070	0,607	52%	6,061
12	135,54	19,17	15,25	8070	0,607	50%	6,091
13	135,54	19,17	15,25	8070	0,59	51%	6,266
14	135,54	19,17	15,25	8070	0,59	52%	6,202
15	135,54	19,17	15,25	8070	0,59	50%	6,193
16	135,54	19,17	15,25	8070	0,624	51%	5,925
17	135,54	19,17	15,25	8070	0,624	52%	5,921
18	135,54	19,17	15,25	8070	0,624	50%	5,925
19	136,02	19,97	15,31	8299	0,607	51%	5,971
20	136,02	19,97	15,31	8299	0,607	52%	6,031
21	136,02	19,97	15,31	8299	0,607	50%	5,992
22	136,02	19,97	15,31	8299	0,59	51%	6,164
23	136,02	19,97	15,31	8299	0,59	52%	6,101
24	136,02	19,97	15,31	8299	0,59	50%	6,185
25	136,02	19,97	15,31	8299	0,624	51%	5,828
26	136,02	19,97	15,31	8299	0,624	52%	5,804
27	136,02	19,97	15,31	8299	0,624	50%	6,127
28	136,49	19,05	15,36	8105	0,607	51%	6,169
29	136,49	19,05	15,36	8105	0,607	52%	6,102
30	136,49	19,05	15,36	8105	0,607	50%	6,123

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
31	136,49	19,05	15,36	8105	0,59	51%	6,289
32	136,49	19,05	15,36	8105	0,59	52%	6,215
33	136,49	19,05	15,36	8105	0,59	50%	6,219
34	136,49	19,05	15,36	8105	0,624	51%	5,946
35	136,49	19,05	15,36	8105	0,624	52%	5,944
36	136,49	19,05	15,36	8105	0,624	50%	5,947
37	136,97	19,36	15,41	8214	0,607	51%	6,074
38	136,97	19,36	15,41	8214	0,607	52%	6,069
39	136,97	19,36	15,41	8214	0,607	50%	6,079
40	136,97	19,36	15,41	8214	0,59	51%	6,224
41	136,97	19,36	15,41	8214	0,59	52%	6,178
42	136,97	19,36	15,41	8214	0,59	50%	6,295
43	136,97	19,36	15,41	8214	0,624	51%	5,909
44	136,97	19,36	15,41	8214	0,624	52%	5,904
45	136,97	19,36	15,41	8214	0,624	50%	5,967
46	137,44	18,43	15,47	8016	0,607	51%	6,250
47	137,44	18,43	15,47	8016	0,607	52%	6,257
48	137,44	18,43	15,47	8016	0,607	50%	6,207
49	137,44	18,43	15,47	8016	0,59	51%	6,385
50	137,44	18,43	15,47	8016	0,59	52%	6,418
51	137,44	18,43	15,47	8016	0,59	50%	6,379
52	137,44	18,43	15,47	8016	0,624	51%	6,037
53	137,44	18,43	15,47	8016	0,624	52%	6,032
54	137,44	18,43	15,47	8016	0,624	50%	6,037
55	137,91	18,74	15,52	8126	0,607	51%	6,217
56	137,91	18,74	15,52	8126	0,607	52%	6,212
57	137,91	18,74	15,52	8126	0,607	50%	6,168
58	137,91	18,74	15,52	8126	0,59	51%	6,344
59	137,91	18,74	15,52	8126	0,59	52%	6,359
60	137,91	18,74	15,52	8126	0,59	50%	6,304

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
61	137,91	18,74	15,52	8126	0,624	51%	5,998
62	137,91	18,74	15,52	8126	0,624	52%	6,045
63	137,91	18,74	15,52	8126	0,624	50%	5,997
64	138,39	19,79	15,57	8424	0,607	51%	6,012
65	138,39	19,79	15,57	8424	0,607	52%	6,064
66	138,39	19,79	15,57	8424	0,607	50%	6,032
67	138,39	19,79	15,57	8424	0,59	51%	6,206
68	138,39	19,79	15,57	8424	0,59	52%	6,221
69	138,39	19,79	15,57	8424	0,59	50%	6,251
70	138,39	19,79	15,57	8424	0,624	51%	5,868
71	138,39	19,79	15,57	8424	0,624	52%	5,810
72	138,39	19,79	15,57	8424	0,624	50%	5,918
73	138,86	19,60	15,63	8411	0,607	51%	6,113
74	138,86	19,60	15,63	8411	0,607	52%	6,111
75	138,86	19,60	15,63	8411	0,607	50%	6,061
76	138,86	19,60	15,63	8411	0,59	51%	6,214
77	138,86	19,60	15,63	8411	0,59	52%	6,260
78	138,86	19,60	15,63	8411	0,59	50%	6,292
79	138,86	19,60	15,63	8411	0,624	51%	5,895
80	138,86	19,60	15,63	8411	0,624	52%	5,894
81	138,86	19,60	15,63	8411	0,624	50%	5,895
82	139,34	18,68	15,68	8208	0,607	51%	6,159
83	139,34	18,68	15,68	8208	0,607	52%	6,180
84	139,34	18,68	15,68	8208	0,607	50%	6,188
85	139,34	18,68	15,68	8208	0,59	51%	6,341
86	139,34	18,68	15,68	8208	0,59	52%	6,405
87	139,34	18,68	15,68	8208	0,59	50%	6,409
88	139,34	18,68	15,68	8208	0,624	51%	6,016
89	139,34	18,68	15,68	8208	0,624	52%	6,060
90	139,34	18,68	15,68	8208	0,624	50%	6,016

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
91	139,81	18,50	15,73	8193	0,607	51%	6,263
92	139,81	18,50	15,73	8193	0,607	52%	6,198
93	139,81	18,50	15,73	8193	0,607	50%	6,211
94	139,81	18,50	15,73	8193	0,59	51%	6,369
95	139,81	18,50	15,73	8193	0,59	52%	6,428
96	139,81	18,50	15,73	8193	0,59	50%	6,471
97	139,81	18,50	15,73	8193	0,624	51%	6,043
98	139,81	18,50	15,73	8193	0,624	52%	6,024
99	139,81	18,50	15,73	8193	0,624	50%	6,043
100	140,28	19,54	15,79	8498	0,607	51%	6,130
101	140,28	19,54	15,79	8498	0,607	52%	6,060
102	140,28	19,54	15,79	8498	0,607	50%	6,080
103	140,28	19,54	15,79	8498	0,59	51%	6,228
104	140,28	19,54	15,79	8498	0,59	52%	6,281
105	140,28	19,54	15,79	8498	0,59	50%	6,216
106	140,28	19,54	15,79	8498	0,624	51%	5,914
107	140,28	19,54	15,79	8498	0,624	52%	5,902
108	140,28	19,54	15,79	8498	0,624	50%	5,967
109	140,76	18,86	15,84	8355	0,607	51%	6,149
110	140,76	18,86	15,84	8355	0,607	52%	6,152
111	140,76	18,86	15,84	8355	0,607	50%	6,258
112	140,76	18,86	15,84	8355	0,59	51%	6,307
113	140,76	18,86	15,84	8355	0,59	52%	6,378
114	140,76	18,86	15,84	8355	0,59	50%	6,404
115	140,76	18,86	15,84	8355	0,624	51%	6,004
116	140,76	18,86	15,84	8355	0,624	52%	5,984
117	140,76	18,86	15,84	8355	0,624	50%	6,004
118	141,23	19,91	15,89	8665	0,607	51%	6,093
119	141,23	19,91	15,89	8665	0,607	52%	6,033
120	141,23	19,91	15,89	8665	0,607	50%	6,043

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
121	141,23	19,91	15,89	8665	0,59	51%	6,195
122	141,23	19,91	15,89	8665	0,59	52%	6,264
123	141,23	19,91	15,89	8665	0,59	50%	6,271
124	141,23	19,91	15,89	8665	0,624	51%	5,879
125	141,23	19,91	15,89	8665	0,624	52%	5,872
126	141,23	19,91	15,89	8665	0,624	50%	5,878
127	141,71	19,23	15,95	8520	0,607	51%	6,182
128	141,71	19,23	15,95	8520	0,607	52%	6,121
129	141,71	19,23	15,95	8520	0,607	50%	6,131
130	141,71	19,23	15,95	8520	0,59	51%	6,276
131	141,71	19,23	15,95	8520	0,59	52%	6,355
132	141,71	19,23	15,95	8520	0,59	50%	6,362
133	141,71	19,23	15,95	8520	0,624	51%	5,964
134	141,71	19,23	15,95	8520	0,624	52%	6,003
135	141,71	19,23	15,95	8520	0,624	50%	6,014
136	142,65	19,11	16,05	8555	0,607	51%	6,206
137	142,65	19,11	16,05	8555	0,607	52%	6,144
138	142,65	19,11	16,05	8555	0,607	50%	6,164
139	142,65	19,11	16,05	8555	0,59	51%	6,300
140	142,65	19,11	16,05	8555	0,59	52%	6,379
141	142,65	19,11	16,05	8555	0,59	50%	6,385
142	142,65	19,11	16,05	8555	0,624	51%	5,987
143	142,65	19,11	16,05	8555	0,624	52%	6,038
144	142,65	19,11	16,05	8555	0,624	50%	5,987
145	143,13	18,19	16,11	8339	0,607	51%	6,333
146	143,13	18,19	16,11	8339	0,607	52%	6,332
147	143,13	18,19	16,11	8339	0,607	50%	6,281
148	143,13	18,19	16,11	8339	0,59	51%	6,440
149	143,13	18,19	16,11	8339	0,59	52%	6,512
150	143,13	18,19	16,11	8339	0,59	50%	6,529

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
151	143,13	18,19	16,11	8339	0,624	51%	6,110
152	143,13	18,19	16,11	8339	0,624	52%	6,161
153	143,13	18,19	16,11	8339	0,624	50%	6,164
154	143,60	18,99	16,16	8590	0,607	51%	6,229
155	143,60	18,99	16,16	8590	0,607	52%	6,168
156	143,60	18,99	16,16	8590	0,607	50%	6,188
157	143,60	18,99	16,16	8590	0,59	51%	6,329
158	143,60	18,99	16,16	8590	0,59	52%	6,392
159	143,60	18,99	16,16	8590	0,59	50%	6,421
160	143,60	18,99	16,16	8590	0,624	51%	6,009
161	143,60	18,99	16,16	8590	0,624	52%	6,004
162	143,60	18,99	16,16	8590	0,624	50%	6,399
163	144,08	20,03	16,21	8912	0,607	51%	6,106
164	144,08	20,03	16,21	8912	0,607	52%	6,031
165	144,08	20,03	16,21	8912	0,607	50%	6,066
166	144,08	20,03	16,21	8912	0,59	51%	6,210
167	144,08	20,03	16,21	8912	0,59	52%	6,287
168	144,08	20,03	16,21	8912	0,59	50%	6,284
169	144,08	20,03	16,21	8912	0,624	51%	5,891
170	144,08	20,03	16,21	8912	0,624	52%	5,930
171	144,08	20,03	16,21	8912	0,624	50%	5,883
172	144,55	18,37	16,27	8489	0,607	51%	6,322
173	144,55	18,37	16,27	8489	0,607	52%	6,259
174	144,55	18,37	16,27	8489	0,607	50%	6,280
175	144,55	18,37	16,27	8489	0,59	51%	6,429
176	144,55	18,37	16,27	8489	0,59	52%	6,488
177	144,55	18,37	16,27	8489	0,59	50%	6,505
178	144,55	18,37	16,27	8489	0,624	51%	6,099
179	144,55	18,37	16,27	8489	0,624	52%	6,108
180	144,55	18,37	16,27	8489	0,624	50%	6,099

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
181	145,02	19,42	16,32	8814	0,607	51%	6,188
182	145,02	19,42	16,32	8814	0,607	52%	5,896
183	145,02	19,42	16,32	8814	0,607	50%	6,137
184	145,02	19,42	16,32	8814	0,59	51%	6,293
185	145,02	19,42	16,32	8814	0,59	52%	6,267
186	145,02	19,42	16,32	8814	0,59	50%	6,365
187	145,02	19,42	16,32	8814	0,624	51%	5,970
188	145,02	19,42	16,32	8814	0,624	52%	5,951
189	145,02	19,42	16,32	8814	0,624	50%	6,016
190	145,50	19,73	16,37	8935	0,607	51%	6,155
191	145,50	19,73	16,37	8935	0,607	52%	6,154
192	145,50	19,73	16,37	8935	0,607	50%	6,104
193	145,50	19,73	16,37	8935	0,59	51%	6,248
194	145,50	19,73	16,37	8935	0,59	52%	6,231
195	145,50	19,73	16,37	8935	0,59	50%	6,333
196	145,50	19,73	16,37	8935	0,624	51%	5,938
197	145,50	19,73	16,37	8935	0,624	52%	5,933
198	145,50	19,73	16,37	8935	0,624	50%	5,937
199	145,97	18,80	16,43	8711	0,607	51%	6,277
200	145,97	18,80	16,43	8711	0,607	52%	6,276
201	145,97	18,80	16,43	8711	0,607	50%	6,225
202	145,97	18,80	16,43	8711	0,59	51%	6,383
203	145,97	18,80	16,43	8711	0,59	52%	6,452
204	145,97	18,80	16,43	8711	0,59	50%	6,459
205	145,97	18,80	16,43	8711	0,624	51%	6,046
206	145,97	18,80	16,43	8711	0,624	52%	6,100
207	145,97	18,80	16,43	8711	0,624	50%	6,055
208	146,45	18,62	16,48	8693	0,607	51%	6,304
209	146,45	18,62	16,48	8693	0,607	52%	6,247
210	146,45	18,62	16,48	8693	0,607	50%	6,252

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
211	146,45	18,62	16,48	8693	0,59	51%	6,399
212	146,45	18,62	16,48	8693	0,59	52%	6,483
213	146,45	18,62	16,48	8693	0,59	50%	6,487
214	146,45	18,62	16,48	8693	0,624	51%	6,081
215	146,45	18,62	16,48	8693	0,624	52%	6,126
216	146,45	18,62	16,48	8693	0,624	50%	6,081
217	146,92	19,66	16,53	9026	0,607	51%	6,179
218	146,92	19,66	16,53	9026	0,607	52%	6,179
219	146,92	19,66	16,53	9026	0,607	50%	6,128
220	146,92	19,66	16,53	9026	0,59	51%	6,273
221	146,92	19,66	16,53	9026	0,59	52%	6,352
222	146,92	19,66	16,53	9026	0,59	50%	6,359
223	146,92	19,66	16,53	9026	0,624	51%	5,961
224	146,92	19,66	16,53	9026	0,624	52%	5,946
225	146,92	19,66	16,53	9026	0,624	50%	5,963
226	147,39	19,48	16,59	9010	0,607	51%	6,205
227	147,39	19,48	16,59	9010	0,607	52%	6,142
228	147,39	19,48	16,59	9010	0,607	50%	6,154
229	147,39	19,48	16,59	9010	0,59	51%	6,310
230	147,39	19,48	16,59	9010	0,59	52%	6,379
231	147,39	19,48	16,59	9010	0,59	50%	6,386
232	147,39	19,48	16,59	9010	0,624	51%	5,986
233	147,39	19,48	16,59	9010	0,624	52%	6,025
234	147,39	19,48	16,59	9010	0,624	50%	5,986
235	147,87	18,56	16,64	8778	0,607	51%	6,324
236	147,87	18,56	16,64	8778	0,607	52%	6,325
237	147,87	18,56	16,64	8778	0,607	50%	6,272
238	147,87	18,56	16,64	8778	0,59	51%	6,431
239	147,87	18,56	16,64	8778	0,59	52%	6,589
240	147,87	18,56	16,64	8778	0,59	50%	6,508

Hull No	L (m)	B (m)	D (m)	Displacement	CP	LCB	T (m)
241	147,87	18,56	16,64	8778	0,624	51%	6,102
242	147,87	18,56	16,64	8778	0,624	52%	6,146
243	147,87	18,56	16,64	8778	0,624	50%	6,103
244	148,34	19,85	16,69	9189	0,607	51%	6,168
245	148,34	19,85	16,69	9189	0,607	52%	6,171
246	148,34	19,85	16,69	9189	0,607	50%	6,130
247	148,34	19,85	16,69	9189	0,59	51%	6,275
248	148,34	19,85	16,69	9189	0,59	52%	6,348
249	148,34	19,85	16,69	9189	0,59	50%	6,350
250	148,34	19,85	16,69	9189	0,624	51%	5,950
251	148,34	19,85	16,69	9189	0,624	52%	5,992
252	148,34	19,85	16,69	9189	0,624	50%	6,006
253	148,82	18,93	16,75	8956	0,607	51%	6,288
254	148,82	18,93	16,75	8956	0,607	52%	6,229
255	148,82	18,93	16,75	8956	0,607	50%	6,234
256	148,82	18,93	16,75	8956	0,59	51%	6,381
257	148,82	18,93	16,75	8956	0,59	52%	6,458
258	148,82	18,93	16,75	8956	0,59	50%	6,468
259	148,82	18,93	16,75	8956	0,624	51%	6,065
260	148,82	18,93	16,75	8956	0,624	52%	6,044
261	148,82	18,93	16,75	8956	0,624	50%	5,999
262	149,29	18,25	16,80	8791	0,607	51%	6,380
263	149,29	18,25	16,80	8791	0,607	52%	6,320
264	149,29	18,25	16,80	8791	0,607	50%	6,328
265	149,29	18,25	16,80	8791	0,59	51%	6,488
266	149,29	18,25	16,80	8791	0,59	52%	6,573
267	149,29	18,25	16,80	8791	0,59	50%	6,566
268	149,29	18,25	16,80	8791	0,624	51%	6,155
269	149,29	18,25	16,80	8791	0,624	52%	6,141
270	149,29	18,25	16,80	8791	0,624	50%	6,159

APPENDIX B: RESISTANCE CALCULATIONS

18 knots				18 knots		
Hull Number	Fung Resistance [kN]	Fung Power [kW]		Hull Number	Fung Resistance [kN]	Fung Power [kW]
Hull_031	356.8	3304.131		Hull_061	368.2	3409.577
Hull_032	356.6	3302.378		Hull_062	370.8	3433.193
Hull_033	355.4	3290.546		Hull_063	368.9	3416.445
Hull_034	372.5	3449.616		Hull_064	374.5	3468.05
Hull_035	372.1	3445.521		Hull_065	374.8	3470.507
Hull_036	373.5	3458.662		Hull_066	368	3407.737
Hull_037	366	3389.574		Hull_067	363.2	3363.5
Hull_038	366.4	3393.272		Hull_068	368.1	3408.371
Hull_039	366.8	3396.645		Hull_069	366.3	3391.728
Hull_040	358	3314.964		Hull_070	385.5	3569.857
Hull_041	361.1	3343.419		Hull_071	379.3	3512.151
Hull_042	359.5	3329.034		Hull_072	388.9	3601.116
Hull_043	377.8	3498.725		Hull_073	373.2	3456.139
Hull_044	377.3	3493.84		Hull_074	372.6	3450.553
Hull_045	380.9	3526.806		Hull_075	365.5	3384.846
Hull_046	356.3	3299.284		Hull_076	362.3	3354.887
Hull_047	355.4	3290.758		Hull_077	365.1	3381.25
Hull_048	353.2	3270.748		Hull_078	364	3370.78
Hull_049	345	3194.579		Hull_079	382.4	3540.622
Hull_050	348.8	3229.899		Hull_080	376.4	3485.584
Hull_051	349.2	3233.414		Hull_081	383.6	3551.872
Hull_052	363.6	3366.705		Hull_082	358.3	3318.042
Hull_053	363.1	3362.063		Hull_083	358.2	3316.695
Hull_054	362	3351.735		Hull_084	358.4	3318.441
Hull_055	360.5	3338.301		Hull_085	350.2	3242.98
Hull_056	360	3333.359		Hull_086	352.7	3265.895
Hull_057	357.8	3313.024		Hull_087	351.9	3258.419
Hull_058	349.2	3233.982		Hull_088	367.9	3406.562
Hull_059	353.8	3276.1		Hull_089	370.7	3432.354
Hull_060	350.5	3245.224		Hull_090	368.3	3410.832

18 knots				18 knots		
Hull Number	Fung Resistance [kN]	Fung Power [kW]		Hull Number	Fung Resistance [kN]	Fung Power [kW]
Hull_091	358.2	3317.221		Hull_121	367.8	3405.821
Hull_092	356.4	3300.399		Hull_122	369.8	3424.386
Hull_093	355.8	3294.719		Hull_123	364.9	3378.524
Hull_094	348.3	3225.025		Hull_124	388.8	3600.59
Hull_095	350.9	3249.795		Hull_125	388.4	3596.282
Hull_096	346.9	3211.874		Hull_126	389.7	3608.869
Hull_097	365.4	3383.153		Hull_127	369.3	3419.6
Hull_098	361.4	3346.548		Hull_128	367.5	3403.017
Hull_099	365.8	3386.845		Hull_129	367.1	3399.166
Hull_100	373.4	3457.405		Hull_130	359.6	3329.506
Hull_101	371.5	3440.31		Hull_131	361.1	3343.45
Hull_102	365.5	3384.836		Hull_132	360.1	3334.88
Hull_103	362.4	3355.461		Hull_133	377.7	3497.836
Hull_104	363.5	3365.744		Hull_134	380.7	3525.207
Hull_105	362.8	3359.793		Hull_135	381.4	3531.308
Hull_106	382	3537.125		Hull_136	368.3	3410.497
Hull_107	377.3	3493.471		Hull_137	366.4	3392.802
Hull_108	385.2	3566.846		Hull_138	365.8	3387.116
Hull_109	361.8	3350.216		Hull_139	358.5	3319.83
Hull_110	362	3352.382		Hull_140	360.2	3335.377
Hull_111	358.8	3322.379		Hull_141	359.5	3328.873
Hull_112	355.3	3290.404		Hull_142	376.5	3486.569
Hull_113	356.6	3301.667		Hull_143	378.8	3507.794
Hull_114	354.8	3285.289		Hull_144	368.6	3413.592
Hull_115	371.4	3439.586		Hull_145	356	3296.955
Hull_116	372.1	3445.996		Hull_146	355.6	3292.97
Hull_117	372	3445.035		Hull_147	353.3	3271.163
Hull_118	379.4	3512.902		Hull_148	346.9	3211.864
Hull_119	377.2	3492.744		Hull_149	349.3	3234.655
Hull_120	377	3491.275		Hull_150	362.8	3359.102

18 knots				18 knots		
Hull Number	Fung Resistance [kN]	Fung Power [kW]		Hull Number	Fung Resistance [kN]	Fung Power [kW]
Hull_181	374.6	3468.544		Hull_211	355.3	3290.064
Hull_182	366.2	3390.77		Hull_212	357.2	3307.938
Hull_183	372	3444.352		Hull_213	355.9	3295.611
Hull_184	364	3370.378		Hull_214	371.4	3438.943
Hull_185	366.3	3391.828		Hull_215	374.3	3465.981
Hull_186	365.3	3382.759		Hull_216	371.3	3438.012
Hull_187	382.8	3544.627		Hull_217	379.5	3514.292
Hull_188	378.6	3505.812		Hull_218	378.8	3508.019
Hull_189	386.3	3577.053		Hull_219	377	3490.805
Hull_190	379.4	3513.385		Hull_220	369.3	3419.75
Hull_191	378.7	3506.815		Hull_221	370.9	3434.61
Hull_192	377	3490.947		Hull_222	370	3426.11
Hull_193	369	3416.912		Hull_223	387.9	3592.043
Hull_194	370.8	3433.891		Hull_224	392.5	3634.137
Hull_195	369.7	3423.636		Hull_225	388.6	3598.007
Hull_196	388.3	3595.995		Hull_226	377.3	3494.033
Hull_197	387.7	3589.911		Hull_227	375.6	3477.882
Hull_198	388.8	3600.664		Hull_228	374.6	3468.779
Hull_199	366.5	3393.832		Hull_229	365.1	3381.034
Hull_200	365.9	3388.673		Hull_230	374.6	3468.779
Hull_201	363.7	3368.221		Hull_231	364.4	3374.478
Hull_202	356.7	3303.232		Hull_232	385.5	3570.147
Hull_203	359.1	3324.918		Hull_233	388.5	3597.114
Hull_204	357.8	3313.424		Hull_234	388.5	3597.115
Hull_205	374.5	3467.458		Hull_235	364.8	3377.815
Hull_206	376.5	3486.497		Hull_236	364.2	3372.373
Hull_207	374	3463.567		Hull_237	361.8	3350.566
Hull_208	364.3	3373.249		Hull_238	355.4	3290.757
Hull_209	362.2	3353.872		Hull_239	360.3	3336.663
Hull_210	361.5	3347.756		Hull_240	356.4	3300.263

18 knots		
Hull Number	Fung Resistance [kN]	Fung Power [kW]
Hull_241	371.6	3440.75
Hull_242	374.5	3467.743
Hull_243	371.3	3438.254
Hull_244	383.8	3554.037
Hull_245	382.8	3544.599
Hull_246	380.3	3521.721
Hull_247	372.6	3450.475
Hull_248	374.7	3469.421
Hull_249	370.2	3428.027
Hull_250	392.2	3631.314
Hull_251	395.4	3661.62
Hull_252	395.5	3661.933
Hull_253	370.6	3431.545
Hull_254	369.6	3422.122
Hull_255	367.8	3405.698
Hull_256	361.3	3345.963
Hull_257	363.3	3364.064
Hull_258	362	3352.074
Hull_259	377.9	3499.04
Hull_260	378.5	3505.031
Hull_261	376.2	3483.891
Hull_262	361.8	3349.99
Hull_263	360	3333.521
Hull_264	358.9	3323.13
Hull_265	351.7	3256.994
Hull_266	355.1	3288.072
Hull_267	351	3250.675
Hull_268	368.1	3408.662
Hull_269	368.5	3412.132
Hull_270	368	3407.573

APPENDIX C: SEAKEEPING CALCULATIONS

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_000	1,198	5,76	0,01267	0,644	0	0,02617
Hull_001	1,217	2,61	0,01423	0,76	0	0,03112
Hull_002	1,23	2,49	0,01415	0,75	0	0,03164
Hull_003	1,22	2,84	0,01405	0,758	0	0,03037
Hull_004	1,24	2,51	0,01453	0,752	0	0,0303
Hull_005	1,232	2,41	0,01463	0,795	0	0,0326
Hull_006	1,207	2,76	0,01417	0,806	0	0,03076
Hull_007	1,238	2,77	0,01417	0,68	0	0,03005
Hull_008	1,232	2,47	0,01424	0,687	0	0,03044
Hull_009	1,223	3,62	0,01359	0,696	0	0,02957
Hull_010	1,18	5,78	0,01431	0,718	0	0,02961
Hull_011	1,209	5,39	0,0148	0,673	0	0,02922
Hull_012	1,17	5,98	0,01422	0,729	0	0,02864
Hull_013	1,197	5,74	0,01473	0,714	0	0,02884
Hull_014	1,19	4,92	0,0148	0,76	0	0,03104
Hull_015	1,17	5,79	0,01421	0,763	0	0,02946
Hull_016	1,189	6,06	0,01417	0,662	0	0,02819
Hull_017	1,198	5,78	0,01436	0,646	0	0,02907
Hull_018	1,175	6,92	0,01353	0,683	0	0,02798
Hull_019	1,15	9,32	0,01437	0,688	0	0,0284
Hull_020	1,179	9,34	0,01499	0,641	0	0,02787
Hull_021	1,144	9,33	0,01418	0,701	0	0,02753
Hull_022	1,167	9,34	0,01491	0,683	0	0,02793
Hull_023	1,157	9,04	0,01485	0,732	0	0,02975
Hull_024	1,131	8,96	0,0144	0,743	0	0,02839
Hull_025	1,163	9,24	0,01428	0,631	0	0,02739
Hull_026	1,17	9,42	0,01445	0,618	0	0,02785
Hull_027	1,184	5,71	0,01326	0,696	0	0,02796
Hull_028	1,188	5,64	0,01408	0,717	0	0,02958
Hull_029	1,215	4,53	0,0145	0,672	0	0,02878
Hull_030	1,18	5,7	0,01392	0,724	0	0,0284
Hull_031	1,202	4,66	0,01454	0,71	0	0,02865
Hull_032	1,198	4,14	0,01456	0,75	0	0,03072
Hull_033	1,177	5,89	0,01398	0,758	0	0,02919
Hull_034	1,203	5,73	0,01399	0,65	0	0,02816
Hull_035	1,204	5,86	0,01411	0,642	0	0,02879
Hull_036	1,181	6,08	0,01331	0,676	0	0,02766
Hull_037	1,178	6,1	0,0138	0,69	0	0,02813
Hull_038	1,204	5,71	0,01452	0,656	0	0,02836
Hull_039	1,171	6,67	0,01386	0,704	0	0,02778
Hull_040	1,178	5,89	0,01451	0,752	0	0,02989

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_041	1,185	5,96	0,0145	0,734	0	0,03003
Hull_042	1,16	5,99	0,01399	0,766	0	0,02882
Hull_043	1,191	6,65	0,0138	0,643	0	0,02741
Hull_044	1,193	6,09	0,0141	0,629	0	0,02816
Hull_045	1,171	8,92	0,01329	0,663	0	0,02737
Hull_046	1,214	3,25	0,0137	0,725	0	0,02975
Hull_047	1,243	2,92	0,0142	0,67	0	0,02902
Hull_048	1,204	3,7	0,01372	0,722	0	0,02879
Hull_049	1,216	2,89	0,0142	0,787	0	0,0309
Hull_050	1,221	2,67	0,01419	0,784	0	0,03111
Hull_051	1,196	3,47	0,01384	0,776	0	0,0295
Hull_052	1,224	3,7	0,01354	0,661	0	0,02821
Hull_053	1,233	3,5	0,01358	0,657	0	0,02886
Hull_054	1,209	3,93	0,01291	0,687	0	0,02785
Hull_055	1,201	3,9	0,01367	0,711	0	0,02903
Hull_056	1,236	3,62	0,01401	0,663	0	0,02837
Hull_057	1,19	4,32	0,01372	0,708	0	0,02814
Hull_058	1,202	3,66	0,01413	0,765	0	0,03006
Hull_059	1,213	3,53	0,01418	0,753	0	0,03056
Hull_060	1,18	4,06	0,01382	0,752	0	0,02882
Hull_061	1,217	4,23	0,01358	0,648	0	0,02775
Hull_062	1,216	3,82	0,01358	0,652	0	0,02857
Hull_063	1,195	5,8	0,01292	0,673	0	0,02722
Hull_064	1,159	9,41	0,01377	0,672	0	0,02734
Hull_065	1,188	7,89	0,01431	0,625	0	0,02697
Hull_066	1,156	8,91	0,01378	0,672	0	0,02705
Hull_067	1,161	7,15	0,01428	0,732	0	0,02873
Hull_068	1,17	6,15	0,0143	0,718	0	0,02902
Hull_069	1,141	8,99	0,01387	0,733	0	0,02768
Hull_070	1,176	9,05	0,01369	0,616	0	0,02643
Hull_071	1,179	8,99	0,01396	0,606	0	0,02682
Hull_072	1,158	9,48	0,01306	0,639	0	0,02637
Hull_073	1,169	6,82	0,01367	0,676	0	0,02779
Hull_074	1,196	6,08	0,01425	0,628	0	0,02712
Hull_075	1,163	9	0,01361	0,676	0	0,02691
Hull_076	1,172	6,08	0,01412	0,722	0	0,02864
Hull_077	1,178	5,8	0,01417	0,723	0	0,02909
Hull_078	1,152	6,95	0,01358	0,734	0	0,02745
Hull_079	1,185	9,08	0,01362	0,615	0	0,02648
Hull_080	1,139	8,91	0,0139	0,697	0	0,02926

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_081	1,163	9,11	0,01294	0,639	0	0,02599
Hull_082	1,209	3,93	0,01329	0,685	0	0,02809
Hull_083	1,234	3,7	0,01389	0,644	0	0,02792
Hull_084	1,15	4,14	0,01352	0,762	0	0,02968
Hull_085	1,211	3,64	0,01382	0,746	0	0,02957
Hull_086	1,216	3,23	0,01385	0,751	0	0,03006
Hull_087	1,189	3,76	0,01341	0,755	0	0,02855
Hull_088	1,222	3,99	0,0133	0,63	0	0,02728
Hull_089	1,227	3,68	0,01319	0,635	0	0,02794
Hull_090	1,201	5,63	0,01262	0,66	0	0,02662
Hull_091	1,21	3,57	0,01327	0,696	0	0,02833
Hull_092	1,234	2,98	0,01366	0,682	0	0,02942
Hull_093	1,214	3,73	0,0131	0,688	0	0,02741
Hull_094	1,219	3,15	0,01363	0,743	0	0,02945
Hull_095	1,223	2,76	0,01368	0,756	0	0,02991
Hull_096	1,197	3,58	0,01317	0,775	0	0,02833
Hull_097	1,229	3,62	0,01328	0,624	0	0,02733
Hull_098	1,233	3,67	0,01314	0,629	0	0,02745
Hull_099	1,212	4,08	0,01241	0,66	0	0,0267
Hull_100	1,174	6,37	0,01335	0,66	0	0,02714
Hull_101	1,193	6,03	0,0138	0,651	0	0,02796
Hull_102	1,17	8,42	0,0132	0,669	0	0,02626
Hull_103	1,176	6,04	0,0138	0,709	0	0,02812
Hull_104	1,182	5,7	0,01379	0,709	0	0,02844
Hull_105	1,159	7,16	0,0134	0,702	0	0,02704
Hull_106	1,188	8,87	0,01325	0,608	0	0,0258
Hull_107	1,194	7,2	0,01326	0,593	0	0,02623
Hull_108	1,172	9,29	0,01261	0,628	0	0,02584
Hull_109	1,206	4,4	0,01301	0,676	0	0,02752
Hull_110	1,22	3,74	0,01351	0,667	0	0,02844
Hull_111	1,207	3,8	0,01299	0,683	0	0,02714
Hull_112	1,201	3,94	0,01303	0,718	0	0,02807
Hull_113	1,212	3,7	0,01358	0,724	0	0,02915
Hull_114	1,187	4,1	0,01319	0,732	0	0,02791
Hull_115	1,211	5,12	0,01304	0,617	0	0,02623
Hull_116	1,221	4,37	0,01304	0,609	0	0,02677
Hull_117	1,196	5,74	0,01238	0,642	0	0,0259
Hull_118	1,162	9,34	0,01324	0,645	0	0,02642
Hull_119	1,189	8,99	0,01373	0,602	0	0,02592
Hull_120	1,157	9,19	0,01308	0,65	0	0,02542

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_121	1,163	8,87	0,01368	0,692	0	0,02734
Hull_122	1,167	6,4	0,01376	0,7	0	0,02781
Hull_123	1,145	9,13	0,01332	0,702	0	0,02672
Hull_124	1,173	9,41	0,0132	0,584	0	0,02518
Hull_125	1,178	9,02	0,01329	0,578	0	0,02564
Hull_126	1,155	10,07	0,01253	0,61	0	0,0247
Hull_127	1,19	5,91	0,01303	0,659	0	0,02714
Hull_128	1,215	5,76	0,01357	0,609	0	0,02636
Hull_129	1,179	6,06	0,01296	0,662	0	0,02585
Hull_130	1,193	5,68	0,01342	0,701	0	0,02783
Hull_131	1,196	4,32	0,01352	0,714	0	0,02838
Hull_132	1,175	5,96	0,01298	0,723	0	0,02702
Hull_133	1,2	6,08	0,01293	0,601	0	0,02547
Hull_134	1,207	6	0,01299	0,592	0	0,0263
Hull_135	1,187	6,4	0,0123	0,616	0	0,02539
Hull_136	1,199	5,67	0,01267	0,658	0	0,02664
Hull_137	1,221	4,65	0,01324	0,61	0	0,02603
Hull_138	1,191	5,75	0,01265	0,655	0	0,02565
Hull_139	1,199	4,62	0,01321	0,694	0	0,02755
Hull_140	1,203	3,92	0,0133	0,709	0	0,02821
Hull_141	1,18	5,72	0,01286	0,703	0	0,02676
Hull_142	1,205	5,74	0,01267	0,595	0	0,02518
Hull_143	1,214	5,73	0,01281	0,579	0	0,02594
Hull_144	1,19	6,11	0,01211	0,614	0	0,02492
Hull_145	1,231	2,63	0,01244	0,683	0	0,0273
Hull_146	1,259	2,48	0,01294	0,623	0	0,0267
Hull_147	1,228	2,9	0,01242	0,674	0	0,02647
Hull_148	1,238	2,49	0,01287	0,718	0	0,02842
Hull_149	1,242	2,35	0,01289	0,731	0	0,02881
Hull_150	1,218	2,68	0,01253	0,737	0	0,02758
Hull_151	1,243	2,84	0,01245	0,609	0	0,02599
Hull_152	1,252	2,61	0,01249	0,597	0	0,02662
Hull_153	1,232	3,28	0,01178	0,631	0	0,02586
Hull_154	1,206	4,61	0,01246	0,651	0	0,02632
Hull_155	1,218	3,98	0,01295	0,639	0	0,027
Hull_156	1,192	5,79	0,01253	0,653	0	0,0254
Hull_157	1,203	4,12	0,01296	0,691	0	0,027
Hull_158	1,21	3,74	0,01304	0,694	0	0,02779
Hull_159	1,184	4,51	0,01265	0,706	0	0,0265
Hull_160	1,209	5,82	0,01252	0,589	0	0,02491

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_161	1,217	5,45	0,01268	0,574	0	0,0256
Hull_162	1,191	4,43	0,01252	0,708	0	0,02658
Hull_163	1,161	8,94	0,01265	0,618	0	0,02492
Hull_164	1,181	9,16	0,01311	0,603	0	0,02579
Hull_165	1,157	9,53	0,01268	0,615	0	0,02441
Hull_166	1,164	9,12	0,01312	0,66	0	0,026
Hull_167	1,167	7,07	0,01319	0,671	0	0,02653
Hull_168	1,147	9,41	0,01275	0,67	0	0,0254
Hull_169	1,176	9,26	0,01263	0,561	0	0,02386
Hull_170	1,181	8,97	0,0127	0,546	0	0,02445
Hull_171	1,157	11,77	0,01198	0,58	0	0,02351
Hull_172	1,224	2,93	0,01231	0,656	0	0,02663
Hull_173	1,254	2,73	0,01276	0,603	0	0,02612
Hull_174	1,226	3,53	0,01215	0,651	0	0,02576
Hull_175	1,234	2,71	0,01267	0,7	0	0,02771
Hull_176	1,239	2,55	0,01265	0,699	0	0,02804
Hull_177	1,214	2,95	0,0123	0,717	0	0,02691
Hull_178	1,237	3,48	0,01221	0,592	0	0,0252
Hull_179	1,235	3,1	0,01238	0,589	0	0,02579
Hull_180	1,226	3,73	0,01154	0,617	0	0,02482
Hull_181	1,188	6,02	0,01238	0,618	0	0,02531
Hull_182	1,213	6,09	0,01297	0,572	0	0,02473
Hull_183	1,183	6,42	0,01225	0,625	0	0,02438
Hull_184	1,19	5,75	0,0128	0,666	0	0,02624
Hull_185	1,195	5,94	0,01281	0,658	0	0,02646
Hull_186	1,175	5,95	0,01232	0,681	0	0,02541
Hull_187	1,2	6,59	0,01222	0,568	0	0,02395
Hull_188	1,203	6,16	0,01233	0,563	0	0,02421
Hull_189	1,186	8,7	0,01171	0,583	0	0,02389
Hull_190	1,177	7,79	0,01236	0,609	0	0,02484
Hull_191	1,202	6,34	0,01286	0,568	0	0,02423
Hull_192	1,173	9,3	0,01225	0,609	0	0,02396
Hull_193	1,179	6,25	0,01277	0,651	0	0,02571
Hull_194	1,183	6,08	0,01278	0,646	0	0,02593
Hull_195	1,16	7,23	0,01243	0,661	0	0,02506
Hull_196	1,188	9,4	0,01225	0,556	0	0,02358
Hull_197	1,194	9,06	0,01233	0,552	0	0,02404
Hull_198	1,17	9,34	0,0117	0,577	0	0,02319
Hull_199	1,213	3,92	0,01207	0,628	0	0,02545
Hull_200	1,238	3,63	0,01259	0,582	0	0,02499

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_201	1,203	4,39	0,01215	0,625	0	0,02466
Hull_202	1,218	3,64	0,01249	0,673	0	0,02654
Hull_203	1,221	3,5	0,01253	0,687	0	0,02699
Hull_204	1,197	3,9	0,01216	0,686	0	0,02573
Hull_205	1,224	4,41	0,01187	0,571	0	0,02424
Hull_206	1,23	3,87	0,01196	0,571	0	0,02491
Hull_207	1,21	5,8	0,01136	0,595	0	0,02383
Hull_208	1,222	3,68	0,01194	0,629	0	0,02552
Hull_209	1,246	3,44	0,01246	0,584	0	0,02512
Hull_210	1,214	3,85	0,01198	0,625	0	0,0247
Hull_211	1,227	3,47	0,01236	0,668	0	0,0265
Hull_212	1,23	2,95	0,01238	0,68	0	0,02703
Hull_213	1,205	3,7	0,01203	0,687	0	0,02574
Hull_214	1,23	3,82	0,01198	0,566	0	0,02421
Hull_215	1,24	3,66	0,01201	0,554	0	0,02488
Hull_216	1,219	4,46	0,01125	0,595	0	0,02381
Hull_217	1,181	6,68	0,0121	0,598	0	0,02435
Hull_218	1,204	6,08	0,01264	0,556	0	0,02378
Hull_219	1,176	9,02	0,01197	0,603	0	0,02341
Hull_220	1,184	6,08	0,01248	0,638	0	0,02517
Hull_221	1,189	5,69	0,01256	0,652	0	0,02583
Hull_222	1,166	6,43	0,01218	0,65	0	0,0246
Hull_223	1,188	9,06	0,01207	0,549	0	0,023
Hull_224	1,199	7,16	0,01218	0,534	0	0,02353
Hull_225	1,176	9,05	0,01145	0,565	0	0,02269
Hull_226	1,189	6,17	0,01197	0,595	0	0,02428
Hull_227	1,215	5,78	0,01244	0,557	0	0,02389
Hull_228	1,184	6,7	0,01185	0,603	0	0,02343
Hull_229	1,191	5,72	0,01235	0,643	0	0,02518
Hull_230	1,196	5,75	0,01242	0,649	0	0,02571
Hull_231	1,177	6,01	0,01192	0,66	0	0,02453
Hull_232	1,201	7	0,01184	0,549	0	0,02302
Hull_233	1,206	6,15	0,01204	0,533	0	0,02371
Hull_234	1,183	9,19	0,01134	0,565	0	0,02269
Hull_235	1,222	3,6	0,01174	0,614	0	0,02485
Hull_236	1,25	3,13	0,01221	0,571	0	0,02447
Hull_237	1,216	3,69	0,01177	0,614	0	0,0242
Hull_238	1,228	3,21	0,01206	0,663	0	0,02582
Hull_239	1,237	2,64	0,01213	0,681	0	0,02684
Hull_240	1,212	3,57	0,01174	0,674	0	0,02524

	18 kn					
	90 deg			180 deg		
	Heave acc.	Roll Deg.	Pitch acc.	Heave acc.	Roll Deg.	Pitch acc.
Hull_241	1,234	3,69	0,01163	0,562	0	0,02368
Hull_242	1,245	3,53	0,01175	0,543	0	0,02435
Hull_243	1,222	4,12	0,01102	0,583	0	0,02331
Hull_244	1,176	9,04	0,01185	0,575	0	0,02341
Hull_245	1,199	7,12	0,01244	0,544	0	0,0231
Hull_246	1,163	8,95	0,01186	0,591	0	0,02272
Hull_247	1,178	7,08	0,01225	0,624	0	0,02442
Hull_248	1,183	6,17	0,01233	0,633	0	0,02503
Hull_249	1,159	8,71	0,01192	0,638	0	0,02376
Hull_250	1,189	8,91	0,01182	0,53	0	0,02242
Hull_251	1,195	9,07	0,01185	0,523	0	0,02286
Hull_252	1,173	9,37	0,01123	0,549	0	0,02222
Hull_253	1,212	4,2	0,01158	0,599	0	0,02416
Hull_254	1,229	3,78	0,01197	0,59	0	0,02492
Hull_255	1,202	5,31	0,01168	0,598	0	0,02346
Hull_256	1,214	3,92	0,01197	0,64	0	0,02496
Hull_257	1,218	3,7	0,01203	0,656	0	0,02566
Hull_258	1,197	4,15	0,01165	0,653	0	0,02442
Hull_259	1,219	5,26	0,01161	0,546	0	0,02296
Hull_260	1,229	4,46	0,01158	0,539	0	0,02339
Hull_261	1,208	5,81	0,01101	0,562	0	0,02262
Hull_262	1,238	2,69	0,01132	0,621	0	0,02471
Hull_263	1,265	2,51	0,01186	0,566	0	0,02436
Hull_264	1,234	2,99	0,01134	0,614	0	0,02393
Hull_265	1,246	2,5	0,01173	0,657	0	0,02579
Hull_266	1,25	2,33	0,01179	0,67	0	0,02647
Hull_267	1,227	2,71	0,01142	0,67	0	0,02506
Hull_268	1,249	2,91	0,01138	0,555	0	0,02345
Hull_269	1,25	2,73	0,01153	0,544	0	0,02394
Hull_270	1,236	3,57	0,01074	0,578	0	0,02312