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Master's degree thesis

IP501909 MSc thesis, discipline oriented master

Parametric Structural Analysis for a Platform Supply Vessel at Preliminary Design Phase - A Sensitivity Study via Design of Experiments

1103/Sthéfano Lande Andrade

Number of pages including this page: 147

Aalesund, 03/06/2016

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Master Thesis 2016

For

STUD.TECHN. Sthéfano Lande Andrade

Parametric Structural Analysis for a Platform Supply Vessel at Preliminary Design Phase – A Sensitivity Study via Design of Experiments

The offshore market has been severely affected by the sudden drop in oil prices, affecting the support vessels industry. This challenged both shipyards and ship designers to find possible solutions that will raise their competitiveness, as structural optimization.

The objective of the project is to create a method capable of performing a sensitivity analysis focusing on the structural optimization of Offshore Support Vessels from the PX family. The sensitivity analysis will be performed according to requirements defined by Ulstein.

Master Thesis' project plan:

- Develop a structural Optimization Routine;
  - Optimization Model based on design of experiments;
  - Structural Analysis to be performed with FEM capable software (Ansys);
- Apply routine to a simple case;
  - Loaded stiffened plate;
  - Different topology configurations;
- Create Finite Element models of PSV;
  - Parametric Model;
  - Define a representative model (section vs entire vessel);
- Run the routine on the model.

Optimization results:

- Propose effective solutions to minimize mass according to the requirements.

Supervisor - Henrique Murilo Gaspar (NTNU)

Co-Supervisor - Sören Ehlers (TUHH)

Finish: 3rd June 2016

Supervisor Signature:

Henrique Murilo Gaspar 

Abstract

Parametric structural design analysis is a promising alternative to diminish the hull's structural mass, resulting in a vessel with higher payload capacity as well as lower construction and maintenance costs. The challenge of investigating a large space of alternatives, e.g. testing topology and materials, is caused by the high amount of engineering time required to model, analyse and evaluate each of the possible configurations. The objective of this paper is to demonstrate the application of a structural sensitivity study for a parametrically model global structure of a platform supply vessel, focused on mass reduction during the preliminary design phase. The methodology starts with the CAD/FEM creation of a parametric model, representing the vessel's middle sectional region. The focus on early design stages allows for simplifications in the structural model, gaining computational time when bypassing local details that would require finer mesh, which is not desirable for any kind of fast analyses procedures. Strength analyses are performed, following procedure of design of experiments methodology, which serves as a tool to understand mass efficiency based on the initially defined variables. The method gathers knowledge on impact of variables on various combined responses, and these are used to map the most efficient parameters and determine a viable solution space that better material usage in comparison to the original design.

Keywords: Parametric Model; Structural Sensitivity Analysis; Response Surface Methodology.

Acknowledgements

Primarily, I would like to thank my family, who always backed me up in my decisions. They encourage me to go beyond and to not doubt myself. Their continuous support and care has always been unparalleled.

I also must thank my friends who were always present to help me in times of need and to commemorate accomplishments together.

I must express my gratitude towards my supervisor, Henrique Gaspar. Beyond supervising, correcting and providing information for the thesis, he showed trust in my capabilities, helped me develop new skills, aided at moments of need and pushed me always do better.

Sören Ehlers, my co-supervisor, provided a large amount of knowledge towards ship structural design and software based finite elements analysis, always with utmost patience. Moreover, during the initial stages of my thesis, Sören offered me the opportunity to study these topics directly at TUHH.

I would like to thank Ulrikke Brandt and Ulstein, who provided technical knowledge about PSV's structural design and helped me outline the boundaries of the case.

Candidate Signature:

Sthéfano Lande Andrade Sthéfano L. Andrade

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Abbreviations

2FI	Two Factor Interaction
APDL	ANSYS parametric design language
CCD	Central Composite Design
CSR	Common Structural Rules
DNV-GL	Det Norske Veritas – Germanischer Lloyd
DoE	Design of Experiments
D-Optimal	Determinant based Optimal Design
FE	Finite Elements
FEA	Finite Elements Analysis
FEM	Finite Elements Methods
IACS	International Association of Classification Societies
NA	Neutral Axis
OCV	Offshore Construction Vessel
OSV	Offshore Support Vessel
PRESS	Predicted Residual Error Sum of Squares
PSV	Platform Supply Vessel
R-Squared	Coefficient of Determination
RSM	Response Surface Methods

1 Introduction

Structural design of ships is a complex problem that invariably leads to a large amount of viable solutions, most of which are not optimal. It involves a diverse array of decisions, such as topology layout, plate thickness, material vs labour cost and main dimensions. However, by using response surface models combined with parametric finite elements methods, it is possible to investigate the effect of key vessel parameters based on their influence on the designer goal, be it stress reduction, material usage improvement or delimitate an ideal range for main parameters. In short, the methodology presented in this study can assist decision making at early design, when main parameters are still flexible at and new solutions can be considered.

1.1 Project background

Structural design of ships involves many variables, this invariably leads to a great amount of viable solutions, most of which are not optimal or in many cases there are different optimal solutions depending on what is the focus of the analysis. This issue has been partially studied in two different works, which this thesis uses a motivation. The first is “Basic Study on better Hull Beam Utilization for OCVs” (Brandt, 2015) and proved that the vessels’ depth has a large influence on material utilization efficiency on Platform Supply Vessels, concluding that increasing that dimension while decreasing Breadth is far more beneficial than the opposite.

The second study, “Statistical Studies on the Influence of Primary and Secondary Structural Members on the Global Strength of Ship Structures“ (Diewald, 2015), has a similar goal, but focuses on structural elements rather than main dimensions. It helps define which structural elements have a higher impact on the structure’s ability to resist to different load types.

This thesis aims to take the next step, by using their conclusions on critical influencing factors for structural strength and mass reduction, a methodology is stablished to help designers understand how factors influence the responses and determine an improved solution space for multiple response combination.

The combination of robustness parametric finite elements analysis and response surface regressions permits the improvement of structural design by analysing parameters interaction and even obtaining distinct viable improved solutions that can be changed depending on the goals defined. For example, Figure 1 and Figure 2 illustrate how the Depth and Breadth influence the linear mass of a PSV MidShip Section when other factors are taken into account.

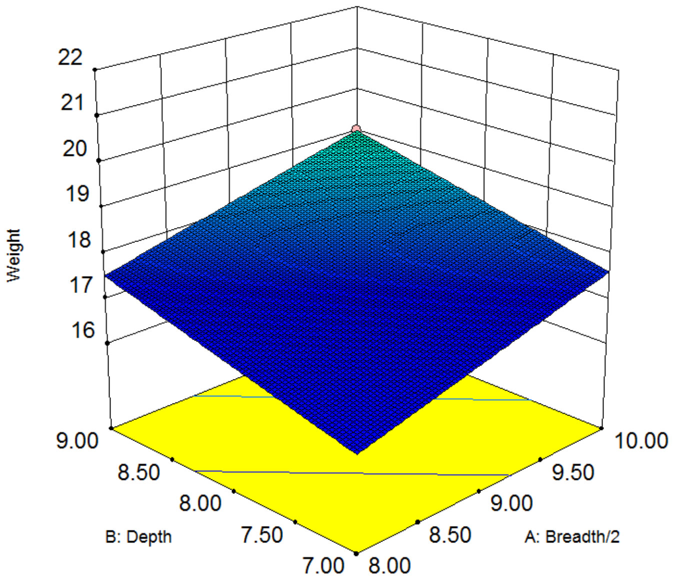


Figure 1: mass response surface for lower plate thickness values.

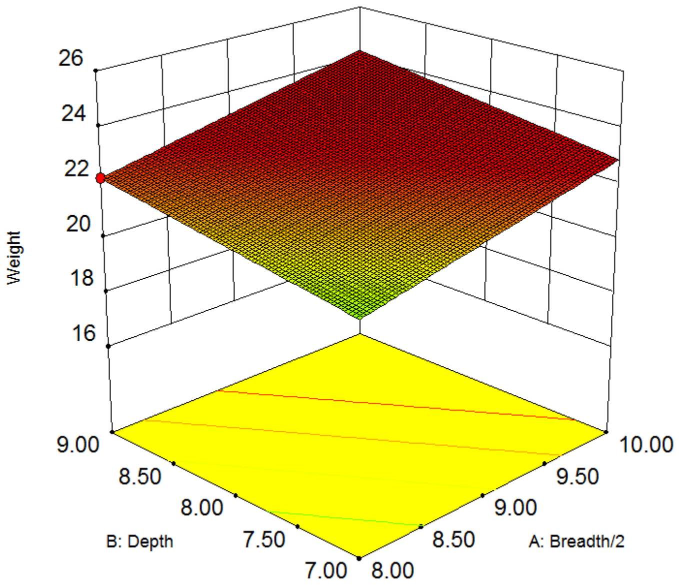


Figure 2: Mass response surface for higher plate thickness values.

1.2 Research Question

How to create a simplified yet relevant parametric finite element model for a PSV that will study it structural strength at early design stages?

How to create a procedure to map complex structural responses solved by finite elements analyses and obtain improved solutions?

1.3 Literature Review

Although the necessity for structural optimization has always been a concern for structural designers, it usually happens when many parameters are already defined and would hardly change, thus not in an early design stage.

Taking this into consideration Brandt and Ulstein performed a basic study on the main dimensions influence on structural strength and mass optimization (Brandt, 2015), which concluded general guidelines for better hull utilization. The next improvement upon this work came from Diewald's project work, (Diewald, 2015), who performed statistical studies on the influence of the structural members on the hull strength focusing on topology and dimensioning variations, his conclusions defined which design variations should affect the primary and secondary structural strength the most. These projects were the standing stones of the current thesis.

It is important to remark that the thesis is focused around early design stages, when decisions affect the project's costs the most, according to Gaspar's PhD on handling conceptual design complexity (Gaspar, 2013). The paper Product Life-Cycle in Ship Design (Andrade, et al., 2015) also comments on this issue.

To create and solve the finite parametric ANSYS Mechanical software is used. The routine was written in ANSYS Parametric Design language (APDL). To design the finite elements model I used information provided by Ehlers modelling course, (Diewald, 2015) and Kõrgesaar's work on A Procedure to Assess the Crashworthiness of an LNG tanker Side Structure (Kõrgesaar, 2010). To define loads, boundaries and guarantee a representative model I also followed the knowledge from Ship Structural Analysis and Design book (Hughes, et al., 2010) and guidelines from IACS' common structural rules (IACS, 2015) and DNV-GL's classification rules (DNV-GL, 2015).

As said previously, I perform the structural sensitivity analysis using Design of Experiments applied to Response Surface Methods, which is a methodology that uses surface regressions to represent how parameters affect a response, but beyond visually informative they also permit a local optimization to be performed, based on the multi-response combination. This methodology is explained in RSM simplified (Anderson, et al., 2005). As the name suggests design of experiments were developed to explain real life complex processes by the use of a set of experiments, however according to Unal's work on Response Surface Model Building and Multidisciplinary Optimization using D-Optimal Designs (Response Surface Model

Building and Multidisciplinary Optimization using D-Optimal Designs, 1998), Response Surface Methods based on Design of Experiments can be used to generate surface regression of complex computer simulations.

1.4 Thesis Scope

The first area of the thesis scope is contained within the structural analysis' field. It is limited to early design stages, where main dimensions can still be changed and design choices are more effective and critical cost-wise, thus the importance of developing a methodology that assists the structural designers' decision making procedure. Although other types of load can be studied, I focus on the effects of global bending moment on the hull beam structure.

The response surface methodology is used to perform the sensitivity analysis and solution improvements, because of the robustness of the method. Design of Experiments reads and performs regression models which are represented as surfaces. This way it is possible to map complex problems with multifactor interactions at low computational cost and produce significant representations of simulation procedures, moreover improvement objectives can be altered after experiments are performed without requiring another run of Finite Element Analysis.

Since Ulstein agreed to provide information necessary to model construction, solving and validation, I apply the methodology on Platform Supply Vessels from the PX family. This also defines the dimension variation that is used in the design interval. Figure 1 shows the scope division in a diagram.

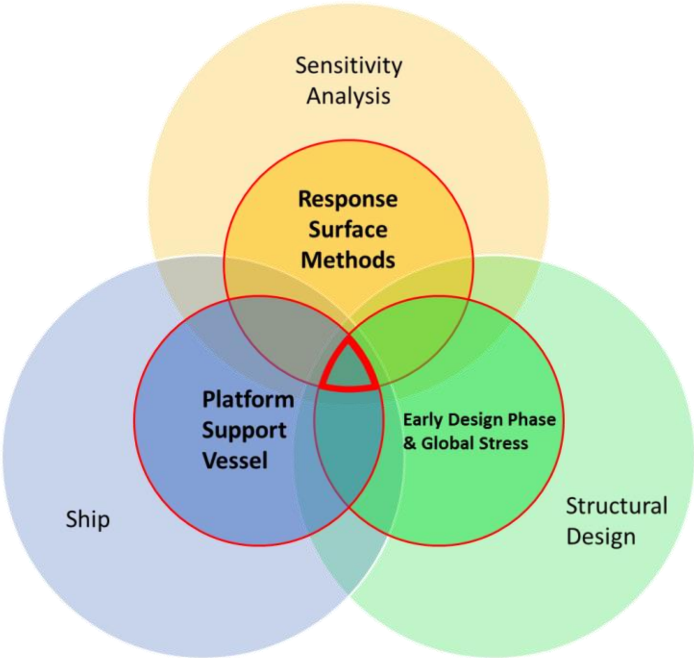


Figure 3: Scope's diagram.

Thus a methodology is created to perform structural sensitivity analysis, at early design stages, of PSV's from Ulstein's PX family by using design of experiments and response surface methods. This methodology is explained in section 4 and is illustrated in Figure 24.

2 Structural Design of Platform Supply Vessels at Early Design Stages

Key concepts of ship's structural design are defined in this section.

2.1 Conceptual Structural Design

Conceptual design is the first step of a ship the value chain, Figure 4. During this phase main dimensions, systems and volume arrangements are defined. Although many characteristics can be changed during detailing design, the difference is relatively marginal to the prior stage, which in winds up defining most of the vessel's life-cycle cost. Figure 4: Ship's Value Chain.

Figure 4: Ship's Value Chain. (Andrade, et al., 2015)

Moreover, according to studies from 1985 by (Kerlen, 1985), the steel price constitutes between 24% to 35% from the total construction costs, thus is a big factor in the vessel's final price. Also, according to (Gaspar, 2013), after the definition of cost in the conceptual design phase, there is only a small margin of changes that can be done in the other phases as 70% of the total costs are assumed committed after the initial design is set. This can be better visualized in Figure 5.

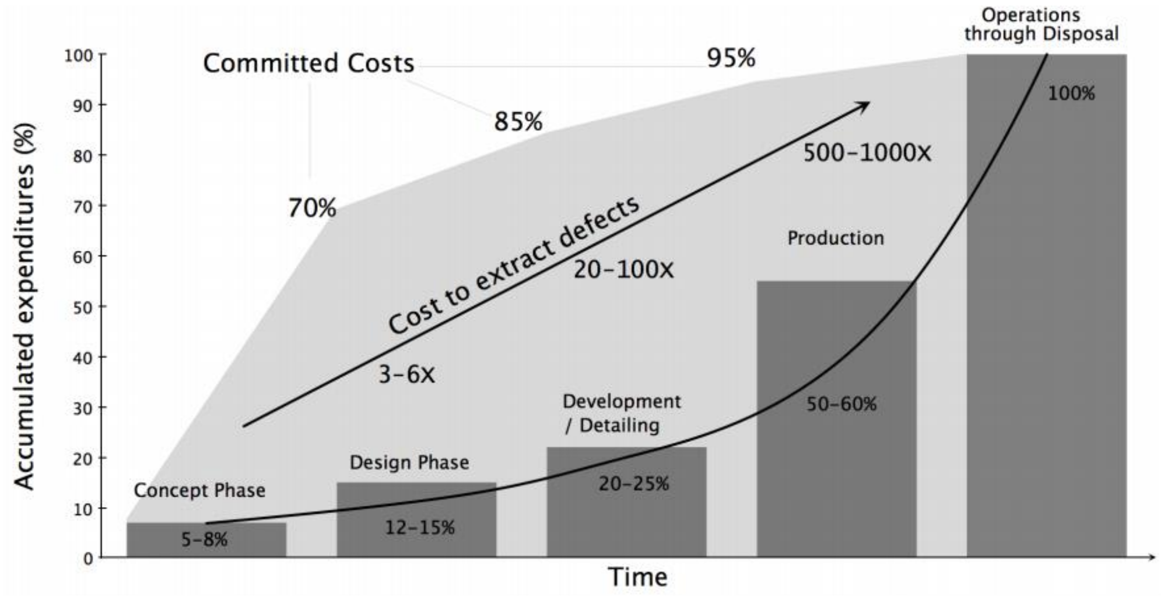


Figure 5: Accumulated expenditures and committed costs in the main design phases. (Gaspar, 2013)

Considering the effects of the conceptual design in the total production cost, the steel cost percent and the difficulty to change main dimensions during later design phases, the best practice for structural optimization would be optimizing key features at an early stage, where changes are easier to make and cost less.

2.1.1 Global Loads

Global load is the combination of all local loads acting on the whole vessel, which consist of the hydrostatic pressure, cargo loads and steel weight. These local loads are integrated through the ship's length to obtain the vertical shear force (2.1) acting on the vessel, which in turn, when integrated one more time, results in the bending moment distribution (2.2).

$$V(x) = \int q(x)\,dx \quad \textbf{(2.1)}$$

$$M(x) = \int V(x)\,dx \quad \textbf{(2.2)}$$

Where:

$q(x)$ is the total local linear load (N/m), taken as the difference between mass and buoyancy;

$V(x)$ is the shear force (N);

$M(x)$ is the Bending Moment (Nm);

The effect of waves on the bending moment is taken into consideration by changing the hydrostatic pressure locally, considering the local changes in pressure caused by wave displacement and the vessel's motion.

However, this whole approach is only possible at later stages in the design as it requires sectional drawing, defined operational profile and general arrangement/mass distribution information, which are only available after an initial structural model can be provided. At conceptual stages, the usual practice is to determine open water bending moment through the use statistical analyses and regressions provided by classification societies rules, such as stated at DNV-GL structural rules[1] (DNV-GL, 2015), which is discussed more in depth in section 4.1.

For this study does not study the effects of local loads on structural dimensioning, only the global loads as defined in section 4.1.

2.1.2 Longitudinal Strength

The hull beam model implicates that:

- The highest global stress is usually located at the middle region of the ship;
- Bending stress is the main consequence of bending moment;
- Two types of vertical bend can occur, sagging and hogging;

The second one is explained in equation (2.3) and illustrated in Figure 6.

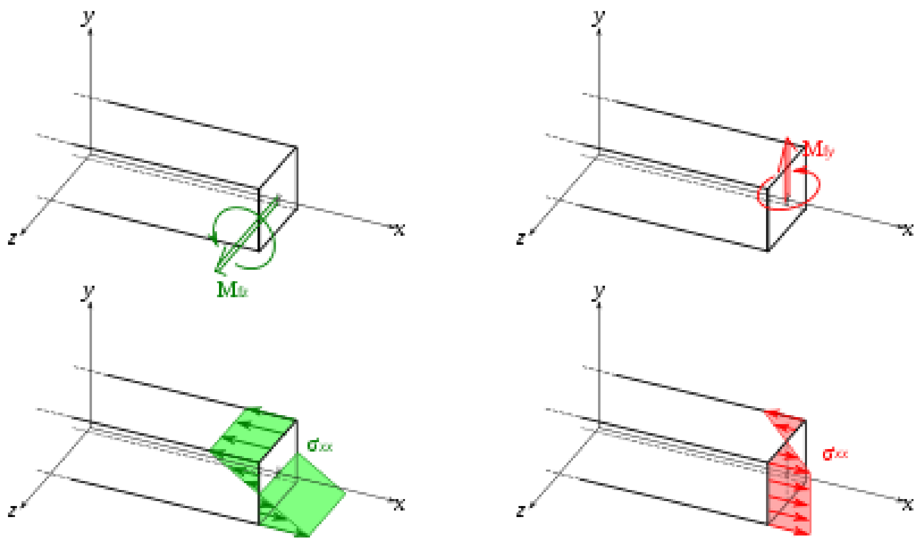


Figure 6: Bending stress distribution. Vertical and horizontal are depicted as example. (Wikipedia, 2016)

[1]DNV-GL structural rules Pt3 Ch4 Sec2.2.1

$$\sigma(y) = \frac{My}{I} \quad \textbf{(2.3)}$$

Where:

$\sigma(y)$ is the bending stress;

M is the bending moment;

y is the distance from a fiber to the neutral axis plane;

I is the area moment of inertia relative to the axis where Moment is applied;

Note that the neutral axis (NA) is defined as the region where the stress is zero and can be determined by calculating the area distribution in relation to a coordinate (y for the case of vertical bending moment), equation (2.4):

$$NA = \frac{\sum A \cdot y}{\sum A} \quad \textbf{(2.4)}$$

Equation (2.3) shows to minimize stress without control over the bending moment, the area moment of inertia must be increased. For a ship's section it can be determined by totalling the moments of area of each individual structural element that makes up the section, or:

$$I_{total} = \sum_{n} \frac{bh^3}{12} + Ad^2 \quad \textbf{(2.5)}$$

Where:

I_{total} is the sum of all individual moments of area;

b is the base length of the element;

h is the height of the element;

A is the element sectional area;

d is the distance from the element sectional area center to the neutral plane;

Note that the bending stress is but one of the possible stresses acting on a hull, which also include torsional and shear. Moreover, it measures but one of the failure modes a hull structure can suffer, the allowable stress for yield limit. The others are failure due to buckling, fatigue and ultimate stress. However, resisting the bending stress at the middle section is usually the first criteria that should be fulfilled, thus it should be the first one analysed.

2.1.3 Finite Elements applied to Ship's Structural Design

By dividing intricate structures into a number of smaller simpler ones, finite elements method allows the solution of complex problems, (Hughes, et al., 2010). A ship structural analysis is such an example, as its structure involves a great number of parts that would be difficult to solve otherwise. The basic idea of Finite Elements Methods is to divide a complex differential equations system into easily solvable individual equations according to the boundaries conditions. (Lin)

As it was said, the essential idea behind finite elements is that a continuum structure is represented by artificial pieces, which can be 2 or 3 dimensional. Each element has its nodes connecting to either the external boundaries or nodes from the adjacent element. The variables measured are the nodes degrees of freedom. Figure 7 exemplifies this methodology application.

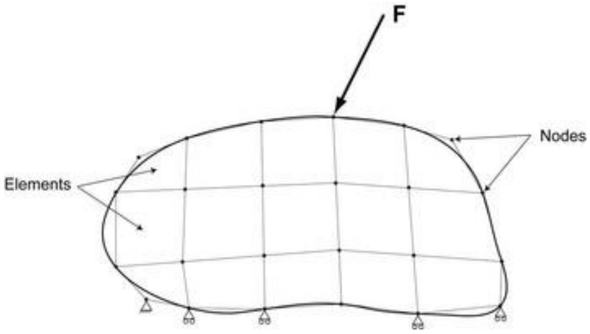


Figure 7: Continuum structure represented by quadrilateral elements with 4 nodes. (Morgan, et al.)

It is important to remark this approach is an approximation and the error comes from the fact that, although nodes respect the boundaries, it cannot be guaranteed that the whole region between two nodes from an element respects the boundaries associated to the continuum, as represented in Figure 8 (Hughes, et al., 2010). But, adjusting the finite elements type, properties and size reduces the error and generates a solution that is closer to the theoretical one.

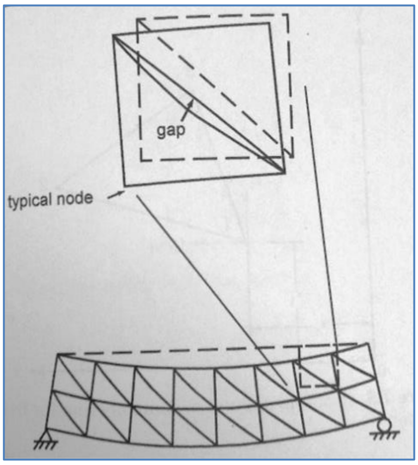


Figure 8: Visual representation of element deformation. (Hughes, et al., 2010)

Reducing elements size, however, means more equations. The alternative is to define element properties suitable for the analysis type being done. Although important to comment, these variations are not studied, since previous works do that. For example, Table 1 taken from Structural Modelling procedures course, summarizes discretization levels and element definition required for different structural analysis types.

Table 1: Discretization levels. (source: Ehlers' modelling course)

Level	Accuracy	Comments
3D solid model mapping all structural details	Very high accuracy, detailed strain information available, low discretization error	Fine mesh required (<1mm) to maintain element aspect ratio, very high computational cost (solving time: months), infeasible for large complex structure
3D shell model mapping all structural details	High accuracy, simplified strain information in thickness direction available, reasonable discretization error	Smallest structural member defines the minimum element size (~bulb width), high computational cost (solving time: weeks), feasible for large complex structures
3D shell model with beam elements for structural details	Accuracy depends on the correspondence between the shell and the beam element (DOF) and the level of deformation to be expected, simplified strain information available, potential risk for discretization error	Smallest structural member is modeled with beam elements, moderate computational cost (solving time: days), feasible for large complex structures
3D shells with enriched functionality (homogenized plates, super elements, macro elements)	Accuracy depends on capabilities of the enrichment, local strain information needs to be obtained from the enrichment, correct element orientation is vital	Element size depends on enrichment, typically one stiffened panel is one element, one element between decks, small computational cost (solving time: hours), standard for complex structures

As observed in Table 1, the more complex the discretization level, the longer is the estimated computational time. However, it is possible to use a medium level discretization, as 3D shell model mapping with beam elements, and reduce its computation time even further by modelling sections of the ship and not the entirety of its hull. Ship Structural Analysis and Design (Hughes, et al., 2010), provides the following finite element models, Figure 9.

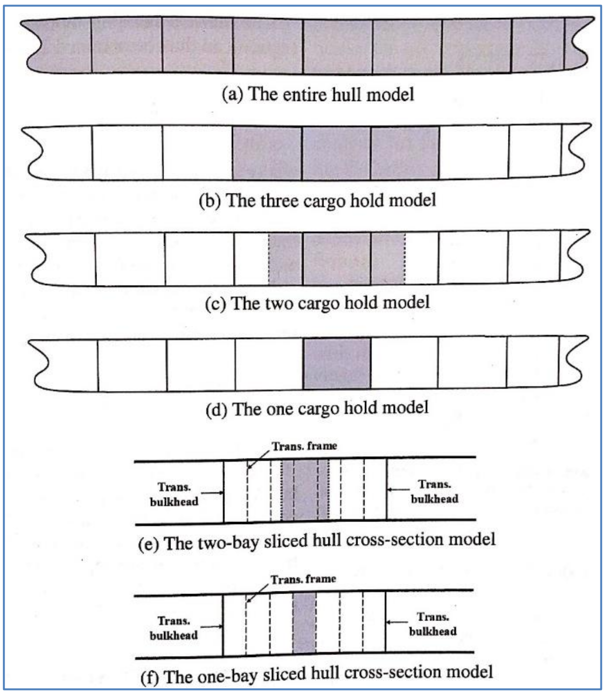


Figure 9: Model types for progressive hull analysis. (Hughes, et al., 2010)

Usually the full model (a) gives the best results for all types of stress analysis, when paired with a high discretization level, however would take a long time to be solved, while (f) presents the fastest solving time and is practical for pure hull-girder load analysis when transversal frame analysis is not desired, as pure horizontal and vertical bending moments, with sufficient precision. The two-bay model (e) already includes the frames, thus making possible to analyse effects on the frames. The one cargo model (d) is able analyse shear force effects and adding more cargo holds to the model, (c) and (b), takes bulkheads into consideration.

Also, classification societies stablish guidelines/suggestions to help the structural designer create a representative model depending on the type of structural analysis desired (IACS, 2015) (DNV-GL, 2015).

One important conclusion is that it is possible to obtain a representative model at early design stages, depending on the analysis level desired. Moreover, choosing a coherent discretization level also allows for a decreased computational time permitting that a number of tests can be done and a mapping of structural effectiveness is possible.

2.2 Platform Supply Vessel

The platform supply vessels are ships specialized in transporting cargo from shore to offshore structures, they might have additional secondary functions like crew transport and firefighting ability, but that is not part of their design. Their mission is to maintain and support offshore operations, Figure 10, and they have a broad range of cargoes, carrying almost everything necessary to maintain the platform operations: ranging from drilling equipment and cargo containers to liquid bulk, fuel and water. (Lamb, 2004)

Their mission must be performed continuously and ideally should be weather independent, which is a tough criterion to fulfil during the autumn and winter seasons on the North Sea, which are notorious for its harsh weather conditions as gale winds and high significant waves, Figure 11. (Burrows, 1996)

Figure 10: PSV main mission. (DAMEN, 2016)

Figure 11: PSV operating in harsh weather. (Marine Traffic, 2016)

PSVs are specialized shipping vessels that have many design and structural differences from what is usual for other cargo vessels such as forward superstructure, presence of cargo rail, presence of inner shell among others. All these characteristics highly influence the structural design of the platform in unique ways, resulting in the following requirements by classification societies (Burrows, 1996):

- Increased side shell thickness on these vessels;
- Enhanced strength of deckhouses and superstructures;
- Mixed or Transverse framing;
- Increased section modulus due to local requirements;

- Reinforced structure around deck equipment (cranes, winches, etc.).
- Presence of cargo rail to protect from green water. (Hansen, et al., 2013)

Many of these differences are related to the fact that they must have an intelligent balance between performance, seakeeping, station keeping, size constraints and safety requirements, since they operate in close distance to platforms in open waters and without mooring. The following section will detail the most significant characteristics according to the thesis scope of global conceptual analysis.

2.3 Structural Optimization

There are three main ways a structure can have its strength/mass ratio optimized. Optimization of Dimension, Topology and Shape.

2.3.1 Optimization of Shape

Optimization of shape aims to improve the structural characteristics by changing a profile main dimensions.

In ships, shape optimization is directly related to its main dimensions, mainly the Beam/Depth ration. Assuming a same sectional area, ships with high B/D will require more material to resist the same loads (Lamb, 2004). This is shown in equation to (2.5), since increasing the height of a profile and decreasing its breadth translates into an bigger Area Moment of Inertia.

This is an important detail that should be thought about when choosing the main dimensions and, although it might not always be under control as seakeeping, stability or draft requirements are affected, it still should be studied as it is one of the most effectives ways of increasing structural strength.

2.3.2 Optimization of Topology

Optimization of topology is directly related to framing style. It involves changing position of all the structural elements in a way that will be more cost effective. This is one main focuses of the structural designer, since the spacing between elements will have a great effect on local and global load strength alike.

As an example, a smaller spacing between longitudinal elements minimizes panel thickness and allows for a more efficient structure in relation to mass, the trade-off is a more difficult painting job and longer welding time.

2.3.3 Optimization of Dimensioning

This type of optimization aims to increase the performance of the section by changing its cross sectional properties in relation to acting stresses. For example Figure 12 depicts the bending tension distribution on a rectangular profile and it can be observed that the tension along the axial fibres that are farthest from the neutral axis.

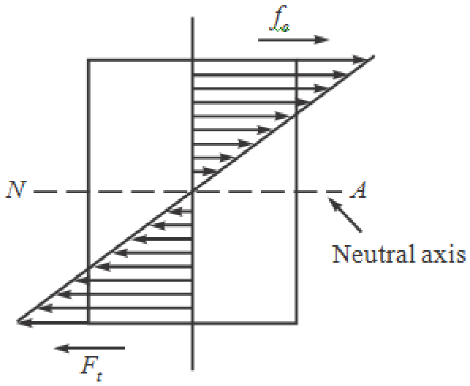


Figure 12: Bending stress distribution on a beam. (Experts Mind, 2012)

Moreover, according to equations (2.3) and (2.5), increasing the amount of material at the extremities is the most effective way of increasing the beam strength to bending stress. The natural solution is to shift material from the centre to the bottom and top, as illustrated in Figure 13. Again, this is shown in equations and (2.5)

Figure 13: Dimension optimization of a beam.

In ships this is made locally by changing the thickness on elements located at the main deck or the bottom.

3 Experimentation and Sensitivity Analysis

This chapter explains the concept of defining an experimentation procedure with the objective of modelling an observed phenomenon and use this information as means to control it and further improve it.

Assuming that the studied process is a black box with controllable factors, uncontrollable variables and a response emerging from it, as illustrated in Figure 14, its behaviour mapped by changing the factors and studying the response.

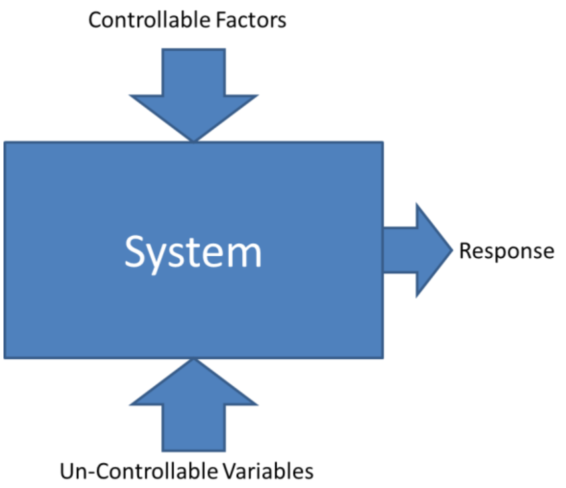


Figure 14: Black box system. (Anderson, et al., 2005)

The methodology presented in Figure 15 shows the steps that should be followed if one wishes to understand and improve such a system using the Design of Experiments and Response Surface Methods.

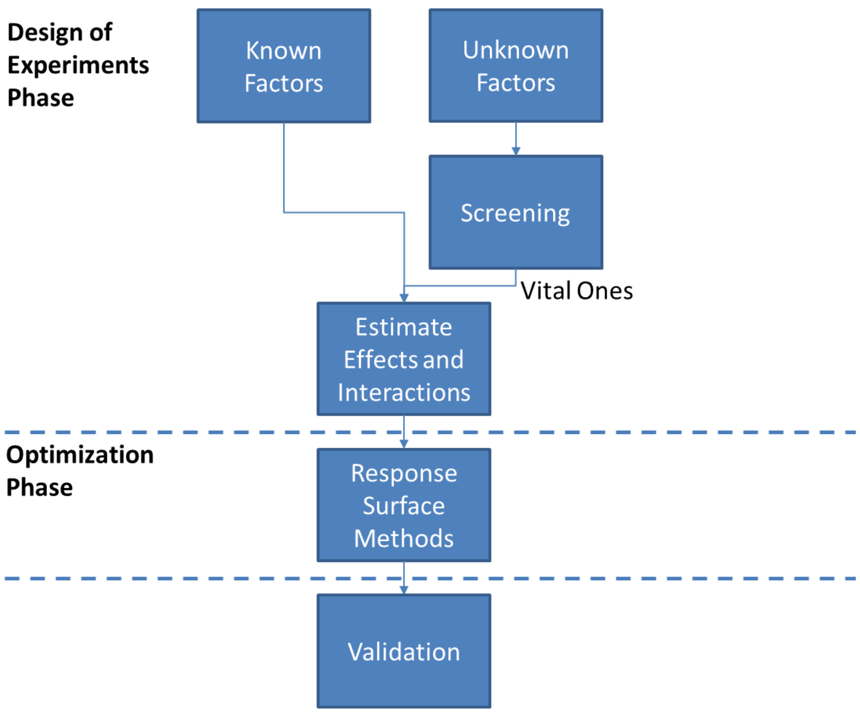


Figure 15: Strategy of experimentation. Simplified version based on (Anderson, et al., 2005).

First step is to analyse the factors and separate vital ones from trivial ones, which has been performed in previous works (Diewald, 2015) and (Brandt, 2015). Then, experiments are created focusing on Response Surface Methods for optimization. The final step is to validate the obtained improved solution by comparing expected and measured responses.

3.1 Design of Experiments

The design of experiments (DoE) objective is to describe the variation of information under conditions that are hypothesized to reflect the variation. The methodology involves selecting key parameters and analysing how their variation influences a type of response. In addition, with enough experiments it is even possible to understand the interaction between parameters and their combined response. (Anderson, et al., 2005)

In DoE the responses are studied by testing variables changes with lower and higher values in relation to the initial viable solution. These variable parameters are called factors and each variation is called level. If the level is varied once up and down, then it is called a 2 level factorial design. The level variation is usually constrained by operational or theoretical limits and the possible combination of factor variations generate a factor space. Figure 16 illustrates a factor space composed of 3 factors and 2 levels. (Anderson, et al., 2005)

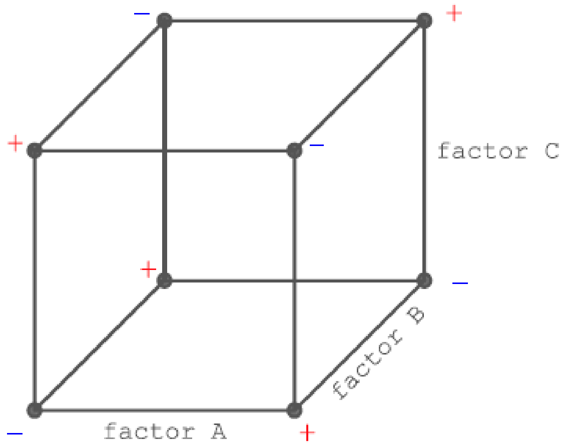


Figure 16: Example a factor space. (Diewald, 2015)

In the case of structural design main dimensions, topology variations, elements dimensioning and cross sectional arrangements are possible factors and the initial viable solution can be given by classification society (DNV-GL, 2015) minimum requirements (initial level) or the information coming from a similar vessel.

For the example show in Figure 16, a minimum of 8 experiments are necessary to obtain each possible parameter variation combination, as explained in equation (3.1).

$$Experiments\ Number = \ Levels\ Number^{Factors\ Number} \tag{3.1}$$

So, the number of experiments increases exponentially depending on the number of levels and factors. Thus for a complex system, like a ship structure, the number of direct experiments might be too great to be feasible. As an example, (Diewald, 2015) studied 23 parameters, that on two level factorial design would amount to 2^{23} experiments. However, there are alternatives to decrease the number of required experiments to obtain a model that explains the studied behaviour. One of them is the use of a screening plan (Figure 17), as devised by Plackett and Burman, which reduces the number of tests to 24 experiments.

	A	B	C	D	E	F	G	H	I	J	K	Q	R	S	T	U	V	W
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
2	-	+	+	+	+	-	+	-	+	+	-	+	-	+	-	-	-	-
3	-	-	+	+	+	+	-	+	-	+	+	-	+	-	+	-	-	-
4	-	-	-	+	+	+	+	-	+	-	+	-	-	+	-	+	-	-
5	-	-	-	-	+	+	+	+	-	+	-	+	-	-	+	-	+	-
6	-	-	-	-	-	+	+	+	+	-	+	+	+	-	-	+	-	+
7	+	-	-	-	-	-	+	+	+	+	-	-	+	+	-	-	+	-
8	-	+	-	-	-	-	-	+	+	+	+	-	-	+	+	-	-	+
9	+	-	+	-	-	-	-	-	+	+	+	+	-	-	+	+	-	-
10	-	+	-	+	-	-	-	-	-	+	+	+	+	-	-	+	+	-
11	-	-	+	-	+	-	-	-	-	-	+	-	+	+	-	-	+	+
12	+	-	-	+	-	+	-	-	-	-	-	+	-	+	+	-	-	+
13	+	+	-	-	+	-	+	-	-	-	-	-	+	-	+	+	-	-
14	-	+	+	-	-	+	-	+	-	-	-	+	-	+	-	+	+	-
15	-	-	+	+	-	-	+	-	+	-	-	+	+	-	+	-	+	+
16	+	-	-	+	+	-	-	+	-	+	-	+	+	+	-	+	-	+
17	+	+	-	-	+	+	-	-	+	-	+	+	+	+	+	-	+	-
18	-	+	+	-	-	+	+	-	-	+	-	-	+	+	+	+	-	+
19	+	-	+	+	-	-	+	+	-	-	+	-	-	+	+	+	+	-
20	-	+	-	+	+	-	-	+	+	-	-	-	-	-	+	+	+	+
21	+	-	+	-	+	+	-	-	+	+	-	-	-	-	-	+	+	+
22	+	+	-	+	-	+	+	-	-	+	+	-	-	-	-	-	+	+
23	+	+	+	-	+	-	+	+	-	-	+	+	-	-	-	-	-	+
24	+	+	+	+	-	+	-	+	+	-	-	-	+	-	-	-	-	-

Figure 17: Screening plan by Plackett and Burman for 23 factors with 2 levels. (Diewald, 2015)

From the computational experimental tests, it is obtained a statistical analysis and estimate effects and interactions between the many factors involved and obtain a regression that better represents the results observed during the simulation events. (Diewald, 2015) uses this methodology to study the influence of structural members on the strength of ship's middle cargo hold section when subjected to vertical bending moment forces. His conclusion states:

> "Regarding longitudinal strength, two loads cases are examined. In a hogging condition increasing the thickness of the deck, adding deck girders or increase their height are the most economic ways to increase the longitudinal strength. One should refrain from increasing the number or the thickness of longitudinal bulkheads because these actions are shown to be the least economic. In a sagging condition it is the thickness of the outer bottom that has by far the highest economic efficiency on the longitudinal strength. Changing the number of longitudinal girders or the number of longitudinals on the outer bottom do almost have the same economic efficiency"

In short, when preparing the design of experiments, it is possible to reduce the number of experiments by analysing those already known to the be most influential. The Plackett and Burman aims screening factor main effects on response, but it is not ideal to generate regression, as it does not map secondary effects (NIST/SEMATECH, 2015). Thus another DoE method called D-Optimal is used to map the design interval.

The next section introduces the nature of response surfaces and section 4.2 explains how they are applied to computer simulations.

3.2 Introduction to Response Surface Method

Response surface are used to analyse the response obtained through design of experiments regression. This is done by generating surfaces that reflect a response in function of any combination of 2 factors. A surface example is illustrated in Figure 18.

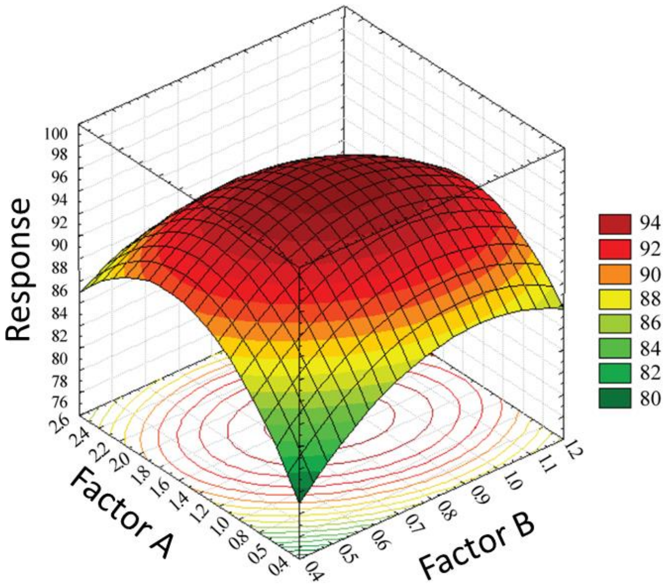


Figure 18: Response surface example. Adapted from (Sridevi V, 2011)

The curve is a great visualization tool and shows how to parameters are expected to affect the response of the system studied. However, there are two important remarks that should be made:

1. First and foremost, the regression is nothing but a simplified approximation of the real phenomenon, but this is actually an advantage for conceptual designs, since it allows the study, comprehension and optimization of complex systems in a shorter amount of time than using other methods. It also is a very reliable way to deal with uncertainties about factor correlation, as one can visualize the effects of changing one factor on the response.
2. Second, the regression and resulting surface are not a global optimum, but a local one, as it tracks the effects of variation on limited range of experiments. Again, this approach has its merits as it allows to improve upon a known design or process with a reduced amount of effort and time, which perfect for early designs.

The surface shown in Figure 18 has only two parameters, but it is also possible to measure effects of other factors using a main curve. Figure 19 compares how the yield of a chemical reaction is affected by temperature, time and, with the help of a second contour, rate of addition.

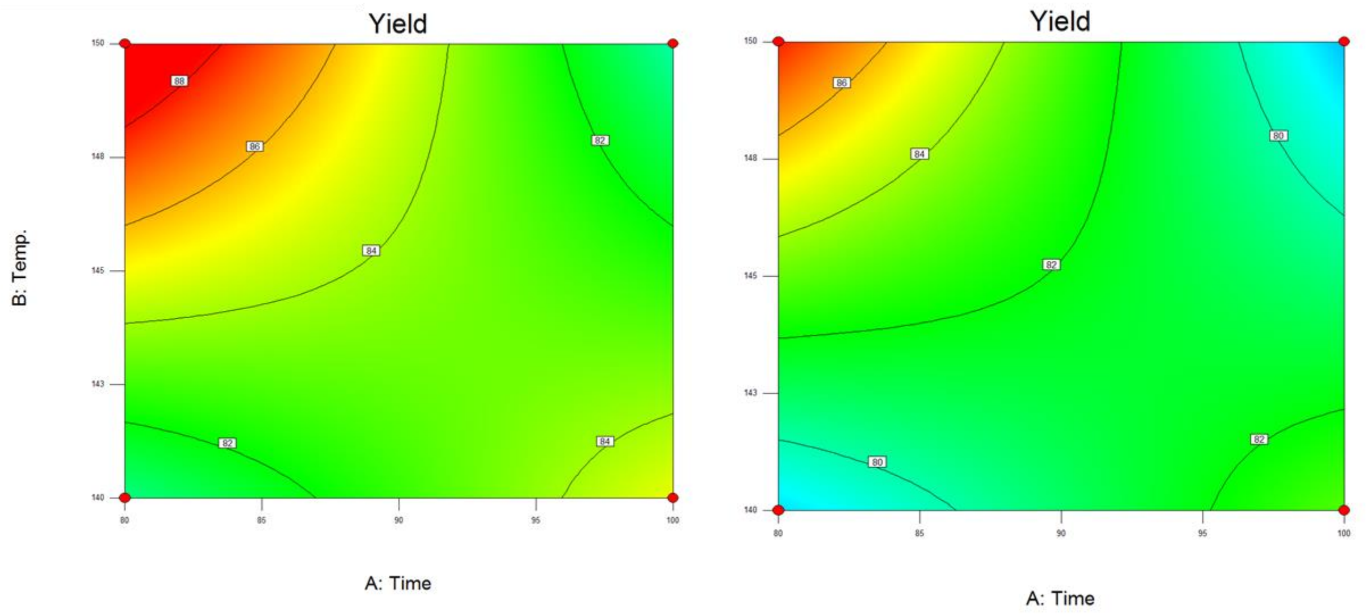


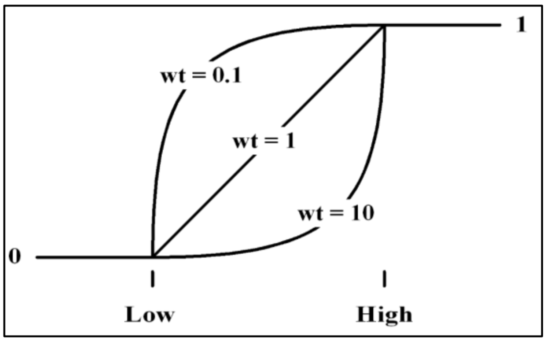
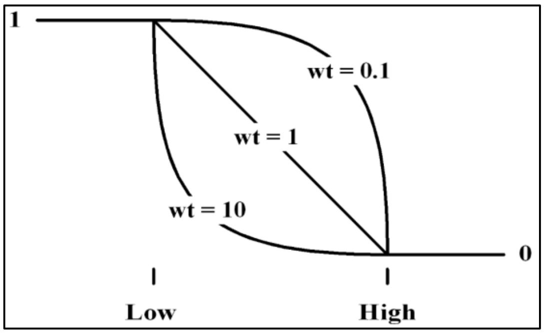
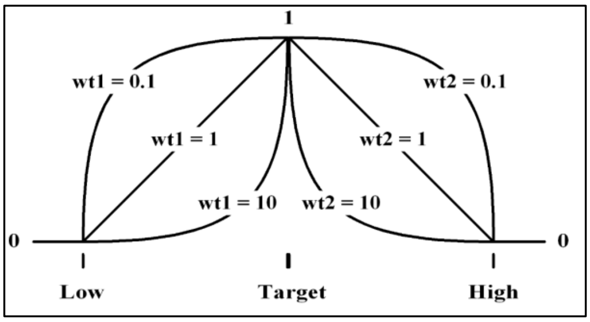
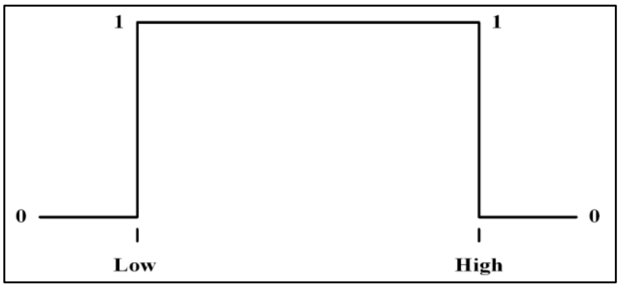
Figure 19: Chemical reaction's yield contour. The one the right has a lower rate of addition than the one on the left. (Anderson, et al., 2005)

The RSM allows the visualisation of not only multiple factors but also multiple responses. This is done through the use of a desirability function.

The desirability function measures how a given response compares to the combination of responses in the solution space criteria. It assigns a desirability grade for each possible solution in the viable solution space according to a stablished goal. The possible goals can be one or a combination of criteria, with maximization, minimization, target and range as objectives. All of them can have different weight and importance.

The desirability measures a solution's ability of achieving the desired goals through an objective function shown in equation (3.2), called the desirability function. It reflects the desirable ranges for each response (d_i). The desirable ranges for these goal parameters range from zero to one (least to most desirable, respectively) and can be modified by adding weights which change the goal curves shape and how desirability is assigned along the range. The following Table 2 explains the weighted goal parameters. (Anderson, et al., 2005) (Stat-Ease, Inc, 2011)

Table 2: Goal Parameters Meaning and weighted curves. (Stat-Ease, Inc, 2011)

 **Figure 20: desirability curves for goal is maximum.**	**Maximum:** $d_i = 0$ if response < low value $0 \le d_i \le 1$ as response varies from low to high $d_i = 1$ if response > high value
 **Figure 21:Desirability curves for goal is minimum.**	**Minimum:** $d_i = 1$ if response < low value $1 \ge d_i \ge 0$ as response varies from low to high $d_i = 0$ if response > high value
 **Figure 22: Desirability curves for goal is target.**	**Target:** $d_i = 0$ if response < low value $0 \le d_i \le 1$ as response varies from low to target $1 \ge d_i \ge 0$ as response varies from target to high $d_i = 0$ if response > high value
 **Figure 23: Desirability curves for goal as range.**	**Range:** $d_i = 0$ if response < low value $d_i = 1$ as response varies from low to high $d_i = 0$ if response > high value The range cannot have weight assigned.

The final desirability is determined through the formula:

$$D = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \tag{3.2}$$

Which can be expanded to include the importance (r_i) of each goal, which varies from 1 to 5 or least to most important.:

$$D = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{\frac{1}{\sum r_i}} \tag{3.3}$$

4 Methodology

The methodology for this structural sensitivity analysis starts with model creation, then the experiments are defined and each one of them is solved using FEA. After that, regression models are created and translated into surfaces that are used as visual representation of factorial response influence. Figure 24 shows this process, which is explained in detail in sequence.

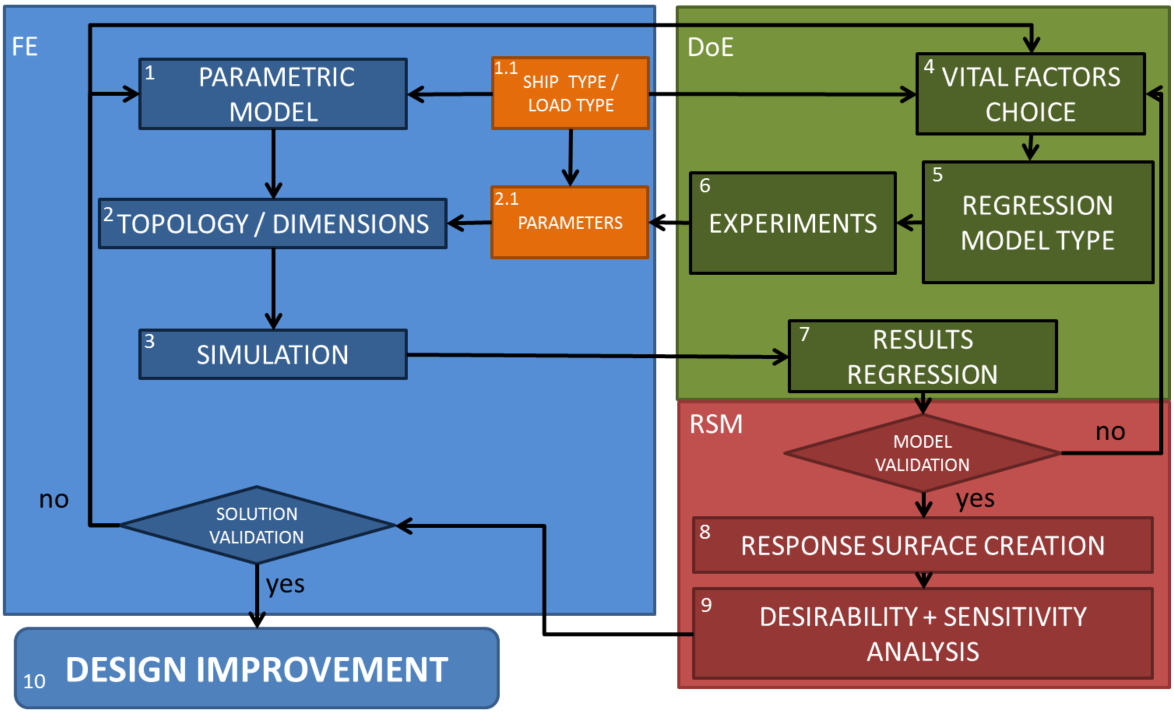


Figure 24: Applied methodology

Following the figure's logic, the first step of the procedure is to select ship type, loads to be applied and responses to study (step 1.1). This defines the parametric model creation directly (step 1). The load type defines the forces acting on the vessel that are studied as: global loads, local loads, bending moments, shear forces, torsional forces, etc. In this case the vertical bending moment is studied acting on a PSV cargo hold model based on the midship section. This process is done by writing an APDL script, which allows the creation of a parametric model, where inputs are changed at will and complex interaction between structural elements is solved using FEA.

The model topologies and dimensions can either be variable or fixed (step 2), but they are defined according to an input file containing all the initial parameters (step 2.1). This file feeds the FE model (step 2) and allows for it to be solved (step 3). However, there are 3 different types of data that define this file:

1. Initial Parameter, which is the original case;
2. Fixed parameters, which are not going to be tested;
3. Variable Parameters, which are defined according to the design space and DoE methodology.

The design space[2] is contained within the case definition (step 1.1) and feeds into the design of experiments procedure, but only parameters that are expected to be the most influential to the response(s) can be selected and this is done by means of a screening process[3] (step 4). They are called vital factors, only vary within the design space and are fed into a DoE procedure (step 5). This procedure generates the experiments necessary to obtain a regression of the system's response(s) within the given design space (step 6).

The vital factors definition for this study follows general conclusions from previous works and case related assumptions and the experiment generation is done according to a procedure for computer simulation responses documented by (Anderson, et al., 2005) called augmented D-Optimal.

Each experiment is different from the other in at least one of the factors and these changes are transferred to the model via an input file (step 2.1), which allows each experiment to generate a new model (step 2) and then be solved (step 3). Because of the uniqueness of each experiment, their total number also defines the amount of runs necessary for the FEA, thus the necessity of a simplified FE model, as complex iterative procedures with fine mesh discretization could require prohibitively long time to solve.

The responses resulting from these simulations (step 7) are sent back to the design of experiments procedure and multifactorial regressions are obtained. These regressions significance should initially be validated for their statistical relevance and their ability to recreate the same responses obtained through the FEA. If deemed valid, they can then be represented in the form of surfaces using Response Surface Methods (step 8), if not, then either the factors chosen are insufficient, the number of experiments too few or the order of the regression not high enough, in any case the DoE procedure must be redone.

To make multi-response model and obtain improved solutions for the system, desirability functions concept is implemented (step 9). This requires goals to be defined, for example: Minimization of a response and maximization of another. The method compares solution and

[2] The design space is defined by the interval variation of each individual parameter.
[3] Note that this process was already performed by previous works.

grades each possible one according to their ability to achieve the defined goals (section 3.2). The best solutions are the ones that have the highest overall desirability. This also allows a response surface derived from the desirability function to be generated (step 9).

Besides obtaining improved design options, it should be possible to understand how changes in key factors affect the desirability by studying the many response surfaces. Moreover, all the best solutions obtained should be validated by comparing regression and simulation responses. If the responses do not agree, then either the DoE procedure must be altered or the model should be revisited from the beginning. Finally, the designer will have obtained a design that is more efficient and elegant in relation to the initial case.

The following sections detail 2 critical steps of this methodology, the FE model creation and the DoE approach for computer simulation.

4.1 FE Model Creation Guidelines

The first step of the methodology is the creation of a finite elements model that is able to be tested for vertical bending moment stresses and emulates the expected results from its real counterpart. This is achieved not only by replicating the structural elements geometry, but also material properties and correct boundaries. The middle ship's finite elements hull model creation can be summarized in a few steps:

1. Create a model with areas that represent one section of the structure. These areas positions and dimensions can be set as function of key input parameters, allowing for a parametric model;
2. Divide these areas into elements;
3. Define the material and sectional properties of these elements;
4. Replicate this frame a number of times necessary to generate the structure;
5. Define the constraints and loads that should be applied to the model;
6. Solve the model and read the desired solution.

I chose a single hold FE model to represent our PSV case, as it is able solve for vertical bending moment, as explained in Figure 9 (section 2.1.3), and is robust enough to accept future vertical shear force and local load analyses.

For the primary structure analyses, it is not required to obtain a perfect finite elements copy of all structural elements composing the region as the small features have little effect on the total section area moment of inertia. Moreover, that would generate a really fine mesh, which analysis would be computationally intensive, a less than ideal scenario for any kind of procedure that requires simulation repetition, as is the case. Figure 25 shows how a midship section FE model typically looks like. (IACS, 2015)

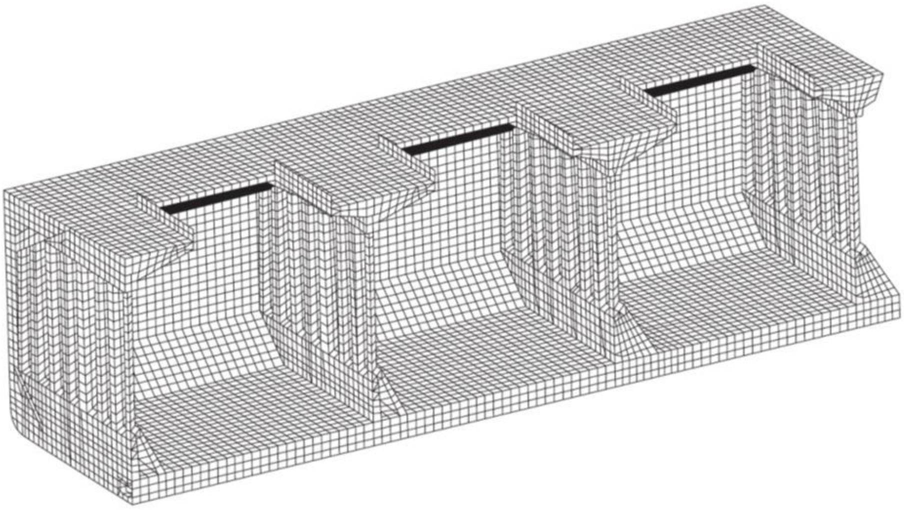


Figure 25: Example of FE model of midship region. (IACS, 2015)

All elements in the section can be translated to areas, except for stiffener heads, these areas are then meshed with shell elements and the material properties are applied. For good meshing results, it is important to guarantee that any area is not intersected by another, thus diminishing the odds that nodes are not connected when finite elements are created. Observe in Figure 26 how one should solve the problem of intersecting areas in the parametric model: the image on the left shows two intersecting areas, which will not generate connected mesh, however this is solved in the image on right by increasing area subdivision.

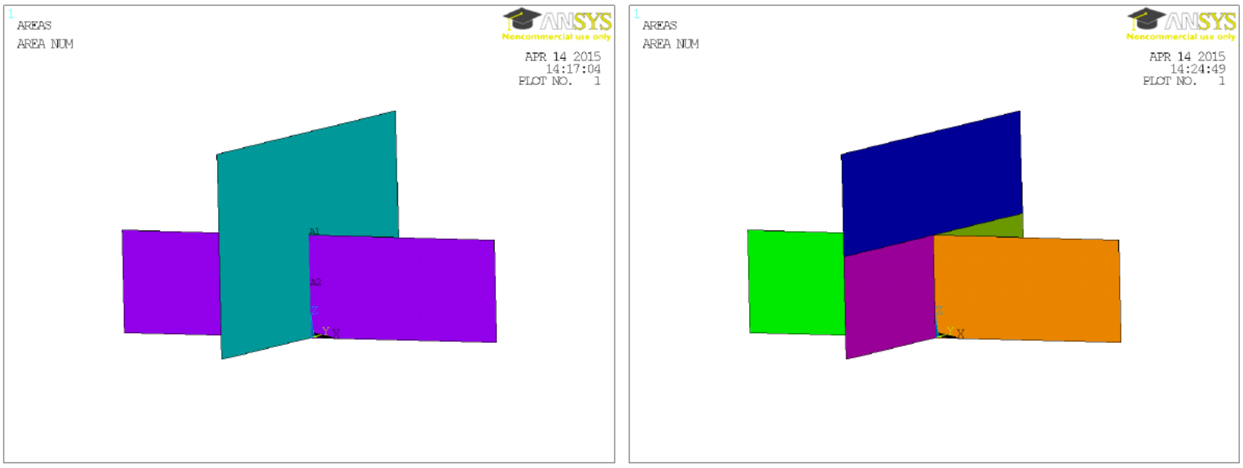


Figure 26: FE Area intersections. The image on the left shows two intersecting areas, which will not generate connected mesh. The image on right shows how to solve the penetration problem. (Diewald, 2015)

With those assumptions in mind, the stiffener is considered the smallest structural member to be modelled and the mesh division should be at least the size of the smallest structural element dimension. If further simplification is desired, stiffeners can be homogenised into the plate model, reducing even more the modelling and solving time, but still attaining acceptable result's precision.

Finite Element Selection

To model plates, webs and frames, a four-node shell type element with six degrees of freedom at each node is used: translations in the x, y, and z directions, and rotations about the x, y, and z-axes (SAS IP, Inc) (STU Bratislava, 2015), moreover, displacements are linear.[4] The element code name within ANSYS is SHELL181, which is well suited for both linear and non-linear applications and allows for a fast processing time, moreover it can also take into consideration thickness changes dues to stretching. (Diewald, 2015)

When modelling bulb flat stiffeners (HP profile), it is not possible to model its head profile properly without decreasing the minimum element size, however it is possible to use beam elements with the same length as the shell elements instead. This procedure requires the beam profile to have same sectional area and area moment of inertia as the stiffener head, but can be modelled as a rectangular section, Figure 27. (Kõrgesaar, 2010)

[4] The equations describing the element can be looked at the ANSYS Help File. (SAS IP, Inc)

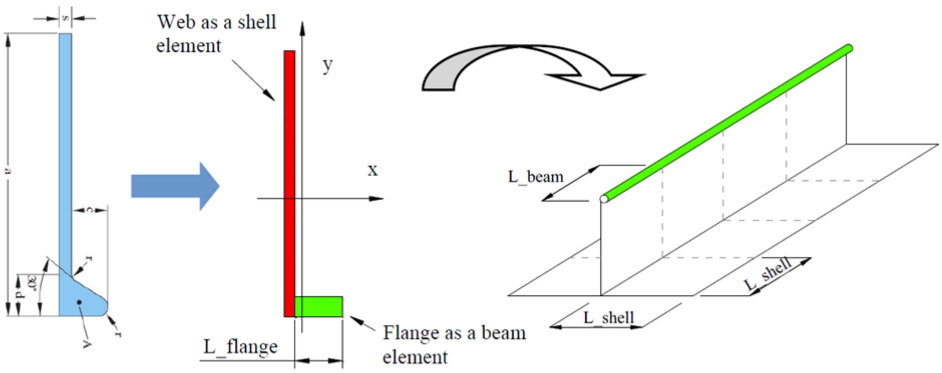


Figure 27: Stiffener discretization. (Kõrgesaar, 2010)

Still, the user must understand that a shell element is more limited than beam element, as the latter is capable reproducing higher order deformations while the former has a bilinear shape function. Nevertheless, for sufficiently small elements, this approach has minor deviations from the original profiles, as shown in Table 3, and should have negligible negative effects on the FEM model. (Kõrgesaar, 2010)

Table 3: FEM modelled HP profiles comparison to real properties. Adapted from (Kõrgesaar, 2010)

Stiffeners Type	Modelled Web		Modelled Head		Modelled Properties		Ruuki - Real Properties	
HP	**Height (m)**	**Thickness (m)**	**Height (m)**	**Base (m)**	**I_{xx} (cm^4)**	**I_{yy} (cm^4)**	**I_{xx} (cm^4)**	**I_{yy} (cm^4)**
100x6	0.1	0.006	0.014	0.013	76	1.72	76	1.7
120x8	0.12	0.008	0.016	0.014	164	3.1	164	3.1
140x8	0.14	0.008	0.018	0.015	266	4.348	266	4.32
160x8	0.16	0.008	0.019	0.018	411	6.55	411	6.55
180x10	0.18	0.01	0.023	0.02	717	12.12	717	12.05
200x10	0.2	0.01	0.026	0.023	1020	17.73	1020	17.21
220x10	0.22	0.01	0.028	0.026	1400	24.73	1400	23.89
240x10	0.24	0.01	0.031	0.028	2130	38.5	2130	37.43
260x12	0.26	0.012	0.034	0.031	2770	49.86	2770	49.11
280x12	0.28	0.012	0.036	0.034	3550	65.43	3550	63.34
300x12	0.3	0.012	0.039	0.037	4460	82.85	4460	80.44
320x13	0.32	0.013	0.041	0.04	5530	104.4	5530	100.8
340x14	0.34	0.014	0.044	0.042	7540	143	7540	138.6
370x13	0.37	0.013	0.047	0.047	9470	182.8	9470	176.7
400x16	0.4	0.016	0.052	0.052	14220	277.2	14220	266.6
430x15	0.43	0.015	0.055	0.055	17260	341.1	17260	327.9

Boundaries

The cargo hold model must be constrained and loads applied. As commented in (Diewald, 2015) and classification society rules (IACS, 2015) (DNV-GL, 2015), this midship model can be analysed as simple supported beam with moment acting on its extremities. Moreover, a ship has longitudinal symmetry on the Z plane, thus only half of a section needs to be modelled when the proper constraints are applied. The ship's usual coordinate system is illustrated in Figure 28. (IACS, 2015)

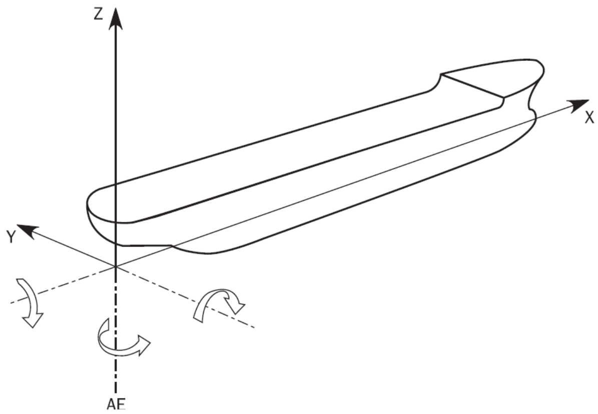


Figure 28: Reference coordinate system. (IACS, 2015)

The constraints requirements are listed in Figure 29 and Figure 30, where all section nodes should have rigid link to the Independent Point (Neutral Axis), which in turn has its degrees of freedom fixed according to the guidance. However, the rules assume a whole section model, if only half of a section is desired, it must include fixed rotation on the Z axis at the Independent Point when applying vertical bending moment (IACS, 2015). Moreover, all nodes located at the symmetry Z plane should be fixed for translation at Y axis, rotation at X, and rotation at Z axis.

Location	Translation			Rotation		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Aft End						
Independent point	-	Fix	Fix	$M_{T\text{-}end}$	-	-
Cross section	-	Rigid link	Rigid link	Rigid link	-	-
	End beam, see [2.5.4]					
Fore End						
Independent point	-	Fix	Fix	Fix	-	-
Intersection of centreline and inner bottom	Fix	-	-	-	-	-
Cross section	-	Rigid link	Rigid link	Rigid link	-	-
	End beam, see [2.5.4]					
Note 1: [-] means no constraint applied (free). Note 2: See Figure 17.						

Figure 29: Boundary constraints at model ends (IACS, 2015).

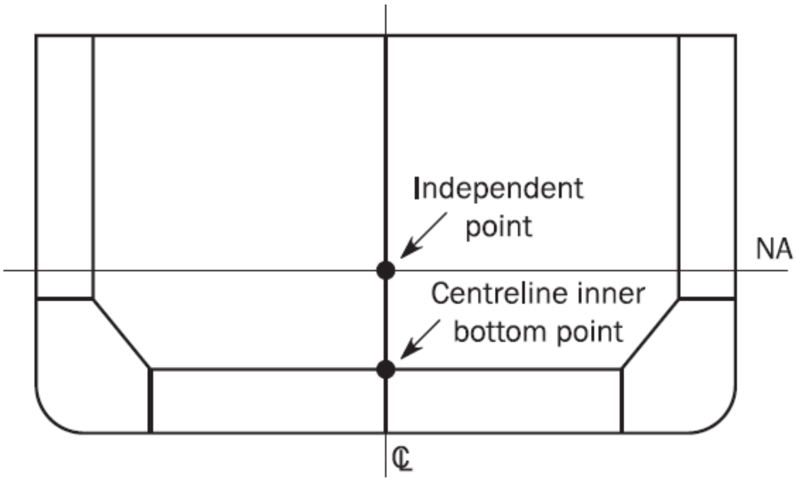


Figure 30: Boundary conditions applied (IACS, 2015).[5]

I chose the vertical bending moment analysis because of the background data from previous works that allows for result comparison, verify the findings and improve upon them. The Bending Moment is calculated using classification societies rules, specifically DNV-GL's guidance values for still water bending and wave induced moment (DNV-GL, 2015). Figure 32 and Figure 31 illustrates the formulations for predicted Sagging and Hogging conditions.

[5] Independent point is coincident to the sectional profile Neutral Axis.

Hogging condition:

$$M_{wv-h} = 0.19 f_{n\ell-vh} f_m f_p C_w L^2 B C_B$$

Sagging condition:

$$M_{wv-s} = -0.19 f_{n\ell-vs} f_m f_p C_w L^2 B C_B$$

Figure 31: Wave induced bending according to DNV-GL rules Pt3Ch4 (DNV-GL, 2015).

Hogging conditions:

$$M_{sw-h-min} = f_{sw} (171 C_w L^2 B (C_B + 0.7) 10^{-3} - M_{wv-h-mid})$$

Sagging conditions:

$$M_{sw-s-min} = -0.85 f_{sw} (171 C_w L^2 B (C_B + 0.7) 10^{-3} + M_{wv-s-mid})$$

Figure 32: Bending moment calculation in seagoing condition according to DNVGL rules Pt3Ch4 (DNV-GL, 2015).

Their total is summed and the biggest between those values is used on the model. These functions are implemented directly in the code and it adjusts for main dimension changes.

Finally, the vertical bending moment is applied at the independent point on both extremities, thus allowing a constant moment distribution along the hull beam model, shown in Figure 33 and Figure 34.

Figure 33: Hull beam support model with vertical bending moment applied at extremities. (Diewald, 2015)

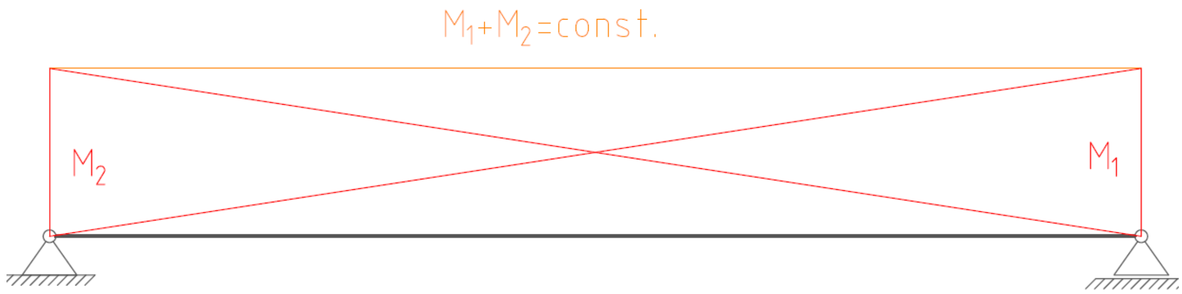


Figure 34: Constant moment distribution. (Diewald, 2015)

The parametric FE model for this report was done by writing an ANSYS Parametric Design Language code. The model is created in code format and after that ANSYS interprets and solves the model. This allows the user to make major initial parameter changes without having to redesign the model manually.(The following sources aided this model creation by teaching APDL technics: (University of Alberta, 2016); (Budgell, 1999) (SimuTech Group, 2016); (STU Bratislava, 2015); (RISA Technologies Inc, 2016)).

APPENDIX A shows the simple case code as example.

The main case model will analyse at first longitudinal strength, but will be complex enough to take effects on frames into consideration and allow the opportunity to implement future local strength analysis through the addition of vertical shear forces represented by the local loads at the frames. Nevertheless, there are other ways to create a parametric model and for different load conditions and the methodology here presented for both model creation, analysis and RSM study should apply to them with equal benefits.

4.2 Design of Experiments applied to simulations

DoE were developed to model, in a simplified way, complex problems that cannot be easily explained or optimized by other means. It has its origins in real life experimentation, but can be applied to computer simulations to help improve designs at lower computational time and cost and this has approach has already been performed by aerospace industry, as an example the wing body optimization work done by NASA and described at (Response Surface Model Building and Multidisciplinary Optimization using D-Optimal Designs, 1998). They suggest optimization models for complex computational designs that try to reduce the amount of experiments required, while maintaining a good level of control over the responses:

1. The first is the use of Central Composite Designs (CCD) model for up to five factors in the design;
2. The second suggests the use of D-Optimal (Determinant based Optimal Design) model for when 6 or more factors are required to be analysed, with an over determination of 50% and geared for quadratic model.

These models are chosen mainly because of their capacity to generate reliable quadratic surface models with reduced amount of experiments necessary. Although our model will be done using D-Optimal methodology, a quick introduction to Central Composite Design is made aiming to explain the reasons behind the model definition choices.

4.2.1 Central Composite Design

Recall that factorial experiments involve varying a variable (factor) through different levels, Figure 16, however CCD adds up to this idea by including axial points on the cubic space solution (or alphas), as illustrated in Figure 35 for a 2 factors CCD.

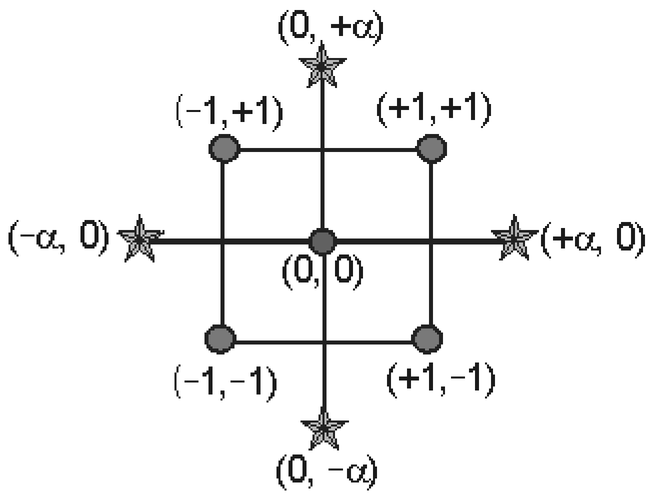


Figure 35: Central Composite Design build up for 2 factors. (Stat-Ease, Inc, 2011)

In summary, the CCD experiments are built up from (Anderson, et al., 2005):

1. Two-level factorial design including the central point;
2. Axial points with alpha distance to the central point;

A typical experiment should contain central point repetitions to estimate the pure error involved in the process, however the nature of computer design simulations means that every experiment at a given setup would result always in the same response, thus one central point is enough in that case. In short each factor has 4 levels, being 2 levels and 2 alphas plus only one centre point. For a 2 factorial CCD with 2 factors a minimal of 9 experiments are needed. The minimum amount of n experiments can be calculated by the following equation (4.1), where k is the number of factors:

$$2^k + 2 * k + 1 = n \tag{4.1}$$

- 2^k determines the factorial level combination;
- $2 * k$ determines the number of alphas;
- 1 represents the centre point;

The axial points help with quadratic curvature generation and better model the boundaries of the test space, contained within the factor levels. (Anderson, et al., 2005) To define these alpha levels, the user should know the real limits of the experimentation, for example if you can only have a maximum of 7 stiffeners on a region it makes no sense idealize an experiment with 8. Usually the alpha value varies from 1 to (face centred CCD) to the square – root of the number of factors ($\sqrt{k}$), to define the desired alpha level refer to (Anderson, et al., 2005).

4.2.2 D-Optimal Overdetermined.

As it was commented, Determinant based Optimal Design will be used to model our experiments, as it can handle a higher number of factors while requiring feasible number of experiments, when compared to CCD. For example, for a quadratic model with 6 factors, CCD would require at least 76 experiments, while a 55% overestimated D-Optimal would require 45, 29 for minimum fitting plus 16 for overestimation (Anderson, et al., 2005) (Response Surface Model Building and Multidisciplinary Optimization using D-Optimal Designs, 1998).

The experiment's points choice for this method is based on Fisher's information matrix $X'X$ determinant maximization. The Fisher's matrix is used to estimate confidence regions for model coefficients. The D-Optimal algorithm selects candidate points that would maximize information matrix determinant, thus minimizing the confidence region for the model coefficients and allowing for a more precise representation of the system's behaviour.

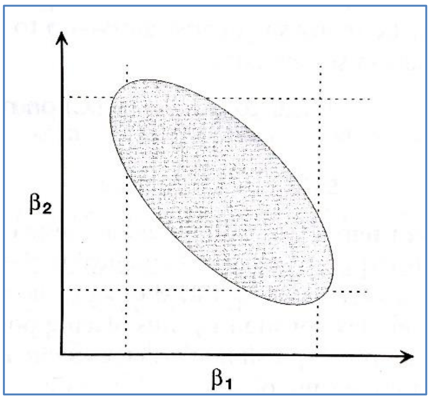


Figure 36: Confidence space ellipsoid. (Anderson, et al., 2005)

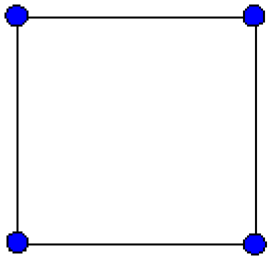
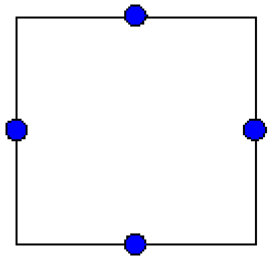
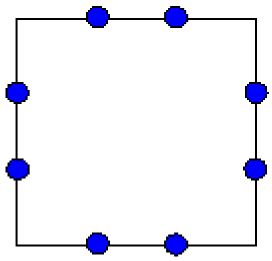
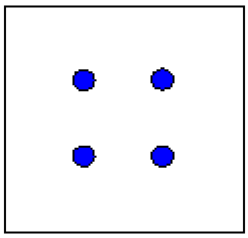
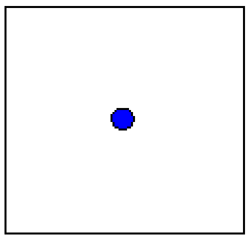
This confidence space, illustrated in Figure 36, represents how precisely the coefficients (β's) can be estimated in the chosen model, with a smaller space meaning a bigger confidence. However, before determining the final desired experimentation points, the initial candidate points should be defined and only then the D-Optimal will refine this choice and select the best ones, according to its algorithm. The authors from RSM simplified propose the following a procedure to select candidate points within the test space according to the expected model type[6]:

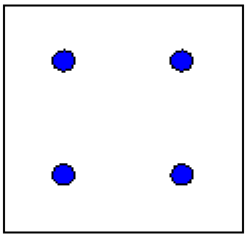
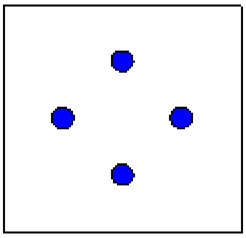
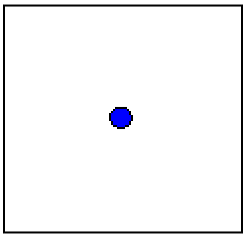
- LINEAR MODEL: Vertices, checkpoints, centroid.
- TWO-FACTOR INTERACTION MODEL (2FI): Same as linear.
- QUADRATIC: Same as above plus centres of edges, constraint plane centroids and interior points.
- CUBIC: Same as quadratic plus thirds of edges and triple bends.

These points locations within the factor space are illustrated in Table 4.

[6] Higher order model types studies can perform lower order regressions, but the opposite is not true.

Table 4: Possible candidate sets for optimal design. (Anderson, et al., 2005) (Stat-Ease, Inc, 2011)

	Vertices: the corners of the design space.
	Centres of edges: midpoints between adjacent vertices.
	Thirds of edges: two points equally spaced between adjacent vertices.
	Triple blends: averages of three adjacent vertices.
	Constraint plane centroid (only applied when a constraint is used in a region of the space): centre points in the planar surfaces of the experimental region

	Checkpoints: the average of the centroids and vertices.
	Interior points: the average of the centroids and (if these points are selected) centres of edges, thirds of edges and constraint plane centroids.
	Overall Centroid: Centre of Design Space.

On the other hand, one might not require all these candidate points to create a relevant model of the response, thus, depending on the type of model desired (linear, quadratic, cubic, etc.), the D-Optimal[7] methodology will determine the minimal required design points for all factors combination. (Anderson, et al., 2005)

After the minimum number of experiments according to the D-Optimal are defined as well as their location on the design space, then a new set of points should be created using distance based method. The distance based design scatters extra experimental points across the space according to an algorithm that maximizes their Euclidian distance from all the other points already in it. (Stat-Ease, Inc, 2011)

Euclidean Distance between coordinates *a* and *b* in a *n-space* is defined as:

[7] The Design Expert Software performs the D-Optimal selection algorithm for the user, thus I will not enter in details about it. However, one can understand more about the process of finding the factors that minimize the information matrix at Atkinson and Donev. (Atkinson, et al.)

$$d(a,b) = \sqrt{\sum_{i=1}^{n}(a_i - b_i)^2} \tag{4.2}$$

where a_i (or b_i) is the point's coordinate at i dimension.

As an example, if a line AB contains a point C, then its maximum Euclidean distance to them would be at the exact middle, however if one desires to add a fourth point D with maximum Euclidean distance, then it could be located between AC and between CB, both of which are correct answers. This is illustrated in Figure 37.

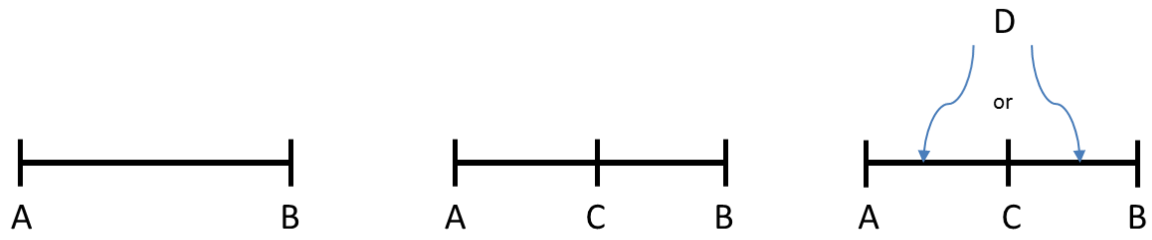


Figure 37: Euclidean distance maximization example illustration.

The number of extra points added using distance based design, according to the proposed procedure, should be at least 50% more than the minimum required by the D-Optimal design method. (Anderson, et al., 2005)

The overestimation's main objective is to "plug the remaining gaps" in the factorial space, allowing the regression to better map the whole experimental region behaviour, not only the region close to the experimental points, (Anderson, et al., 2005). For example, if one expects a system to behave in a linear way, then choosing only 2 experiment points within the solution space should be enough to describe its linear function. However, if one is not sure, then a few extra experiments could be added based on the distance method and be sure to obtain a regression that will explain the design space in an improved way. Figure 38 compares these situations.

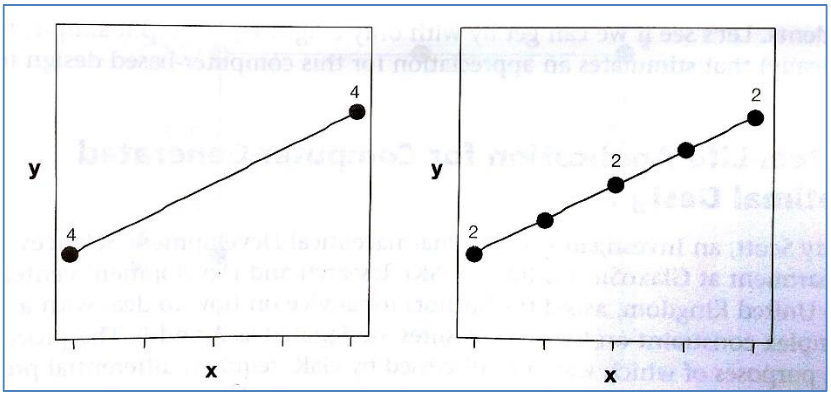


Figure 38: Assuming 8 experiments are performed to test a supposed linear model. The left image represents optimal design to represent a model and the right image represents a sensible design, where the designer can check if the linearity is fitting. (Anderson, et al., 2005)

The final step is replicate definition, which are repeated experiments with same level for all factors, then they can be used to predicted internal experimental errors. Since the study involves computer simulations, there should be no difference between replicates, however it is recommended to add at least one replicate to map possible code changes, (Anderson, et al., 2005).

These multifactorial design of experiments methods are complex to perform manually, thus the program Design Expert 8 will be used to assist at experimentation definition, points creation, regression analysis, response surface plotting and multi-response study. APPENDIX - B explains how to obtain the experiments necessary for a RSM optimal design model for simulation purposes using Design Expert 8.

5 Methodology Application – Simple Hull Beam Case

A simple case is performed to validate the methodology. The parameters and boundaries are based on the OCV case study by (Brandt, 2015) on hull beam material utilization. The work concluded among others that:

> "A midship section with increased depth and narrowed beam has a better material utilization."

The methodology presented in section 4, Figure 24, is used to perform the simple case study.

5.1 Simple Hull Beam – Initial Conditions and Design Interval (Step 1.1)

I analyse a ship section as if it were a simplified beam without other features, as illustrated in Figure 39, and generate a parametric model accordingly, which is solved for vertical bending moment.

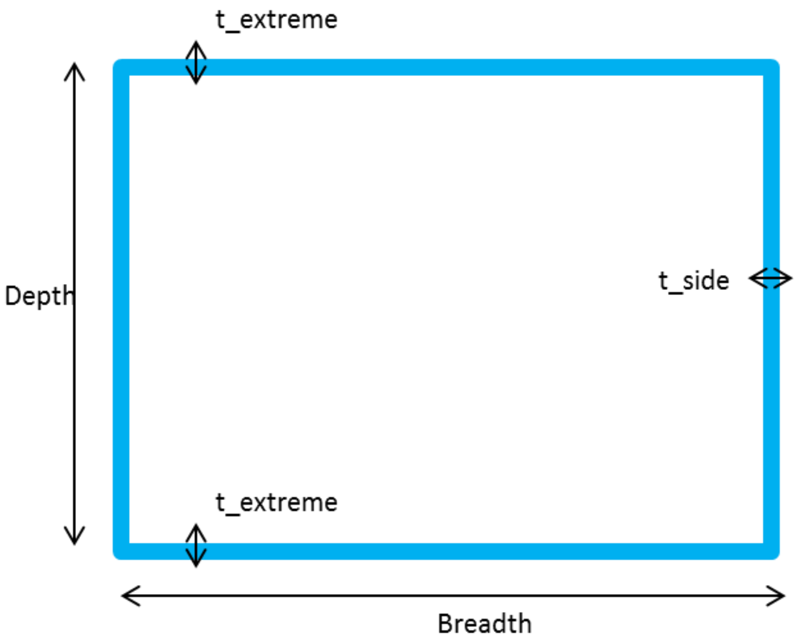


Figure 39: Simple case hull section representation.

The design interval is defined as:

- Depth: 8m-10m;
- Breadth: 18m-23m;
- Extremities thickness: 0.03m-0.04m;
- Sides Thickness: 0.01m-0.02m;

Moreover, I assume a constant beam length of 79,5m to perform all stress simulations. Finally, 3 responses will be analysed for each experiment:

- Internal Area;
- Maximum Bending Stress;
- Section's linear mass,

The internal area is approximated by:

$$Area = Depth * Breadth \tag{5.1}$$

The linear mass by:

$$Linear\ Mass = 2 * 7{,}8 * Depth * t_{extremes} + 2 * 7{,}8 * \ Breadth * t_{sides} \tag{5.2}$$

Where 7,8 ton/m^3 is the steel's specific mass.

Finally, the stress shall be determined by finite elements analysis.

5.2 Simple Hull Beam Parametric Model (Step 1, 2 and 3)

A simple parametric hull beam model was created using ANSYS parametric design language and the code is shown in Appendix A. Moreover, the same procedure described on section 4.1 was applied and the boundary conditions. These are the steps 1 and 2 of the methodology, Figure 24. The simplified hull section is described by only 2 main dimensions, Depth and Breadth, and 2 main thicknesses, sides thickness and extremes thickness. The bending moment is applied and its magnitude depends on the Breadth value that comes from rules formulation.

After each experiment is solved, step 3, data is gathered the maximum von Misses equivalent stress measured at the longitudinal middle of the model, as exemplified in Figure 40.

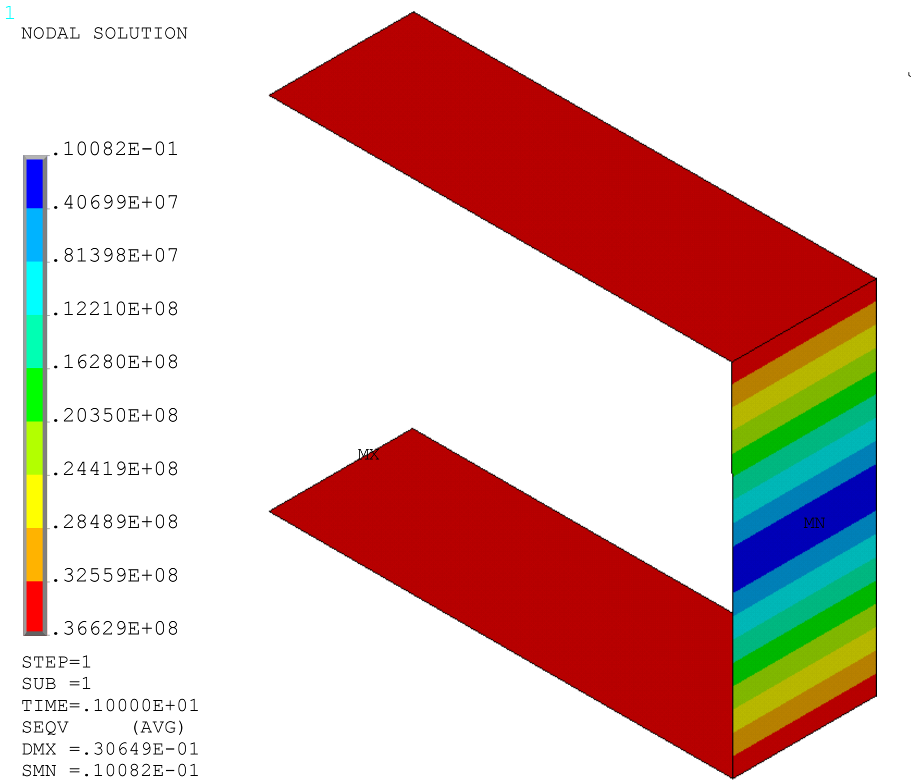


Figure 40: Nodal maximum von Misses stress.

But before proceeding to the FE simulations, the experiments inputs must be defined.

5.3 Simple Hull Beam Case - DoE using Design Expert 8. (Steps 4, 5, 6)

The vital factors are defined as being: Depth, Breadth, Extremities Thickness and Side Thickness.

I start by applying the Augmented D-Optimal methodology, section 4.2.2, to define the experiments that shall be performed (Steps 5 and 6), this process is done with aid of a specialized Design of Experiments software, Design Expert 8. The procedure is explained in APPENDIX-B.

There are 4 factors with varying ranges, depth, breadth, side thickness and extremes thickness, all of which were assumed continuous. The following Table 5 summarizes the experiments that are performed according to the design interval and experiment generation criteria[8].

[8] Although the CCD is recommended for less than 6 factors, D-Optimal is applied here to maintain agreement with the main case. The results show that the regression obtained is relevant and that results match, thus this does not impose any problem.

Table 5: Simple case experiments

Experiment	Breadth (m)	Depth (m)	Side thickness (m)	Extremities Thickness (m)
1	23	8.95	0.01	0.03
2	18	10	0.01	0.03
3	18	8	0.0152	0.03
4	23	8	0.02	0.03
5	20.625	10	0.02	0.03
6	18	8.75	0.0102	0.031551
7	18.25	10	0.016072	0.032
8	21.25	8.8	0.01895	0.03355
9	23	10	0.014836	0.0336
10	20.4	8	0.01	0.03365
11	18	9.05	0.02	0.03365
12	20.375	9.55421	0.011	0.0345
13	23	8.58	0.01375	0.03525
14	20.375	9.9	0.02	0.036302
15	20.38218	8	0.012288	0.038918
16	23	8	0.01	0.04
17	18	8.4	0.01	0.04
18	18	10	0.01	0.04
19	22.125	10	0.01	0.04
20	21.075	8.773925	0.01615	0.04
21	18	10	0.018	0.04
22	18	8	0.02	0.04
23	18	8	0.02	0.04
24	23	10	0.02	0.04

For each of these experiments three response are analysed: Linear Mass, Stress and Area. The individual results are listed in Table 6. (Step 3 repetition)

Table 6: Simple case experiments measured response.

	Factor				Response		
Experiment	**Breadth (m)**	**Depth (m)**	**Side thick. (m)**	**Extrem. Thick. (m)**	**Mass (ton/m)**	**Stress (MPa)**	**Internal Area (m^2)**
1	23	8.95	0.01	0.03	12.1602	36.627	205.85
2	18	10	0.01	0.03	9.984	32.202	180
3	18	8	0.0152	0.03	10.32096	39.787	144
4	23	8	0.02	0.03	13.26	39.708	184
5	20.625	10	0.02	0.03	12.7725	30.873	206.25
6	18	8.75	0.0102	0.031551	10.2518	35.325	157.5
7	18.25	10	0.01607	0.032	11.61759	29.37	182.5
8	21.25	8.8	0.01895	0.03355	13.72328	32.259	187
9	23	10	0.01483	0.0336	14.37014	28.703	230
10	20.4	8	0.01	0.03365	11.95678	36.718	163.2
11	18	9.05	0.02	0.03365	12.27252	30.658	162.9
12	20.375	9.55421	0.011	0.0345	12.60533	29.658	194.66702
13	23	8.58	0.01375	0.03525	14.48811	32.38	197.34
14	20.375	9.9	0.02	0.036302	14.62745	26.224	201.7125
15	20.3821	8	0.01228	0.038918	13.90796	31.694	163.05745
16	23	8	0.01	0.04	15.6	31.207	184
17	18	8.4	0.01	0.04	12.5424	29.433	151.2
18	18	10	0.01	0.04	12.792	24.53	180
19	22.125	10	0.01	0.04	15.366	24.734	221.25
20	21.075	8.77392	0.01615	0.04	15.3613	27.718	184.91046
21	18	10	0.018	0.04	14.04	23.696	180
22	18	8	0.02	0.04	13.728	29.904	144
23	18	8	0.02	0.04	13.728	29.904	144
24	23	10	0.02	0.04	17.472	23.937	230

FEA is validated using the methodology from section 2.1.2.[9] The results from Table 7 show that the results obtained through the Finite Element Analysis are in accordance to the expected values, with minimal difference.

[9] Note, this is not regression validation, but FEA results vs theoretical results.

Table 7: Simple case stress (MPa) validation.

Stress FEM	Stress formulation	%
36.627	36.619	0.02%
32.202	32.192	0.03%
39.787	39.770	0.04%
39.708	39.688	0.05%
30.873	30.854	0.06%
35.325	35.314	0.03%
29.37	29.356	0.05%
32.259	32.244	0.05%
28.703	28.692	0.04%
36.718	36.709	0.02%
30.658	30.642	0.05%
29.658	29.649	0.03%
32.38	32.370	0.03%
26.224	26.211	0.05%
31.694	31.686	0.02%
31.207	31.20	0.01%
29.433	29.426	0.02%
24.53	24.524	0.02%
24.734	24.728	0.02%
27.718	27.70	0.03%
23.696	23.686	0.04%
29.904	29.892	0.04%
29.904	29.892	0.04%
23.937	23.926	0.04%

The next step is to perform the regression for all the responses and investigate the surface model representation.

5.3.1 Simple Hull Beam Case - Response Regression, Validation and Analysis (Step 7 and 8)

The objective here is to choose a regression model that would represent a given behaviour with as much fidelity as possible. The software suggests the best fitting model and the user should be always looking for Low standard deviation, R-squared near 1 and relatively low PRESS (Predicted Residual Error Sum of Squares), as quoted at the software help file:

> "If the model is significant, lack of fit insignificant, there is good agreement between adjusted and predicted R^2, adequate precision is over 4 and the residuals are well behaved; then the model provides good predictions for

AVERAGE outcomes. A low R-squared indicates there is variation around the average predictions." (Stat-Ease, Inc, 2011)

Figure 41, Figure 42 and Figure 43, taken directly from Design Expert 8, informs that the software was able to obtain a highly significant model for all responses. Note that more than one regression models are possible for most responses, however (Anderson, et al., 2005) recommend to always choose the simpler model (lower order ones).[10]

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.18	0.9922	0.9905	0.9855	1.08	
2FI	0.000	1.0000	1.0000		+	Suggested
Quadratic	0.000	1.0000	1.0000		+	
Cubic	0.000	1.0000	1.0000		+	Aliased

+ Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model maximizing the "Adjusted R-Squared" and the "Predicted R-Squared".

Figure 41: Mass model summary statistics from Design Expert 8.

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.57	0.9870	0.9843	0.9774	10.67	
2FI	0.44	0.9947	0.9907	0.9728	12.83	
Quadratic	0.050	1.0000	0.9999	0.9995	0.23	Suggested
Cubic	0.000	1.0000	1.0000		+	Aliased

+ Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model maximizing the "Adjusted R-Squared" and the "Predicted R-Squared".

Figure 42: Stress model summary statistics from Design Expert 8.

[10] This is due to the Occam's Razor principle (philosopher): "When confronted by many equally accurate explanation, then the simpler one most likely is the best choice."

Model Summary Statistics						
	Std.		Adjusted	Predicted		
Source	Dev.	R-Squared	R-Squared	R-Squared	PRESS	
Linear	1.88	0.9956	0.9946	0.9921	119.81	
2FI	0.000	1.0000	1.0000		+	Suggested
Quadratic	0.000	1.0000	1.0000		+	
Cubic	0.000	1.0000	1.0000		+	Aliased

+ Case(s) with leverage of 1.0000: PRESS statistic not defined

"Model Summary Statistics": Focus on the model maximizing the "Adjusted R-Squared" and the "Predicted R-Squared".

Figure 43: Internal area model summary statistics from Design Expert 8.

2FI models are used for Mass and Internal Area regressions. Quadratic model is used stress responses. The software predicts that a cubic analysis would probably result in an even better model, but the improvement would be marginal and require a greatly increased numbers of experiments to be performed. Figure 44, Figure 45 and Figure 46 show the regression equations obtained. These are the first stages methodology's step 8.

Final Equation in Terms of Actual Factors:

Weight =
+2.50772E-013
-2.71769E-014 * Breadth
+4.62497E-014 * Depth
-3.00043E-011 * t_sides
+5.08922E-012 * t_extremes
+7.75130E-017 * Breadth * Depth
+2.71827E-013 * Breadth * t_sides
+15.60000 * Breadth * t_extremes
+15.60000 * Depth * t_sides
-2.43325E-012 * Depth * t_extremes
+2.05786E-010 * t_sides * t_extremes

Figure 44: Simple case mass equation factors.

Final Equation in Terms of Actual Factors:

Internal Area =
-6.97157E-012
+1.36314E-013 * Breadth
+6.03467E-013 * Depth
-1.59408E-010 * t_sides
+2.69229E-010 * t_extremes
+1.00000 * Breadth * Depth
-5.60354E-012 * Breadth * t_sides
-2.63690E-012 * Breadth * t_extremes
+2.14442E-011 * Depth * t_sides
-3.03093E-011 * Depth * t_extremes
+2.60831E-009 * t_sides * t_extremes

Figure 45: Simple case internal area equation factors.

Final Equation in Terms of Actual Factors:

Stress	=
+186.89938	
+0.39401	* Breadth
-14.81441	* Depth
-427.33095	* t_sides
-3366.71152	* t_extremes
-2.35969E-003	* Breadth * Depth
+5.34636	* Breadth * t_sides
-4.27659	* Breadth * t_extremes
-1.37547	* Depth * t_sides
+101.27028	* Depth * t_extremes
+5991.13205	* t_sides * t_extremes
-5.14845E-003	* Breadth2
+0.42343	* Depth2
-47.41148	* t_sides2
+22971.44563	* t_extremes2

Figure 46: Simple case stress equation factors.

In addition to that, I compared the model's response regression predicted values versus the actual measured/calculated responses, which are shown in Figure 47, Figure 48 and Figure 49. They show that the regressions obtained fits closely the responses.

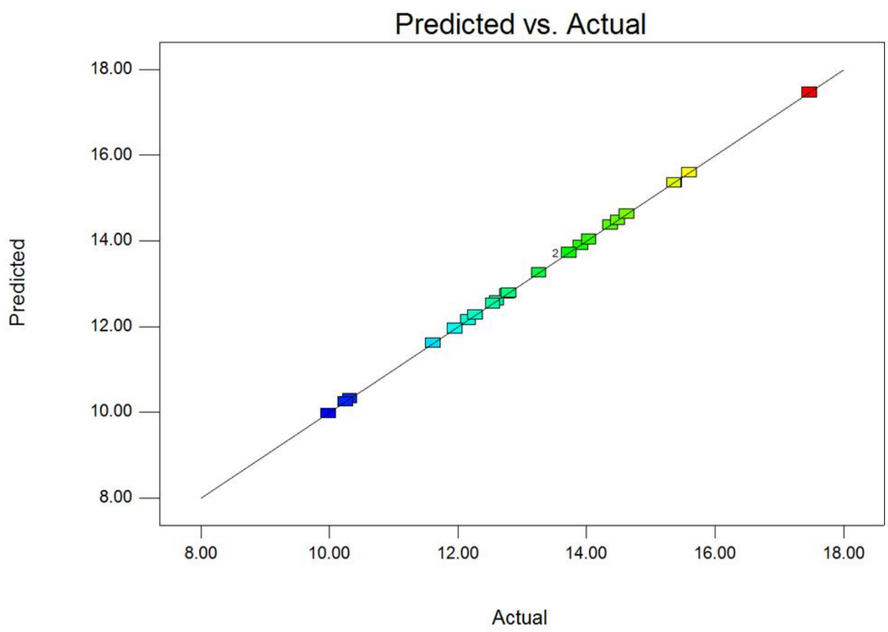


Figure 47: Mass predicted vs actual response curve.

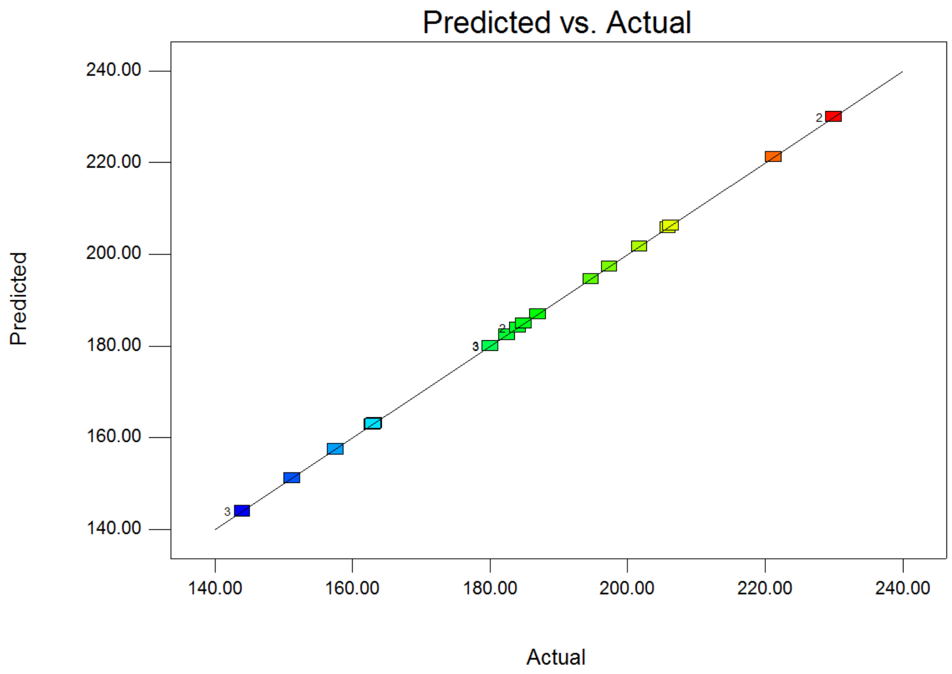


Figure 48: Internal Area predicted vs actual response curve.

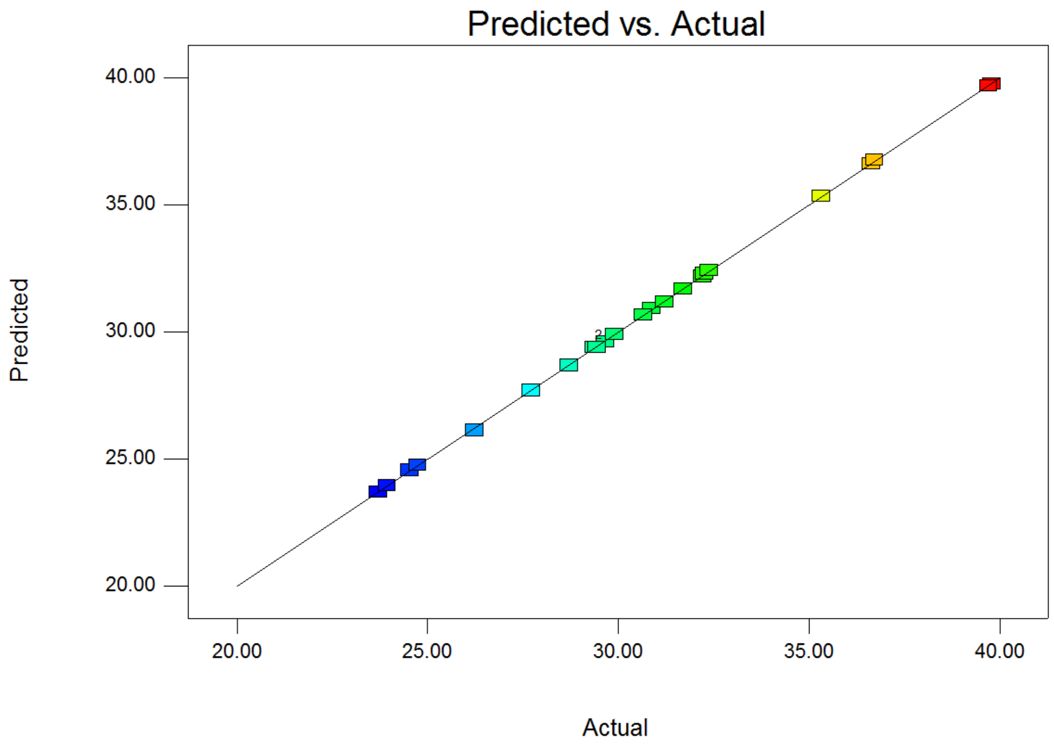


Figure 49: Stress predicted vs actual response curve.

The program also presents a 3D surface visualization for all responses, where factor/response interaction is observed. Since there are 4 factors, the 3D response surface plots can only be done in function of 2 at a time. However, the factors that are not included in the plot can be changed at will and their effect on the curve observed. This is shown in Figure 50, Figure 51 and Figure 52.

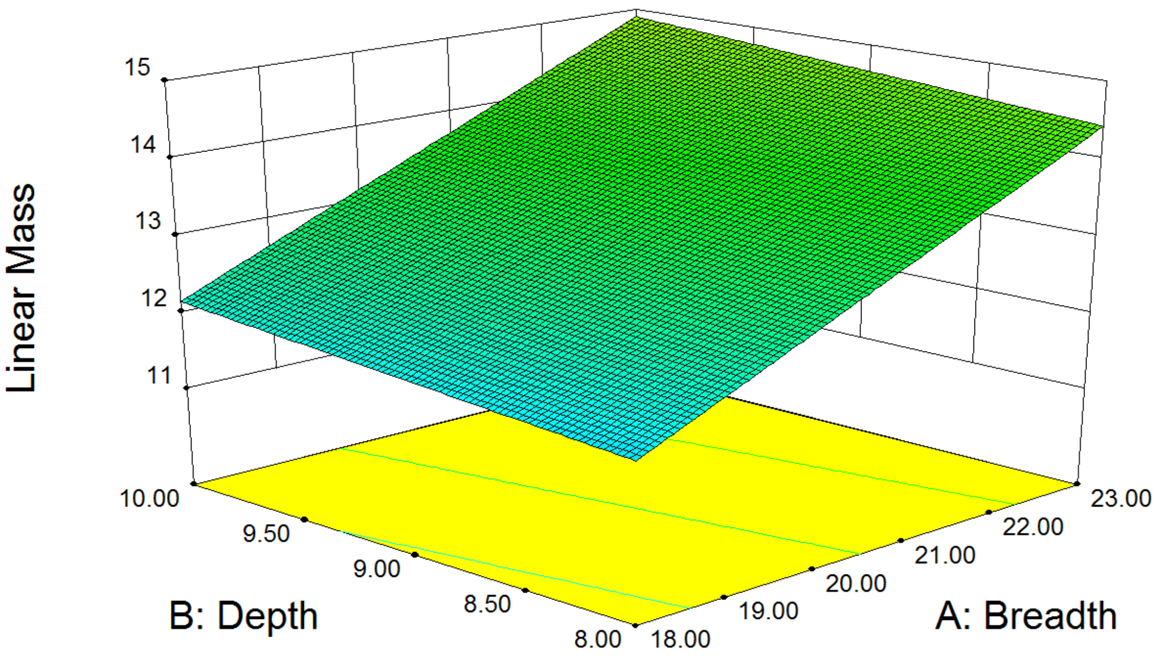


Figure 50: Mass response surface in function of depth and breadth. (t_{sides} = 0.015 and $t_{extremes}$ = 0.035).

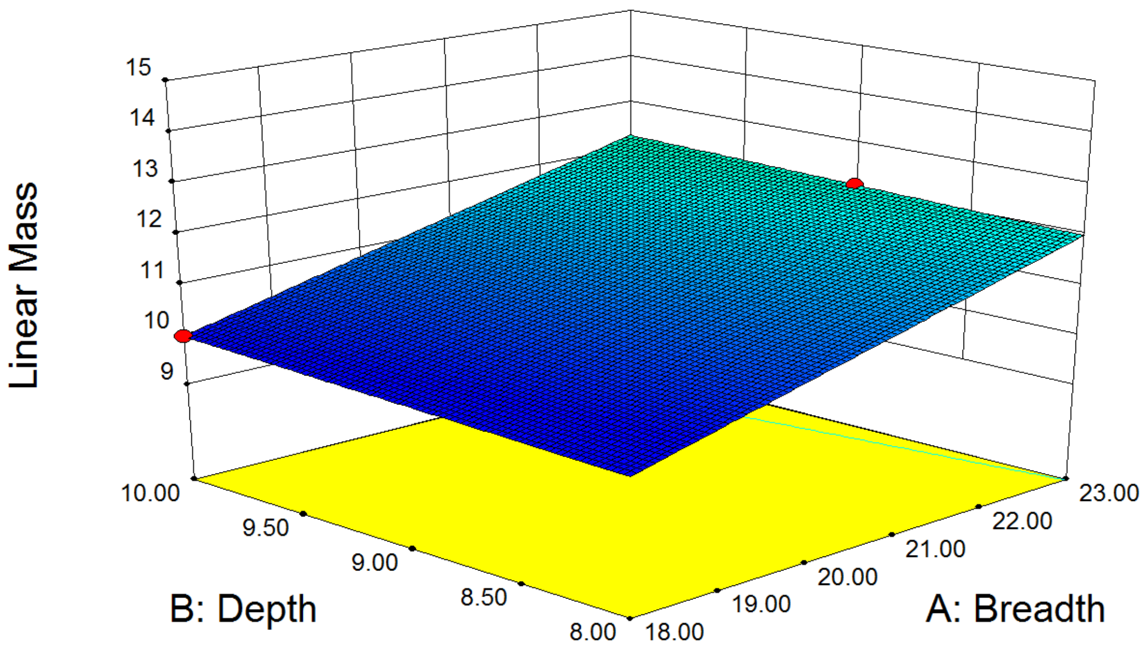


Figure 51: Mass response surface in function of depth and breadth. (t_{sides} = 0.01 and $t_{extremes}$ = 0.03).

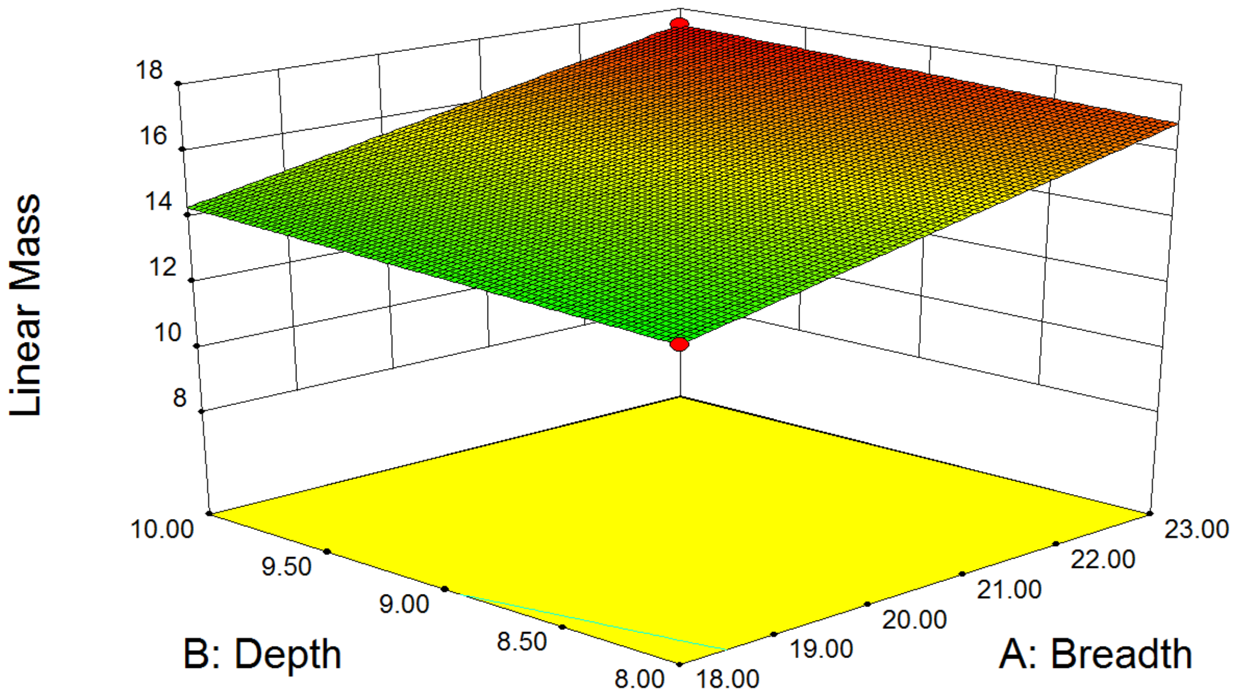


Figure 52: Mass response surface in function of depth and breadth. (t_{sides} = 0.02 and $t_{extremes}$ = 0.04).

Mass depends on dimensions and thickness interaction and the regression reflects this perfectly. Increasing either dimensions or thickness also increases the mass and the surface shows this behaviour. However, this is but one response and the objective is to understand the amalgamation of stress, mass and internal area responses, thus the next step is to define the desirability function.

5.3.2 Simple Hull Beam Case – Goals Definition for Desirability function (Step 9)

Two main solution objective studies are performed:

1. Maximize Internal Area;
2. Target Internal Area of 180 m2 (same as (Brandt, 2015)):

Moreover, following the original case, I set the maximum allowable stress as 160 MPa[11]. The following are desirability goals description for all responses and factors:

- Depth, Breath and thicknesses: **in range goals** according to the defined design interval. They will have the desirability form as defined in Figure 23.

[11] This value for allowable stress is defined at (Brandt, 2015). However, it also defined at (DNV-GL, 2015) regarding longitudinal strength for stiffened plates made of regular steel (235 MPa yield stress).

- Mass: minimize goal, Figure 21, with importance factor of 4 (high).
- Stress: **goal minimize** with average importance (3) and weight 1. The point of 0 desirability is the maximum allowable stress of 160 MPa.
- The internal area will have two different goals: one is **target** (Figure 22) at 180 m^2 with average importance (3) and weight of 1. The other is **maximize** with average importance (3) and weight of 1.

5.3.3 Simple Hull Beam Case - Solution 1: Maximize Internal Area

According to the optimization routine the solution that offers the highest overall desirability factor is the following:

Table 8: Simple case parameters solution 1.

Parameter	**Value**
Breadth (m)	22.76
Depth (m)	10
Sides Thickness (m)	0.01
Extremes Thickness (m)	0.03
Response	
Mass (ton/m)	12.2
Internal Area (m^2)	227.6
Stress (MPa)	32.6

The overall desirability score obtained is of 0.844 and the individual goals' desirability are shown in Figure 53:

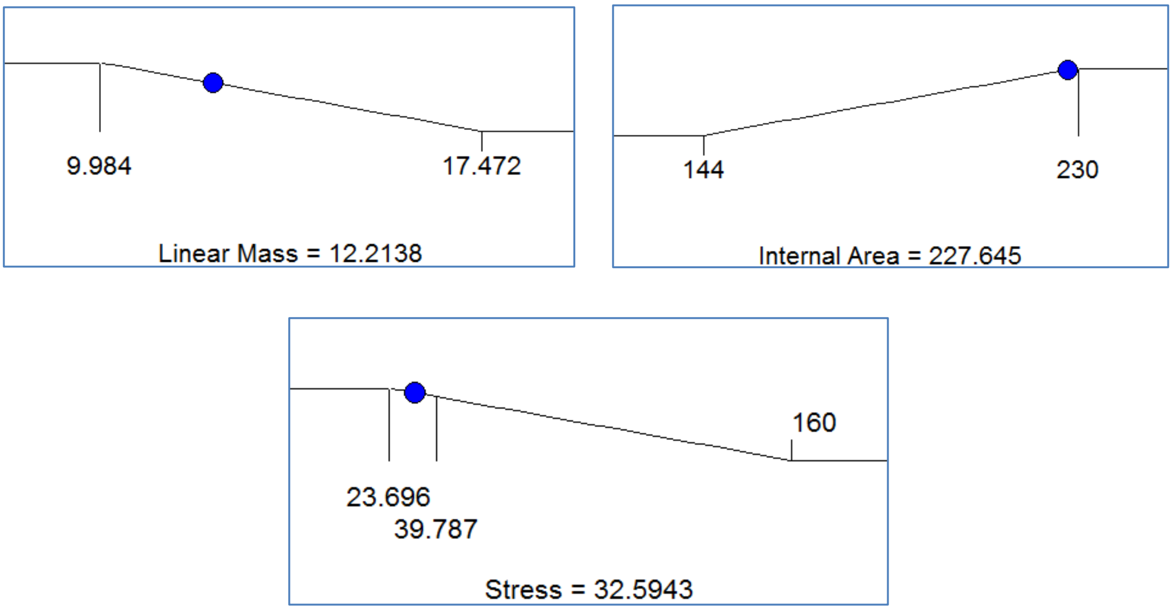


Figure 53: Response goals and solution for internal area maximization. Simple case.

The desirability response surface for Depth vs Breadth (at $t_{extremes}$=0.03 m and t_{sides}=0.01 m) has the following contour and 3D surfaces, Figure 54 and Figure 55:

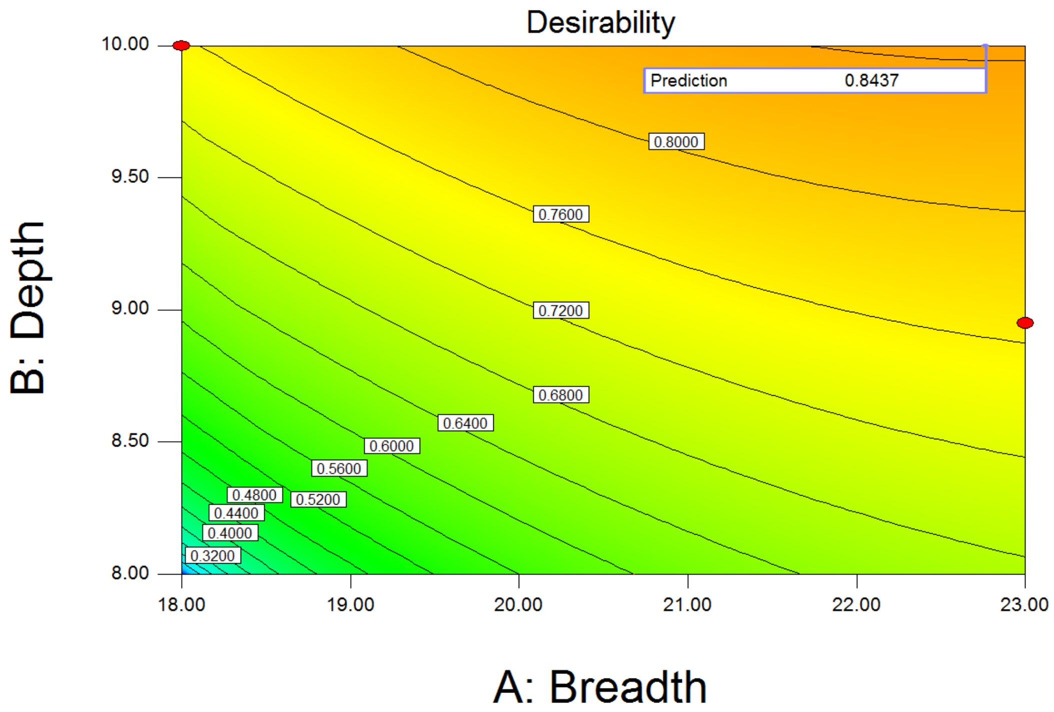


Figure 54: Simple case solution 1, desirability contour.

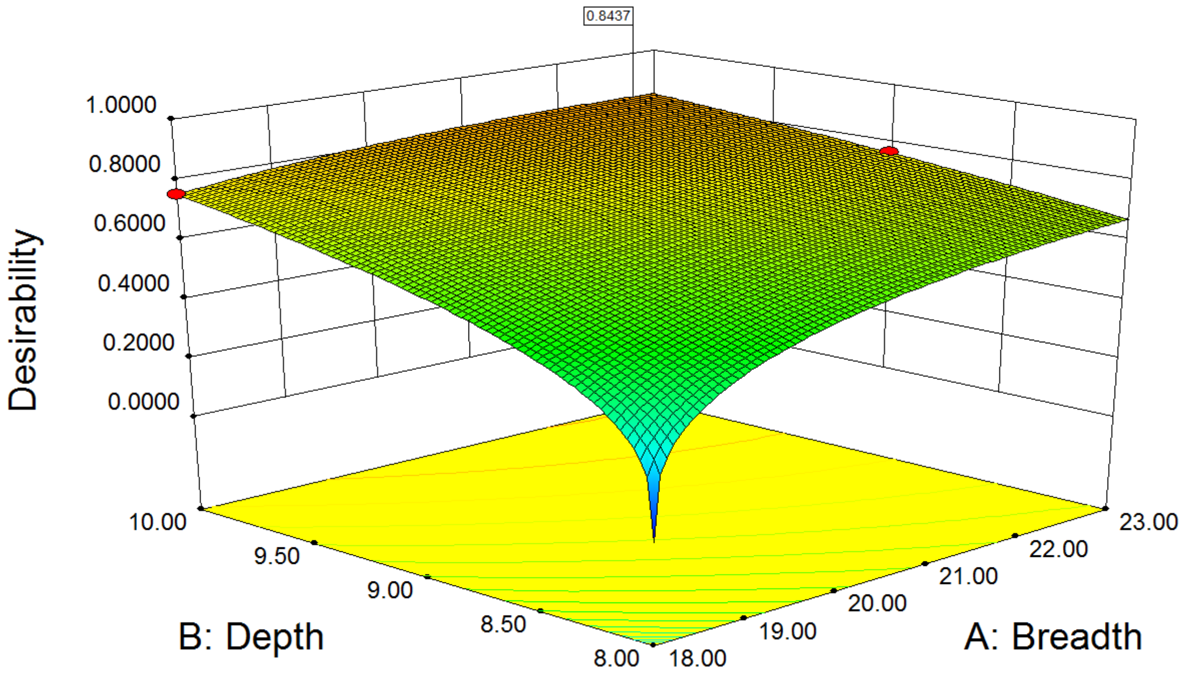


Figure 55: Simple case solution 1, desirability surface plot.

If one increases the thickness values to their maximum limit within the design space, the previous surface changes drastically by reducing overall maximum desirability to below 0.6 and big increments in breadth are not viable solutions in this case, as it reduces drastically the desirability, Figure 56.

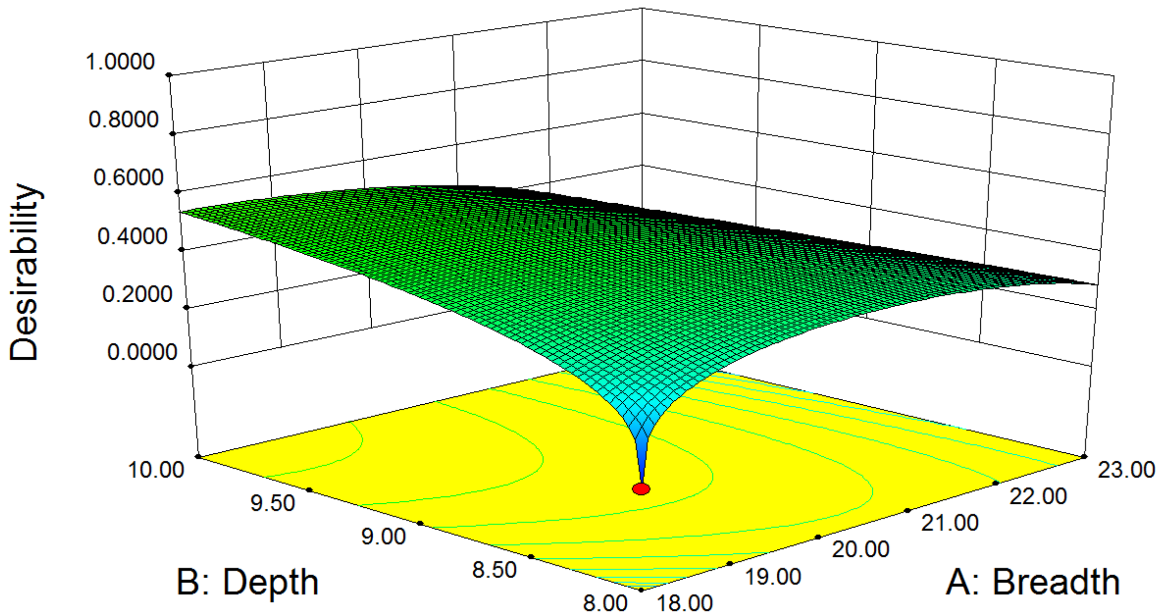


Figure 56: Simple case solution 1, desirability surface plot with increased overall thickness.

Finally, the solution's verification is performed. Table 9 shows that the model's a responses are extremely close to the expected calculated values, thus confirming that this solution's responses are accurate.

Table 9: Solution 1 verification.

Response	Regression Values	Calculated Values	Difference
Mass (ton/m)	12.219	12.2117	0.06%
Internal Area (m^2)	227.645	227.6	0.02%
Stress (MPa)	32.5943	32.6111	-0.05%

5.3.4 Simple Hull Beam Case - Solution 2: Target Internal Area of $180m^2$

According to the optimization routine the solution that offers the highest overall desirability factor is the following:

Table 10: Simple case parameters solution 2.

Parameter	Value
Breadth (m)	18.0
Depth (m)	10
Sides Thickness (m)	0.01
Extremes Thickness (m)	0.03
Response	
Mass (ton/m)	9.99
Internal Area (m^2)	180
Stress (MPa)	32.18

The overall desirability score obtained is of 0.981 and the individual goals desirability are shown in Figure 57:

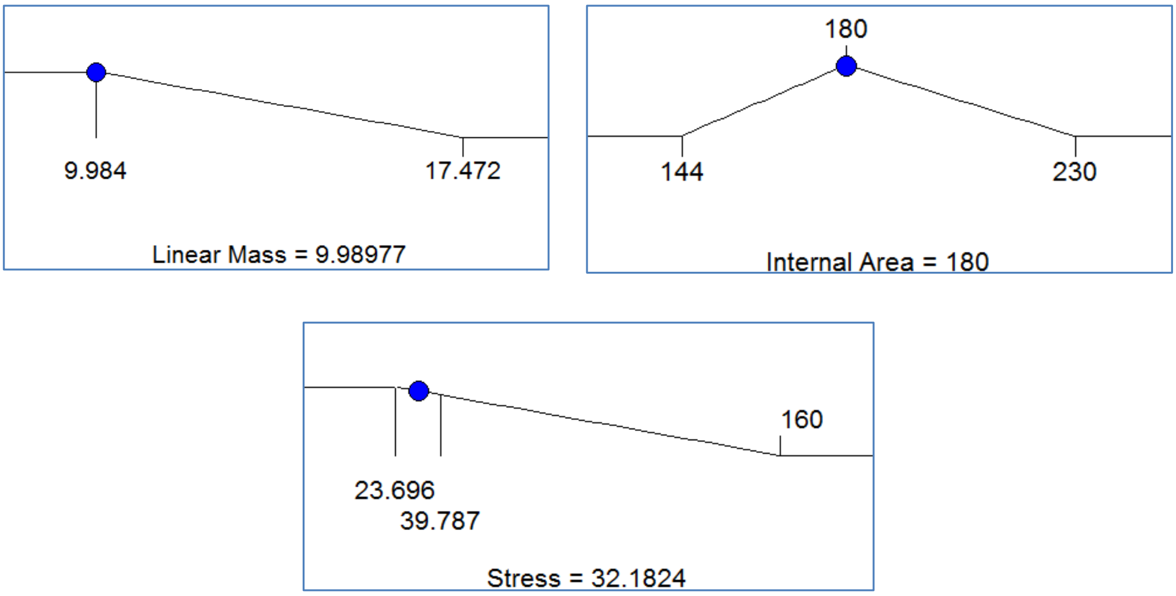


Figure 57: Response goals and solution for internal area maximization. Simple case.

The desirability response surface for Depth vs Breadth (at $t_{extremes}$=0.03 m and t_{sides}=0.01 m) has the following contour and surface, Figure 58 and Figure 59:

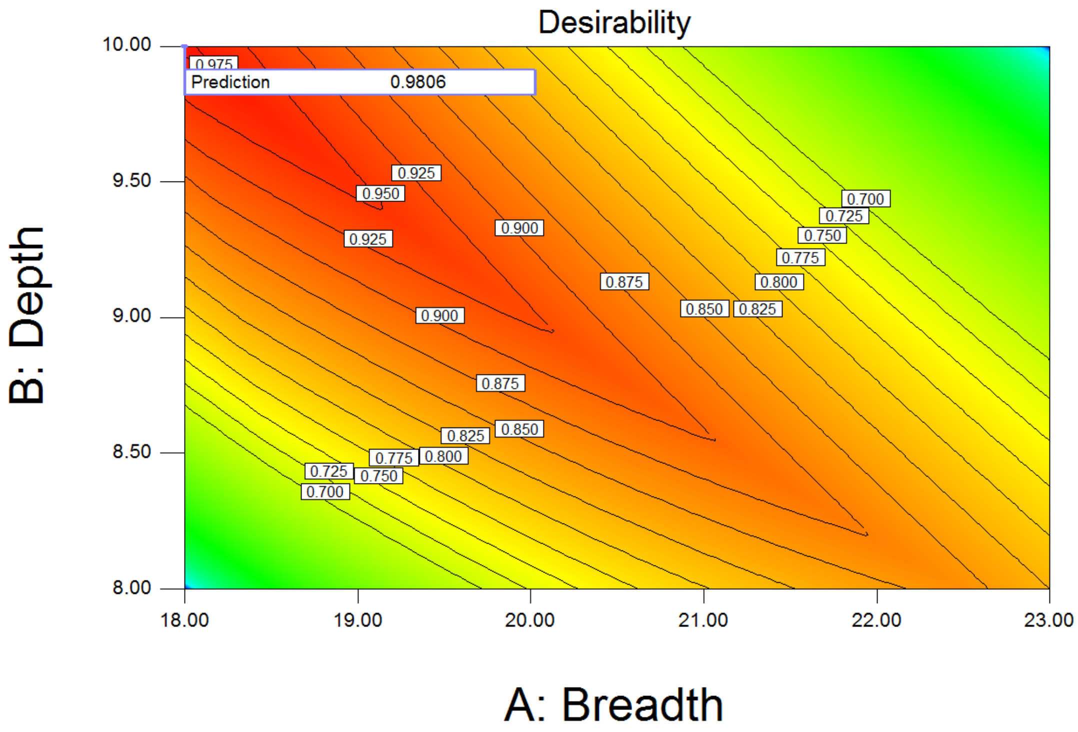


Figure 58: Simple case solution 2, desirability contour.

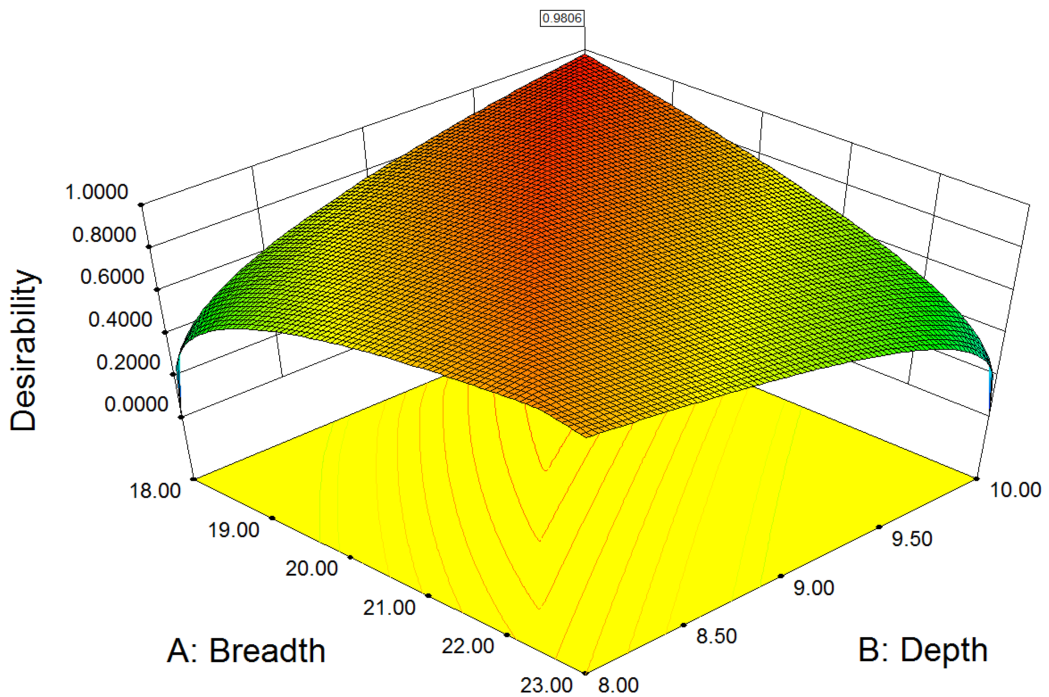


Figure 59: Simple case solution 2, desirability surface plot.

The solution 2 desirability surface, Figure 59, clearly shows the influence of the target internal area goal on the desirability, as the surface crest is aligned with the region where Breadth times

Depth equals 180 m^2. Additionally, it is also notable the depth influence on the desirability, as the best local solutions are located at the maximum depth region of the design space.

Table 11 shows that the model's a responses are close to the expected calculated values:

Table 11: Solution 2 verification.

Response	Regression Values	Calculated Values	Difference
Mass (ton/m)	9.98747	9.984	0.03%
Internal Area (m^2)	180	180	0.00%
Stress (MPa)	32.1824	32.202	-0.06%

5.4 Simple Hull Beam Case - Conclusion

Both solutions, show the same behaviour: The most effective way of using material is to increase the Depth of the PSV. For the goals analysed, regardless of other factorial combinations, the best local solutions are always located at the maximum depth. This agrees with section 2.3.1 and (Brandt, 2015).

This simple case proves that it is possible to obtain an improved local solution through statistical means using the Design of Experiments Methodology applied to finite element simulations. Moreover, the method can be quite reliable to predict the results when all the initial conditions and response models are set in a good way and that the derived surfaces are an excellent way of visualising the factorial and response interactions along the solution space.

The next step is to apply the concept to a more complex finite elements model and test the viability of the approach to that case.

6 Main Case - PX121 Study

Application of the same methodology described in section 4 and illustrated in Figure 24, but this time for a complex case, with more factors and detailed sectional design.

6.1 Main Case - Definition (step 1.1)

The finite element model of the case study is based on typical PSV midship section and the dimensions are based on the PX121 family

Figure 60: PX121 PSV example. (Ulstein)

The principal dimension values for this vessel are.

- Rule Length: 79.5m
- Breadth: 18m
- Depth (to Main Deck): 8m
- Draught: 6.7m

Ulstein suggested the following plate thickness distribution as guidance values:

- General Plate Thickness: 11 mm;
- Bottom and Tank Top Plate thickness: 12 mm;

The stiffeners have the following values:

- General Stiffener Profile Type: HP 160x8;
- Main Deck Stiffener Profile Type: HP 260x12;

The load type studied is the vertical bending moment. This is applied to a cargo hold model of the vessel. The responses studied are:

- Main Deck, Bottom and Cargo Rail top plate stresses;
- Linear Mass;
- Internal Area.

6.2 Main Case – Model Creation (step 1 and 2)

A typical PSV's middle section 2D drawing was translated into a parametric virtual model, however with less structural detailing version and some simplifications. The following Figure 61 shows a typical PSV midship section drawing and how it was translated into the virtual environment. Besides detailing simplifications, as holes, openings and small brackets not taken into consideration, these are the main differences:

1. Continuity of longitudinal elements was preserved. The longitudinal bulkhead and floor longitudinal girder were assumed aligned and thus draw as one in ANSYS.
2. The tween deck was left out, as it was not a continuous element, being constantly interrupted by the presence of cargo tanks.
3. Stiffener spacing was assumed dependant on the stiffener number, not on relative distance.
4. The bilge region was modelled with straight plates.

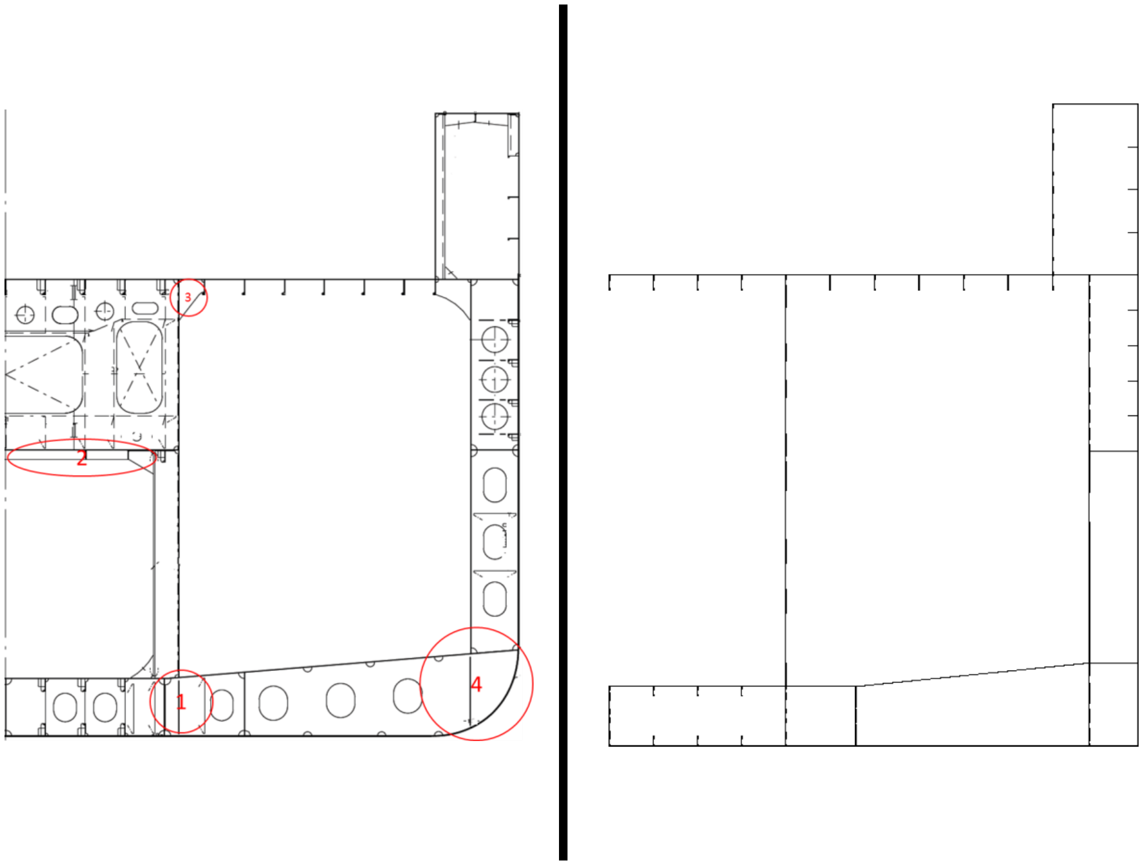


Figure 61: Typical midship section drawing (left). Drawing representation in ANSYS (right).

The main reasoning behind these simplifications was to facilitate the simulation procedure, as element number and size directly influence the time it takes for a solution to be found using FEA. These lines are then extruded to form the areas that represent the longitudinal plates of a single half-frame, then transversal areas are added. Figure 62 shows an example of a possible frame model.

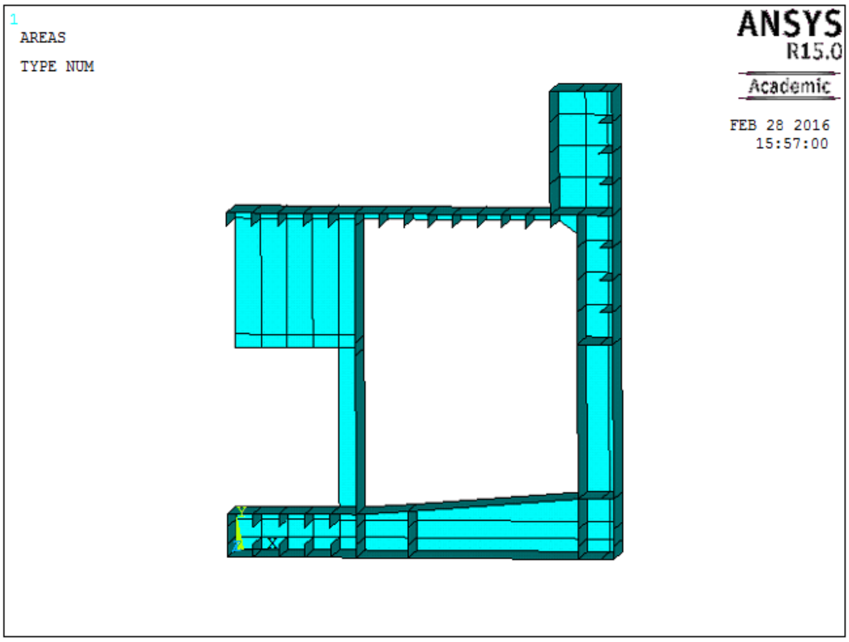


Figure 62: Developed ANSYS Model Frame.

Then, the areas are meshed and the elements have material and section properties assigned according to region and function. As with the main dimensions, these values are entered as initial parameters and are subject to change according to the user's requirements, thus accomplishing the parametric requirement (step 2.1 from Figure 24).

The stiffeners were modelled according to the procedure presented in Figure 27. A single frame is then repeated *n* times, forming a cargo hold model, Figure 63 shows one model example. It was determined that the spacing between stiffeners should be 700 mm and that the cargo hold region extended through 43 frames, this was based on typical PSV general arrangement.

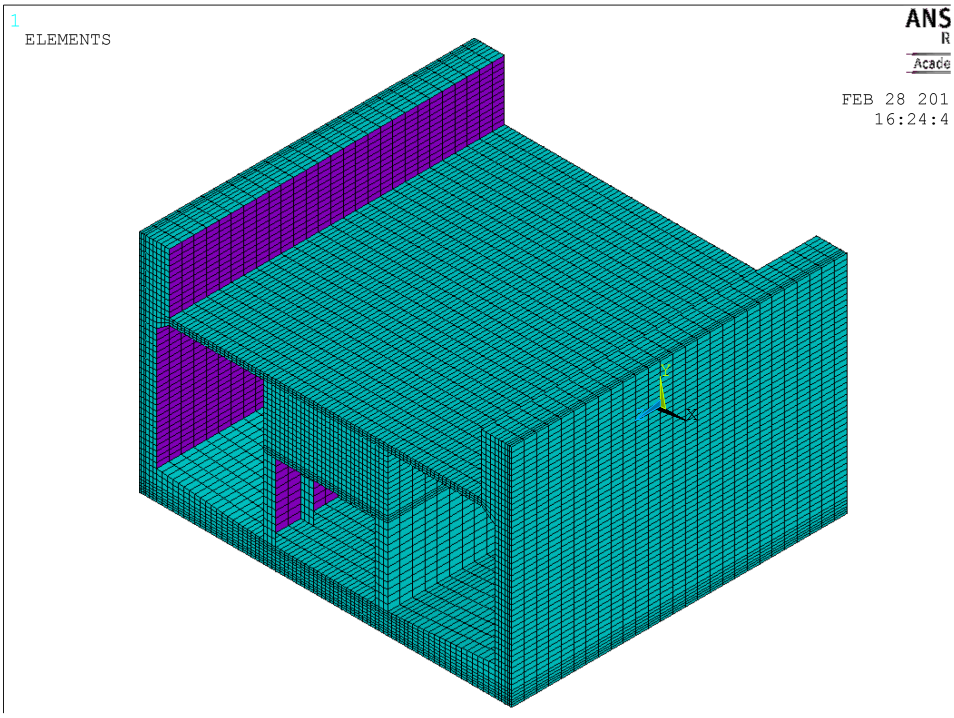


Figure 63: Cargo hold model example.

The next step is to define the model's boundaries which are divided into loads and constraints. The methodology applied to this case was already defined previously in section 4.1, but as a summary:

1. The vertical bending moment and it is the combination of the still water bending moment and wave induced bending moment. The equations presented in Figure 32 were implemented into the model code and should update according to dimensional changes.
2. The model is constrained to vertical bending moment according the IACS guidelines, Figure 29.
3. To reduce the calculation time, the section is divided at its longitudinal symmetry plane.

6.3 Main Case – Model Solving (step 3)

The previous information allows the finite elements model to be solved. A single simulation example is shown in Figure 64.

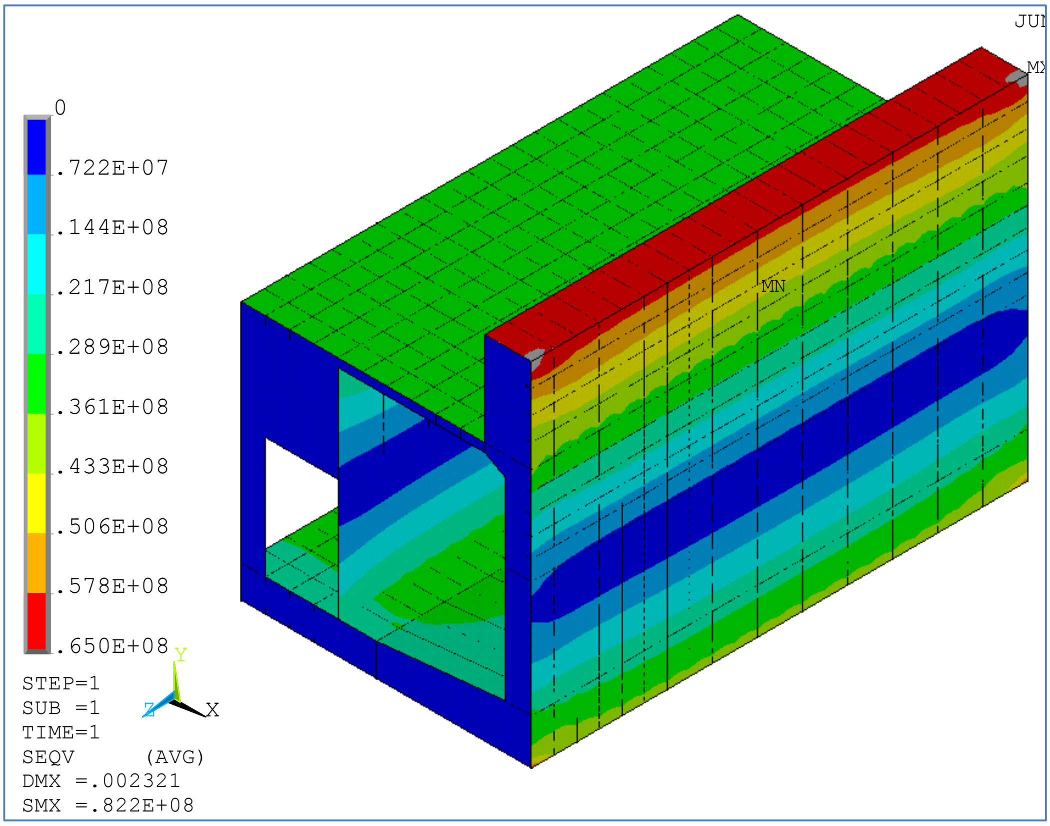


Figure 64: Von Misses Equivalent stress distribution.

However, some nodes located at the boundary region have higher value due to stress concentration. This variance is smoothed and reduced towards the central region of the model. This means that stress measurement is performed between the 2 middlemost frames of the model, Figure 65.

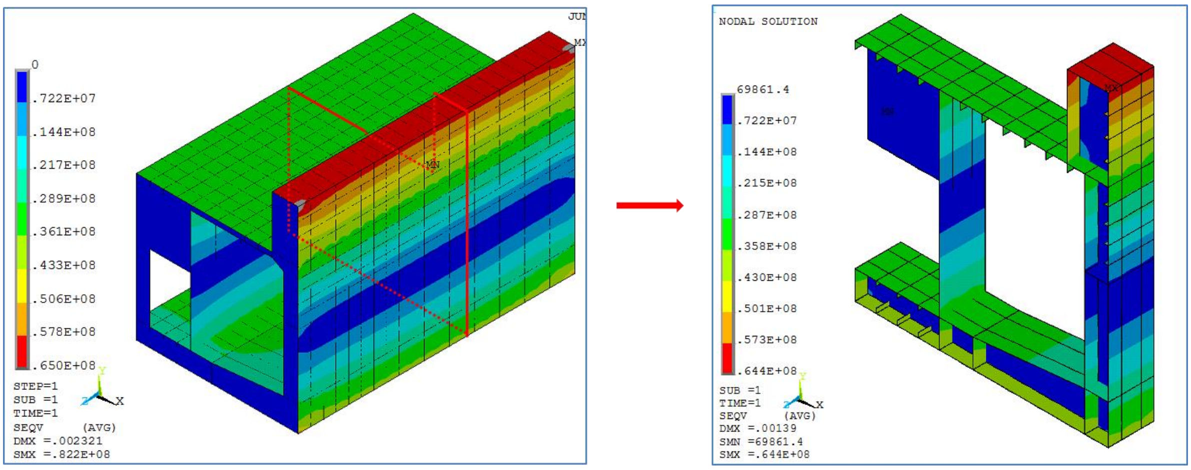


Figure 65: Stress Measurement ant the model centre.

Then paths are traced to measure the stress variations at key regions, shown in Figure 66.

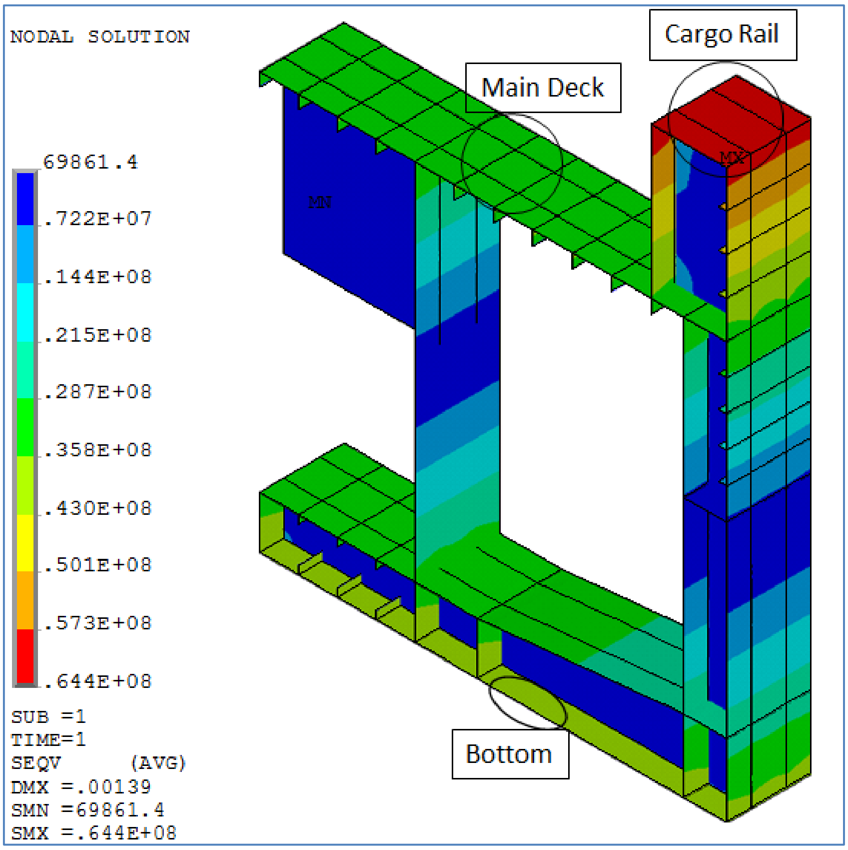


Figure 66: Path for stress measurement and curve plot.

I define the measurement paths at: Main Deck, Bottom and Cargo Rail top plate. These values are stored in an array and highest local values are saved in an output file, together with the linear mass of the model. An additional term to measure cargo space variation is added, the Internal Area, which is Breadth multiplying Depth.

For the base case setup, as presented in the main case definition, the following response were measured, Table 12.

Table 12: Results for the base case

Result	Value	Unit
Mass	19.43	ton/m
Stress Deck	34.91	MPa
Stress Bottom	40.39	MPa
Stress Cargo Rail	61.82	MPa
Internal Area	144	m^2

6.4 Main Case - DoE applied to Parametric Hull Model. (Steps 4, 5 and 6)

The next step is the experiments definition. Factors are analysed to determine their influence on the target responses. As stated previously, previous studies have already factorial screening for a vertical bending moment, and the critical factors are:

- Depth;
- Half-Breadth[12];
- Main Deck Thickness;
- Bottom Plate Thickness.

In addition to that, (Diewald, 2015) also mentions that longitudinal girders have some influence on stress response, but, since this model doesn't have girders on the main deck, I study stiffeners with the factors:

- Number of stiffeners on Main Deck and Bottom;
- Stiffener Type.

Finally, there is a structural element that wasn't studied before, the cargo rail. Its plate thickness is assumed as a vital factor:

- Cargo Rail Plate Thickness.

In total 7 vital factors are used to generate the experiments. The factors have the following design interval[13]:

[12] This is simply Breadth/2. This is done to simplify the input file generation for ANSYS based on information generated by Design Expert 8.

[13] Notice that the initial case coincides with the centre of each factor's interval.

- Numerical Continuous
  - Half - Breadth (B/2): 8 to 10 m;
  - Depth (D): 7 to 9 m;
  - Deck thickness (t_main): 0.008 to 0.014 m
  - Bottom thickness (t_bot): 0.009 to 0.015 m
  - Cargo Rail thickness (t_cg): 0.008 to 0.014 m
- Numerical Discrete:
  - Stiffener Number Multiplier (n): 3 / 4 / 5 / 6 / 7 , where the number of stiffeners is defined as: $MainDeckCenter = 2n - 1$; $Bottom = n$; $MainDeckSide = 2n + 1$. Refer to Figure 67.
- Categorical
  - Stiffener Type HP (type): Smaller (o-) / Standard (o) / Bigger (o+)

Table 13: Stiffener Types.

Location	**Stiffener Type (o-)**	**Stiffener Type (o)**	**Stiffener Type (o+)**
Main Deck	HP 240x10	HP 260x12	HP 280x12
Others	HP 180x10	HP 160x8	HP 140x8

Figure 67 explains where these factors are located in the section.

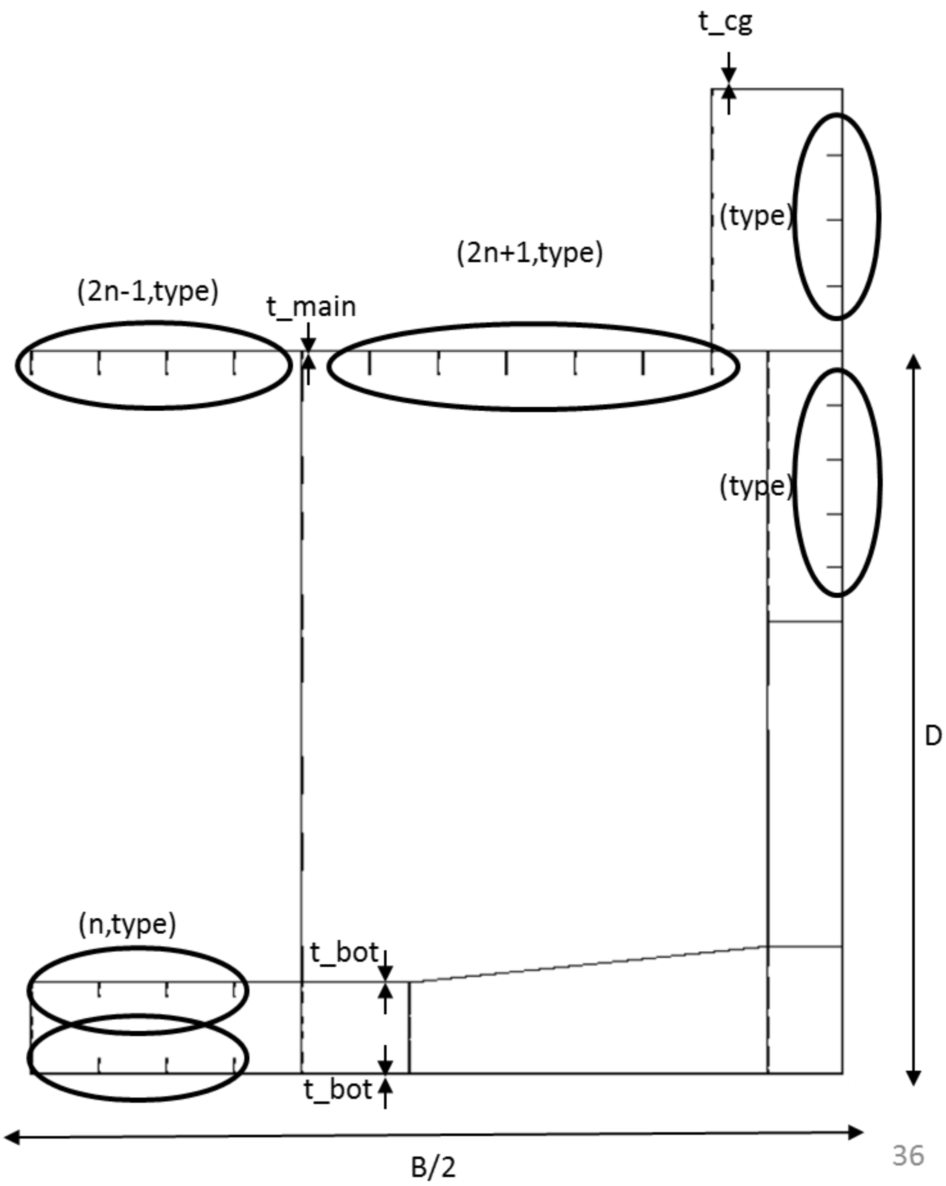


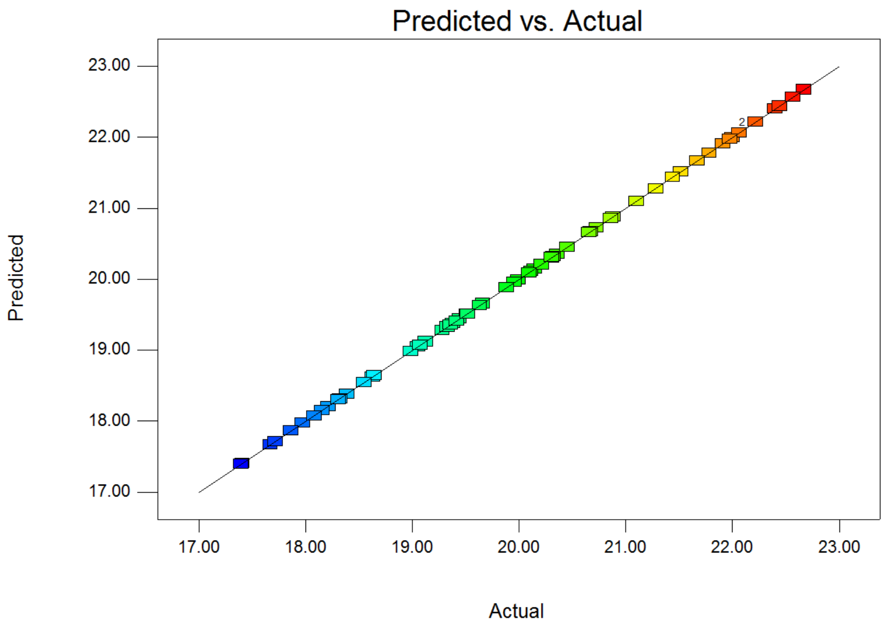
Figure 67:Design Interval Variables.

The next step is to apply the Augmented D-Optimal methodology, section 4.2.2, to define the experiments that shall be performed (Steps 5 and 6). This process is done with Design Expert 8 and the procedure is explained in APPENDIX-B.

6.5 Main Case – Responses and Regression. (Steps 3 and 7)

This results in 64 different experiments setups, which then are fed into the FE model and a series of simulations are run. The responses are again measured and transferred to the Response Surface Software. These are shown in detail at APPENDIX – C.

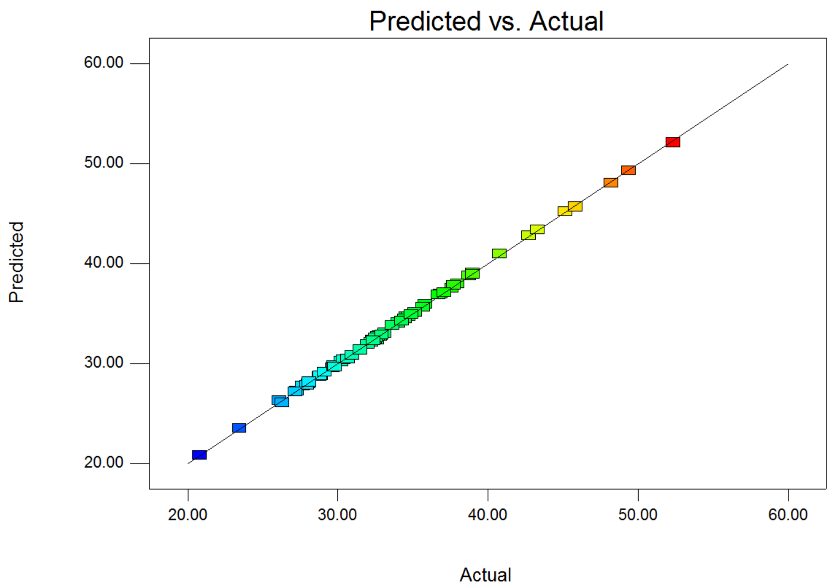
To perform the regression, the model type (one factor, two factor interaction or quadratic) that fits the responses better must be studied. After that, the program generates a surface regression for each response and compares the actual vs predicted response curves. The results for each response model generation are summarized in the next Figures and the regression equations are located in APPENDIX – D.



Linear Mass Regression:

- 2FI model;
- Significant Model;
- Good Correlation;
- R-Squared = 1;

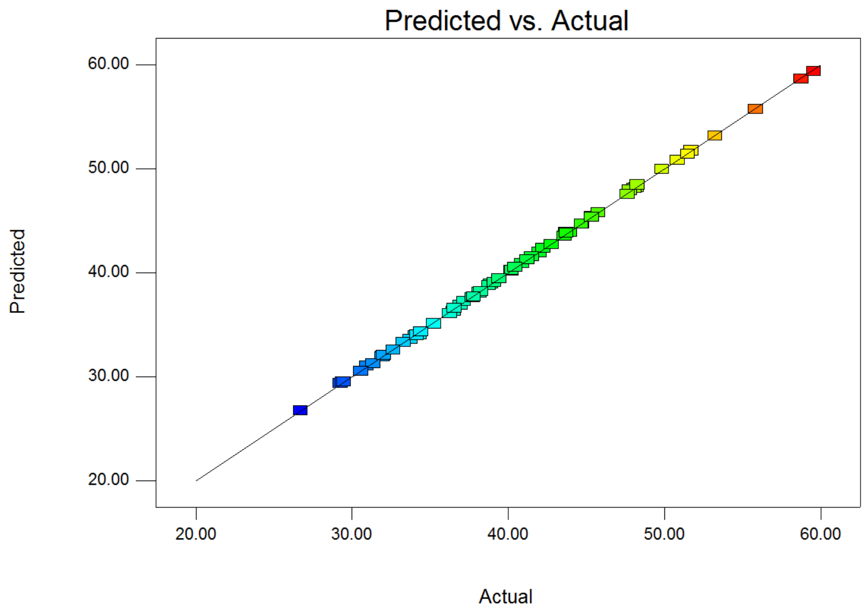
Figure 68: Experiments' Mass response prediction curve. (ton/m)



Main Deck Stress Regression:

- Quadratic model;
- Significant Model;
- Good Correlation;
- R-Squared = 0.9997;

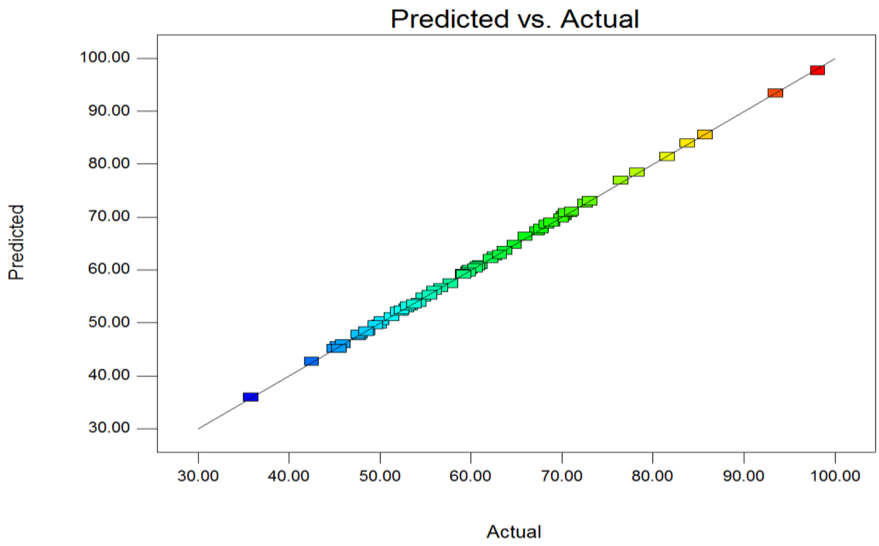
Figure 69: Experiments' Stress at Main Deck response prediction curve. (MPa)



Bottom Stress Regression:

- Quadratic model;
- Significant Model;
- Good Correlation;
- R-Squared = 0.9999;

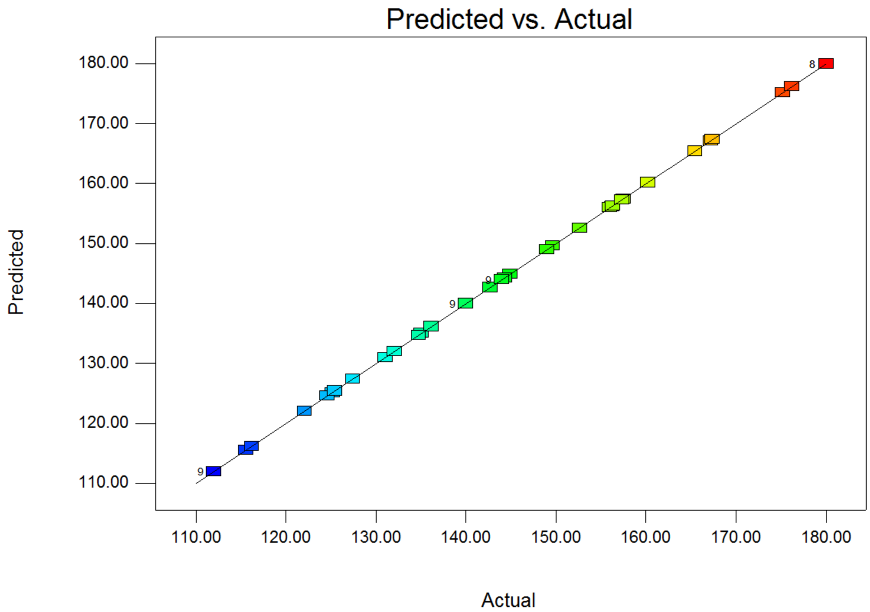
Figure 70: Experiments' Stress at Bottom response prediction curve. (MPa)



Stress at Cargo Rail Regression:

- Quadratic model;
- Significant Model;
- Good Correlation;
- R-Squared = 0.9998;

Figure 71: Experiments' Stress at Cargo Rail response prediction curve. (MPa)



Internal Area Regression:

- 2FI model;
- Significant Model;
- Good Correlation;
- R-Squared = 1;

Figure 72: Experiments' Internal Area response prediction curve. (m^2)

6.6 Main Case –Design Improvement Analysis (Steps 8 and 9)

As with the simple case, multiple responses are involved in the analysis, thus it is required to define goals and desirability. The main objective is to understand the complex relation between the responses and the factors, not each response individually. Table 14 explains the symbols used in this section:

Table 14: Result Analysis Legend.

Symbol	Factor	Unit
A	Breadth / 2	m
B	Depth	m
C	Main Deck Thickness	mm
D	Bottom Thickness	mm
E	Cargo Rail Thickness	mm
F	Stiffeners' Number	-
G	Stiffener Type	-
R1	Linear Mass	ton/m
R2	Main Deck Stress	MPa
R3	Bottom Stress	MPa
R4	Cargo Rail Stress	MPa
R5	Internal Area	m^2
D	Desirability	-

Two different optimization objectives are studied. They are composed by distinct set of desirability goals.

6.6.1 Main Case – Objective 1 – Definition and Results

The aim is to minimize mass, minimize stresses and have at least the same cargo capacity of the base case. For this, the following goals are defined (refer to Table 14 for factor nomenclature reference):

1. All factors (A, B, C, D, E, F, G) should be within the design interval, thus defined with an **in range goal**;
2. The mass reduction is the main objective and this goal is defined with a **minimization** criterion with highest importance (**level 5**);
3. All stresses have a **minimization** goal with average importance (level 3). However, the response space does not have a stress that is above the allowable stress (160 MPa), thus this constraint is not required;
4. The internal area measures the cargo capacity variation. It is defined with the objective of improving or, at least, keeping it at the same level of the original vessel, which means a **maximization** goal with lowest acceptable limit of **144 m^2**. The importance level is also average (level 3).

The software solves the desirability function and returns a set of 100 solutions with highest desirability possible. The first 8 best solutions have the following factor and response values:

Table 15: Objective 1, Best Solutions.

	Factors							**Responses**					
Solution	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**R1**	**R2**	**R3**	**R4**	**R5**	**D**
1	9.38	9	8.5	9.1	14	3	o-	19.363	32.061	40.817	55.077	168.763	0.641
2	9.37	9	8.1	9	14	4	o-	19.472	31.508	40.564	54.260	168.662	0.641
3	9.37	9	8.8	9	14	3	o-	19.376	31.774	41.024	54.767	168.656	0.641
4	9.37	9	8	9.3	14	3	o-	19.343	32.406	40.449	55.409	168.620	0.640
5	9.34	9	8.3	9.5	14	3	o-	19.427	32.062	39.924	54.786	168.176	0.640
6	9.28	9	8.5	9.1	14	3	o-	19.288	31.821	40.627	54.696	167.049	0.64
7	9.37	9	8	9	14	3	o	19.465	31.446	40.754	54.206	168.637	0.64
8	9.27	9	8.1	9	14	3	o	19.393	31.138	40.586	53.738	166.910	0.64
Base Case	9	8	11	12	11	3	o	19.425	34.914	40.392	61.816	144	-

To better illustrate the extent of the factor variation on the responses, the following curves are presented:

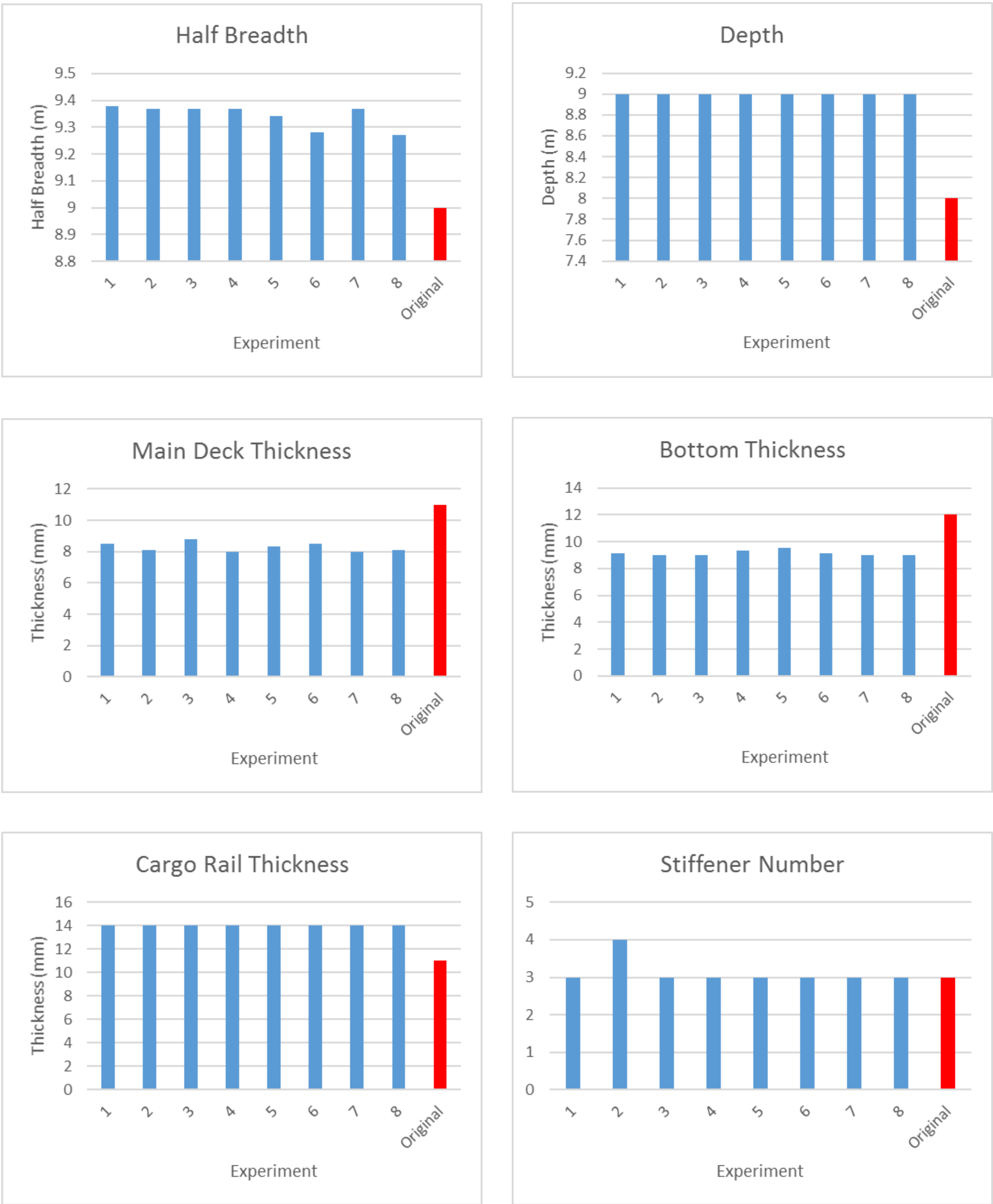


Figure 73: Factor comparison between solutions and base case. Objective 1.

The main trends noted for the factor variations columns shown in Figure 73, when the solutions are compared to the original design, are:

- Increase in Breadth, but still under the maximum limit (10 m) of the design space;
- Maximum use of Depth;
- Decrease of Main Deck and Bottom Plate thicknesses;
- Increase in the Cargo Rail Plate thickness up to the design space limit;
- Generally, minimal use of stiffener numbers and smallest type, but not a necessity;

The following curves show the response variation for each solution in comparison to the base case:

Figure 74: Response variation for the Objective 1 solutions.

In relation to the response variation, Figure 74 shows the following trends:

- Minimal Mass and Bottom Deck Stress changes overall;
- Expressive Main Deck and Cargo Rail stress reduction;
- Expressive increase in Internal Area.

These results were obtained with minimal computing effort and required only 64 experimentations to obtain a viable improved solution. They indicate that, to obtain an increased internal area, the best way is to increase depth. Moreover, the solutions indicate that is possible to increase size without increasing weight. These conclusions are valid for vertical bending moment.

New simulations are performed on ANSYS To verify the results from Table 15. Comparison is made in Table 16:

Table 16: Main case response simulation. Objective 1.

Solution	Mass (ton/m)	Stress at Deck (MPa)	Stress at Bottom (MPa)	Stress at Cargo Rail (MPa)	Internal Area (m^2)
1	19.36813	32.06752	40.91543	55.14937	168.84
2	19.46464	31.605	40.7446	54.48505	168.66
3	19.37382	31.81645	41.09614	54.87778	168.66
4	19.34825	32.42233	40.49456	55.47635	168.66
5	19.4303	32.05595	39.96045	54.82258	168.12
6	19.29074	31.81724	40.71412	54.75264	167.04
7	19.45892	31.67598	40.83872	54.70455	168.66
8	19.3967	31.34085	40.62024	54.19594	166.86

Note that the regression has agreed with the simulated values, as all response deviate less than 1% when compared to the finite elements calculations, as shown in Table 17:

Table 17: Percentage difference between simulation and regression results. Objective 1.

Solution	Mass	Stress at Deck	Stress at Bottom	Stress at Cargo Rail	Internal Area
1	0.02%	0.02%	0.24%	0.13%	0.05%
2	-0.04%	0.31%	0.44%	0.41%	0.00%
3	-0.01%	0.13%	0.18%	0.20%	0.00%
4	0.03%	0.05%	0.11%	0.12%	0.02%
5	0.02%	-0.02%	0.09%	0.07%	-0.03%
6	0.02%	-0.01%	0.21%	0.10%	-0.01%
7	-0.03%	0.73%	0.21%	0.91%	0.01%
8	0.02%	0.65%	0.08%	0.84%	-0.03%

Finally, the contour plots for the case solution are studied. There are many combinations of factors that can be plotted, thus only a few key interactions are examined:

Breadth versus Depth:

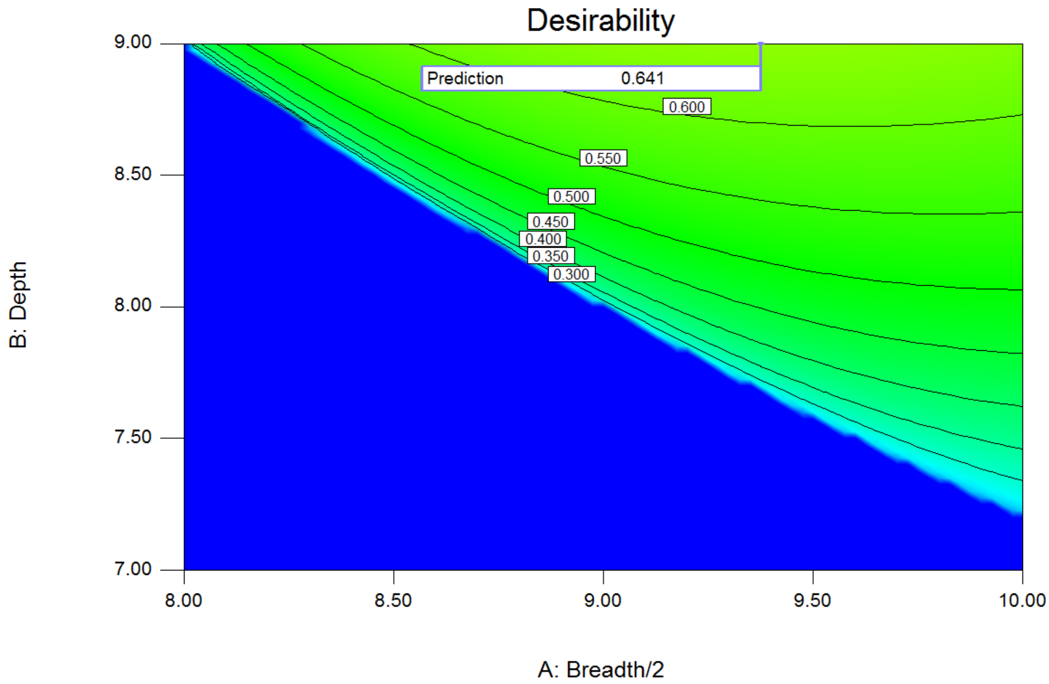


Figure 75: Breadth versus Depth Desirability Contour Plot. Objective 1.

Figure 75 shows that at lower desirability levels, both depth and breadth have a positive influence on the model, increasing the solution rating as they grow (noticeable through the almost diagonal contour lines between 0.3 and 0.45 desirability ratings). However, as the depth values increase so does its influence on the desirability, while the opposite response occurs for the breath, showing that augmenting depth values is more effective than breadth structurally.

Breadth versus Cargo Rail Plate Thickness:

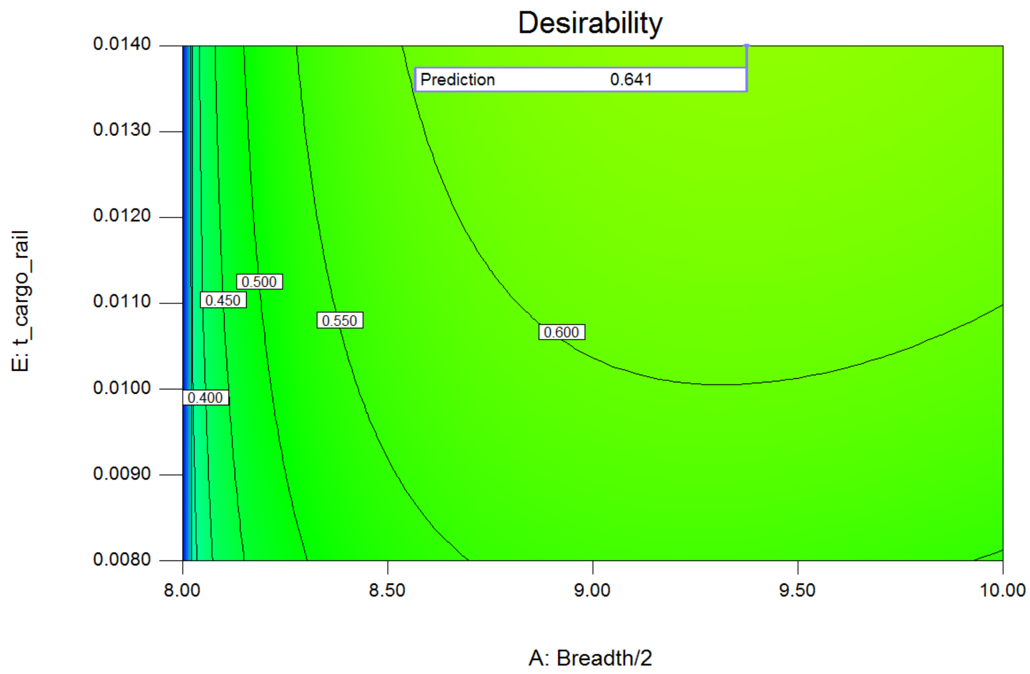


Figure 76: Breadth versus Cargo Rail Thickness Desirability Contour Plot. Objective 1.

Figure 76 shows that at lower desirability levels the cargo rail thickness has almost no influence over those values, which are more breadth dependant. But, as the breadth increases, so does the cargo rail thickness influence to the desirability.

Breadth versus Bottom Plate Thickness:

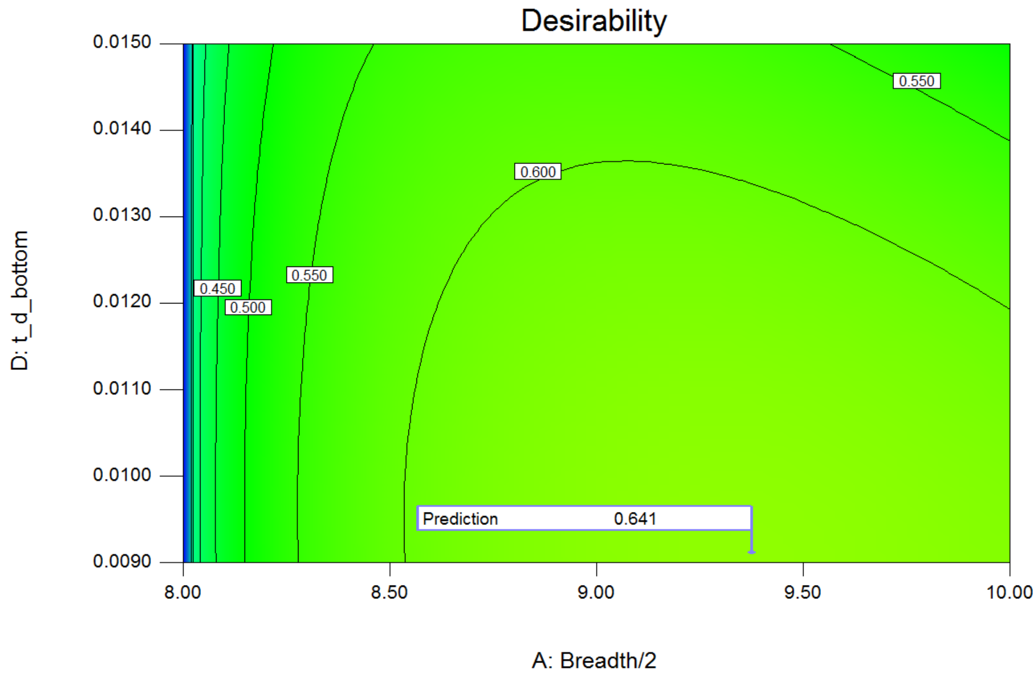


Figure 77: Breadth versus Bottom Thickness Desirability Contour Plot. Objective 1.

In contrast to Figure 76, Figure 77 shows that the bottom plate thickness influences the desirability negatively. Other factor interactions, as exemplified in Figure 78, seem to have lesser levels of response on the desirability function.

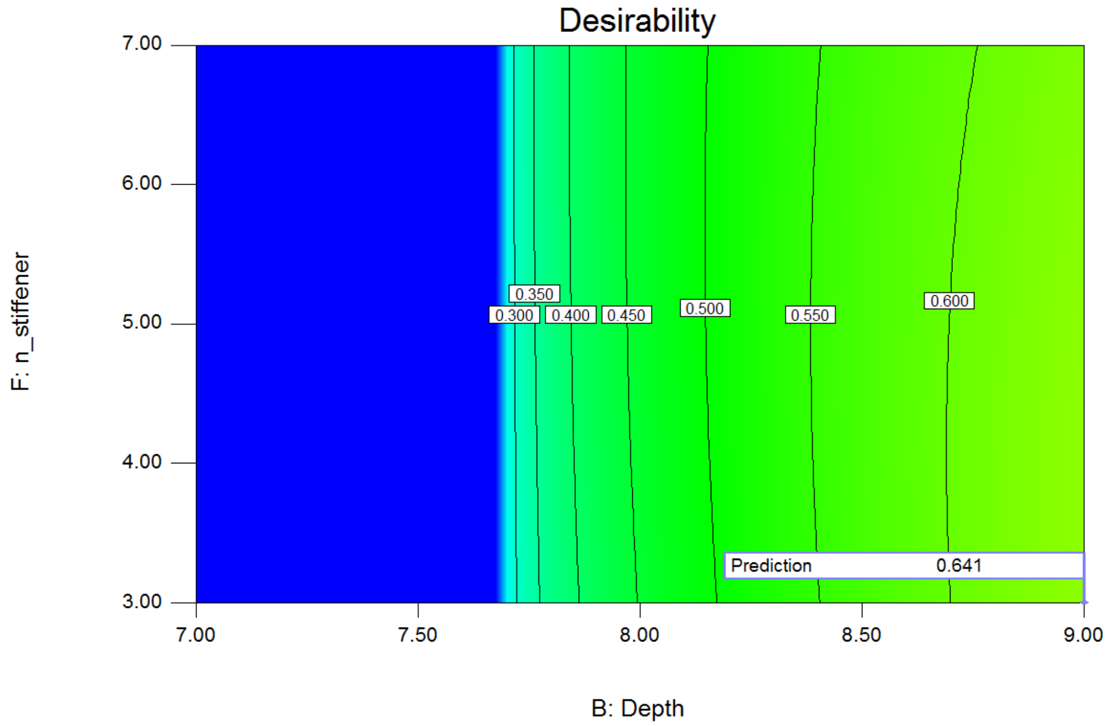


Figure 78: Depth versus Stiffener Number Contour Plot. Objective 1.

The previous statements present a few possible types of sensitivity analyses that can be performed in addition to the local optimization routine. The contour plots add to the information previously obtained and show important behaviour patterns of the model created.

6.6.2 Main Case – Objective 2 – Definition and Summarized Optimization Results

I defined another solution goal set to simulate different design objectives. This new objective assumes that it is not possible to perform major changes in the main dimensions due to yard restrictions and that cargo space is to be kept unchanged, then the following goals are defined:

1. Factors (A, B, C, D, E, F, G) should be within the design interval, thus defined with an **in range goal**, however Half-Breadth and Depth are limited to a **maximum of 0.5 m** changes in both directions.
2. The mass reduction is still the main objective and this goal is defined with a **minimization** criterion with highest importance (**level 5**);
3. All stresses have **minimization** goal, but with lower importance (**level 2**). Again, our response space does not have a stress that is above the allowable stress, thus this constraint is not required;

4. The internal area is defined with **target** goal of **144 m²**. The importance level is average (**level 3**).

5. **Table 18: Objective 2, Best Solutions.**

	Factors							Responses					
Solution	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**R1**	**R2**	**R3**	**R4**	**R5**	**D**
1	8.5	8.47	8.3	9.3	14	3	o-	18.337	31.551	41.541	56.105	144.0	0.762
2	8.5	8.47	8.4	9.6	14	3	o-	18.442	31.446	40.765	55.698	144.0	0.762
3	8.5	8.47	8.3	9.2	13.8	3	o-	18.296	31.802	41.781	56.519	144.0	0.761
4	8.5	8.47	8	9.5	14	4	o-	18.537	30.927	40.649	54.936	144.0	0.761
5	8.5	8.47	8	9.8	13.8	3	o-	18.416	31.929	40.538	56.261	14.00	0.761
6	8.5	8.47	8.7	9.1	14	3	o	18.532	30.210	41.643	54.277	144.0	0.76
7	8.5	8.5	8.4	9	14	3	o-	18.287	31.469	42.045	56.076	144.5	0.76
8	8.5	8.47	9.7	9.3	14	3	o-	18.531	30.477	41.359	54.611	144.0	0.76

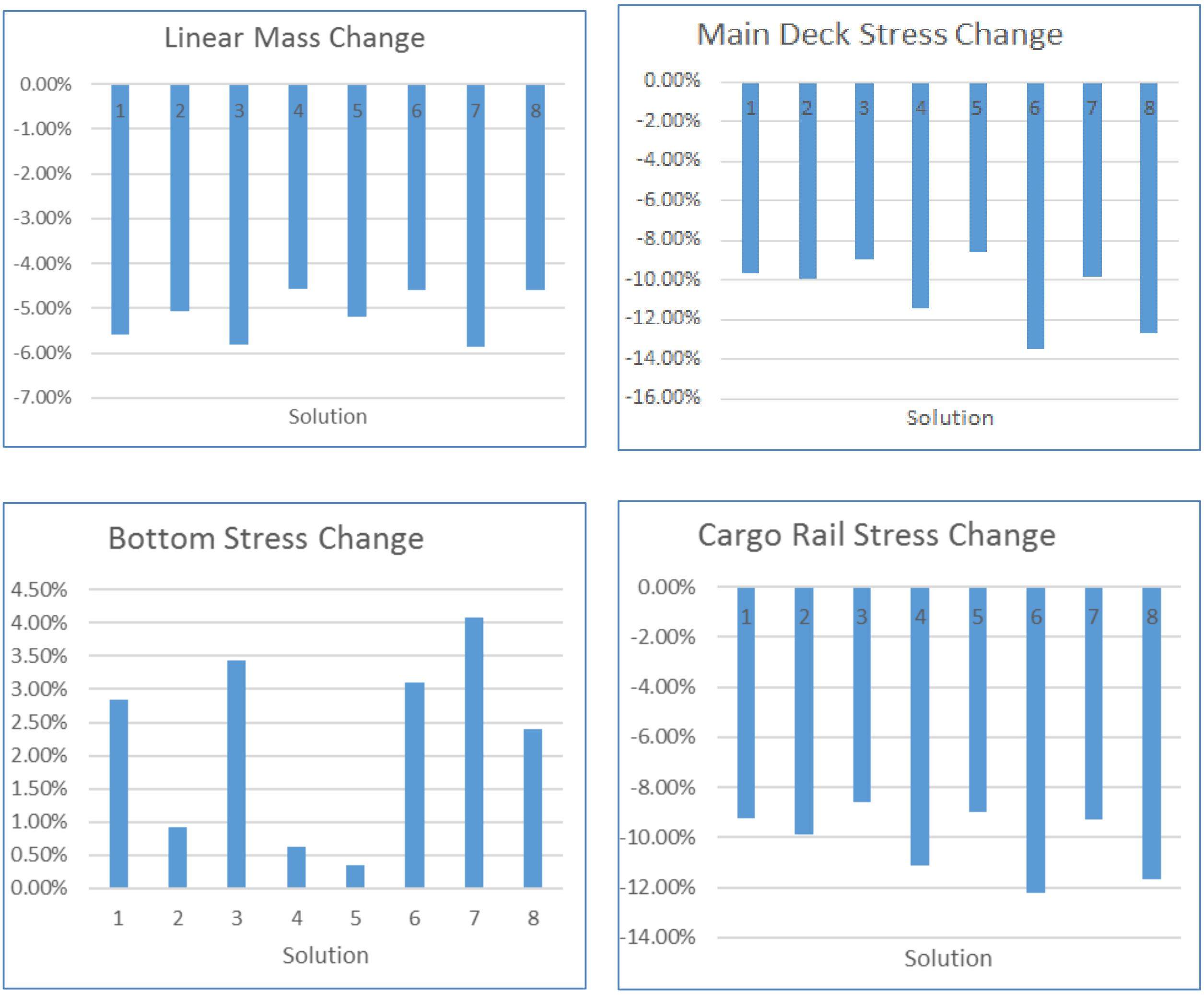


Figure 79: Response variation for the Objective 2 solutions.

In relation to the response variation for the second set of goals:

- Reduction in Sectional Mass;
- Expressive Main Deck and Cargo Rail stress reduction;
- Low average increase in Bottom stress.

The next Figures compare the same factors studied in the first set of goals:

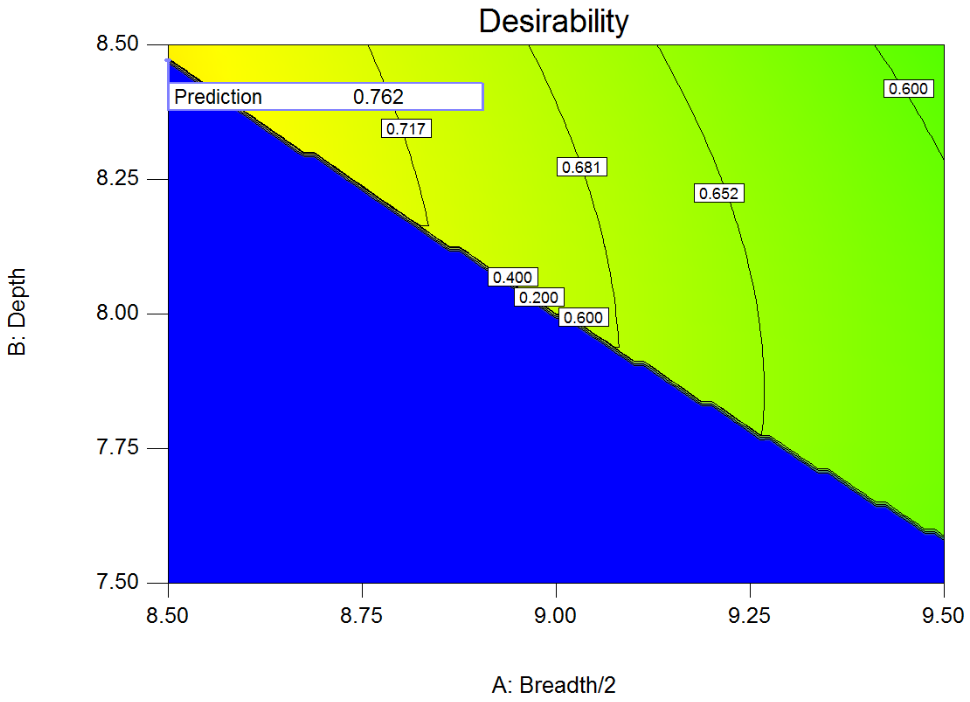


Figure 80: Breadth versus depth desirability contour plot. Objective 2.

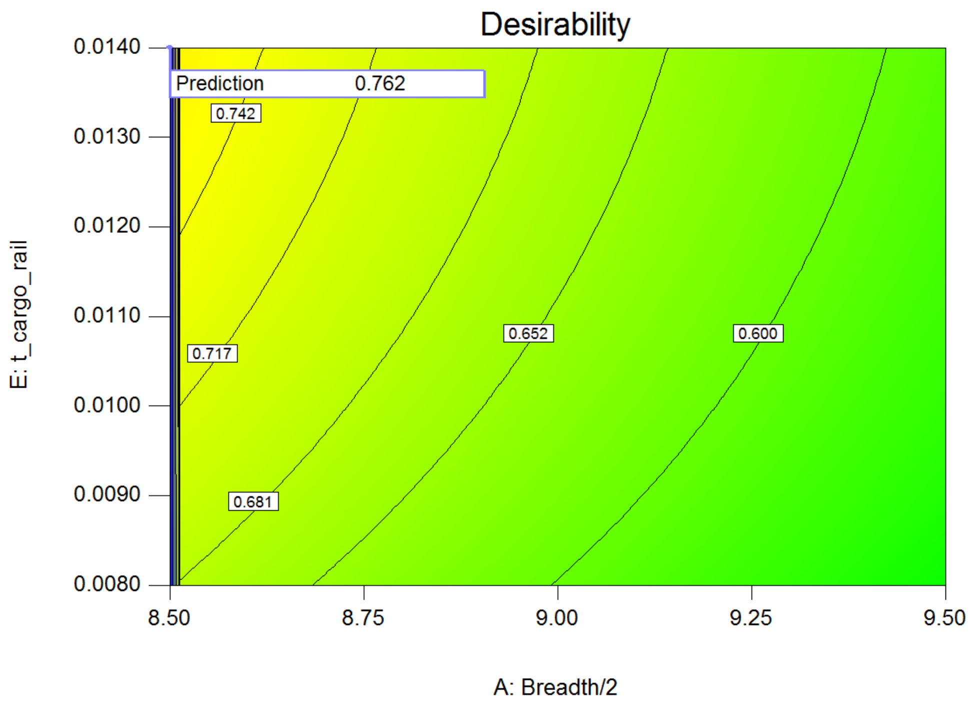


Figure 81: Breadth versus cargo rail thickness desirability contour Plot. Objective 2.

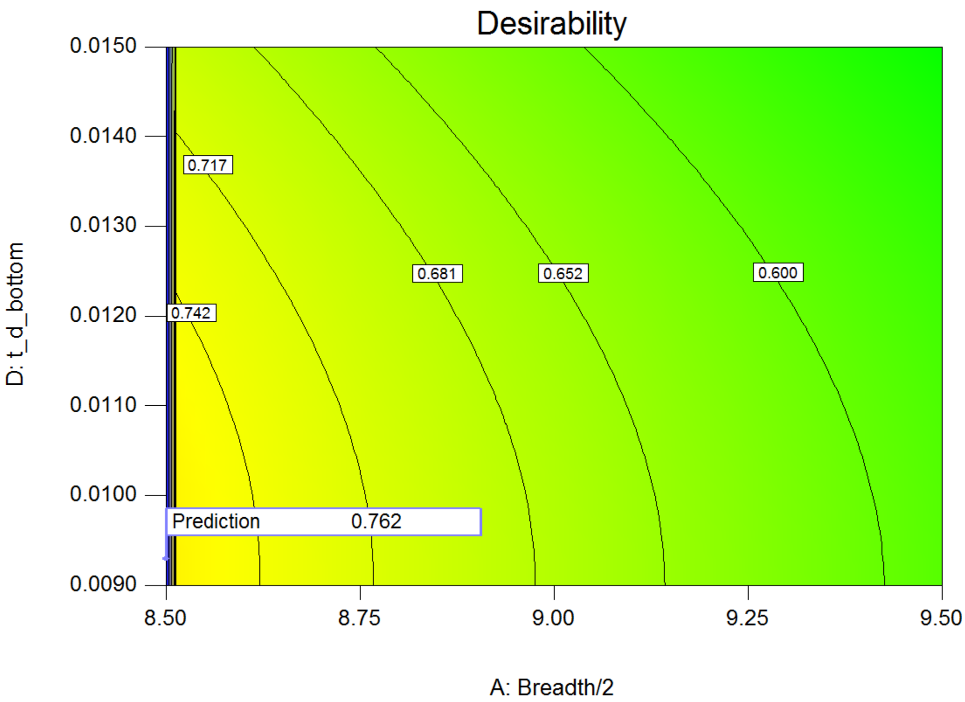


Figure 82: Breadth versus bottom thickness desirability contour plot. Objective 2.

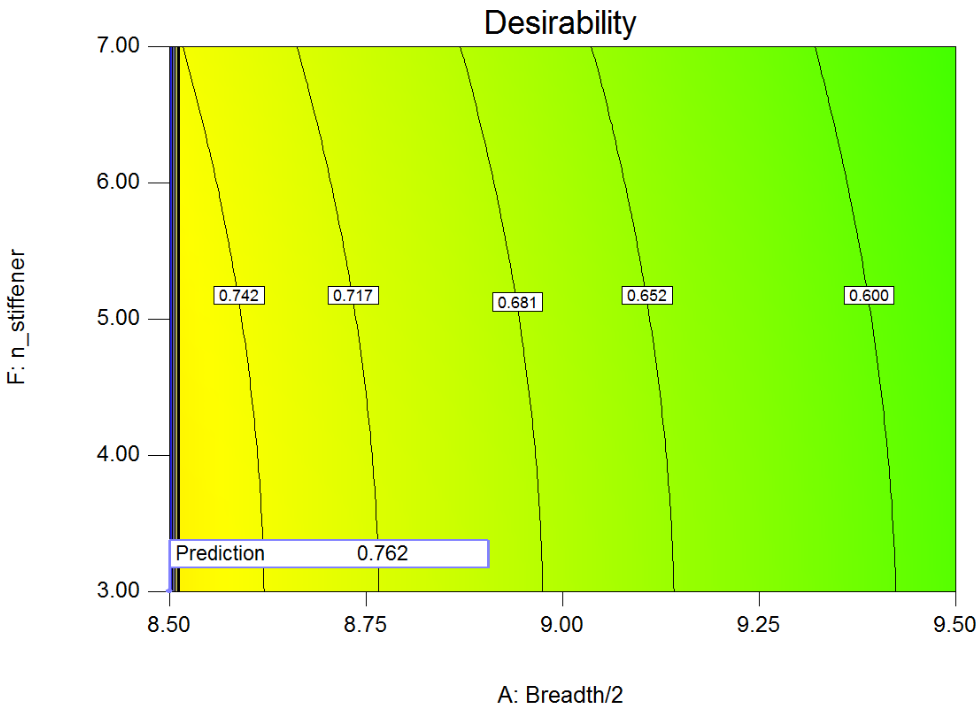


Figure 83: Depth versus stiffener number contour plot. Objective 2.

It is possible to note that changing goal objective has also affected how each factor combination influences the desirability. For the second set of goals, depth effects are more prevalent, as it has a great effect in the desirability increase, Figure 80. The lower the breadth value, the greater is the thickness influence on the desirability, positively for cargo rail increments, Figure 81, and negatively for bottom plate increments, Figure 82. Finally, the influence of number of stiffeners is more apparent for the second set of goals, showing higher desirability for lower stiffener numbers, Figure 83.

6.7 Main Results and Discussion (Step 10)

During this PSV structural design study I was able to apply the methodology, create a parametric finite element model, obtain a significant regression, test two different objectives and obtain an improved design for both solutions. The following table summarizes the improvements upon the original design.

Table 19: Main case objective solution summary compared to original design.

Objective	Linear Mass Change	Maximum Stress Change	Internal Area Change
1	-0.32%	-10.91%	17.20%
2	-5.60%	-9.24%	0.00%

The first objective aimed at an improved solution regarding material usage. The solution increased internal area, reduced stress and had practically the same amount of material than the original design. The second objective involved dimensional restriction and aimed at a reduced amount of material usage. The solution reduced the material usage for a similar sized design and reduced the maximum acting stress.

The experimentation procedure was only done once and still allowed for 2 distinct improvement studies, with the possibility of more being performed. The only restriction is that it should involve same vital factors, same responses and is only valid at the studied design interval. Thus, the methodology was proved flexible by handling a different array of goals, without requiring more experiments, and reliable, since there was an agreement between simulation and regression. Moreover, by studying the response surfaces obtained from the desirability function, complex factor interactions can be studied and used to plan design choices accordingly. For example, it was noticed that main dimensions had a significant influence in the desirability, with depth being more predominant. Also, cargo rail and bottom plate thickness have opposite effects on the desirability. The number of stiffeners influence varied depending on the objective, being more important on the second analysis.

As a final remark, it is interesting to note that adding a local structural analysis would increase the range of possible design improvements, as stiffeners' related factors would more than likely have a higher influence on the final desirability response surface. Also, frame distance and other factors could be included in the study. However, this would require a few changes in the finite elements model, as 2 different load cases would have to be simulated, thus increasing the amount of runs and total solving time (Even more if other factors are considered, since jumping from 7 to 12 factors increases the experiment's number from 64 to 138). However, this type of analysis would still be feasibly performed in less than one day, after which no more runs should be necessary, except for validation purposes.

7 Conclusion

This study's objective was to demonstrate that design of experiments used for response surface creation is a viable, reliable and fast way to create improved structural design solutions for PSVs. Initially it was determined how a ship's section parametric model can be created for experimentation purposes at early design stages. This requires a simplified but representative model that is able to be solved for the desired responses. For this purpose, it was decided that a cargo hold finite elements model, with stiffeners as smaller structural part, should be able to achieve those conditions. This assumption was supported by information and practices from different described sources. (Okumoto, et al.), (Hughes, et al., 2010) and (IACS, 2015).

This model's purpose was to allow a regression function to be obtained from each desired response. The necessity of regression comes from the complexity involved in structural stress analysis for models with many structural parts, as a ship's section. Such problem is usually difficult to be accurately solved, thus the comprehensive use of finite elements analysis methods. Added to that, it is even more complex to be optimized. It was shown that it is possible to determine valid regressions for ships structural models at a conceptual level. To obtain this function, design of experiments methodology is applied.

The first step for the DoE application is the screening for vital factors. This step had already been performed in other studies, (Diewald, 2015) and (Brandt, 2015), and a few others were added, resulting in 7 vital factors: Depth, Breadth, Main Deck Plate Thickness, Bottom Plate Thickness, Cargo Rail Plate Thickness, Stiffener Type and Number. Using an 50% augmented D-Optimal methodology, (Anderson, et al., 2005), an experimental set was created based on a design space defined for those factors. Simulations were performed for a total of 64 experiments and 5 responses measured: 3 stresses, linear mass and internal area. A regression was obtained for each response. Each of them can be explained in the form of a response surface, expressed in function of the vital factors, 2 at a time. However, the objective was to generate an improved solution that would satisfy multiple optimization objectives. Thus desirability functions were defined and 2 different objectives set.

The first objective aimed at an improved solution regarding material usage. The solution increased internal area, reduced stress and had practically the same amount of material than the original design. The second objective involved dimensional restriction and aimed at a reduced amount of material usage. The solution reduced the material usage for a similar sized design and reduced the maximum acting stress. Both solutions were validated with minimal deviation from the finite elements simulation, showing that the regression models were valid.

The method proved to be a useful tool to aid designers in defining critical parameters at conceptual design levels, however it has limitations. Complex and detailed structural models are not ideal to be implemented in an iterative routine. Also, factor selection is crucial, since they directly influence on the experiment numbers, thus the addition of non-crucial factors would only increase run time and would not add any meaningful information to the designer. Finally, the conclusions are only valid within the stablished design interval.

On the other hand, this approach can be performed to decrease computational effort while maintaining good reliability in its results. Moreover, local optimization isn't the only possible outcome, since the factor interaction and multi-response analyses generate a great deal of important information to structural designers. Through these analyses the designer can find factors relevance and importance for different responses combinations. When a solution indicates that the best outcomes are at the edge of the design interval, the designer could consider increasing the design space, whenever feasible, and study that region.

There is still space to improve the methodology. As discussed, future work could combine other types of load analyses using the same model type with modifications. Local loads, vertical shear force and horizontal bending moment could be feasibly included in the simulation. More factors could be studied, as individual girders, framing distance and different material properties. The extra analysis would take a longer, as it would involve an increased amount of experiments, but it could still be feasibly performed within a day.

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Appendix A – Simple Case APDL code.

```
/clear,all
/prep7
/VIEW,1,1,1,1
/ANG,1
/REP,FAST
Breadth=23
Depth=8.95
thickness_center=0.01
thickness_extremes=0.03
dens=7.8
Length=79.5
Cb=0.69
mesh_size=Depth/20
ET,1,SHELL181            !SHELL TYPE
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,EX,1,,210000000000
MPDATA,PRXY,1,,0.3
!!DEFINE PLATE THICKNESS - LONGITUDINALs
!Decks
sectype,1,shell,,deck
secdata, thickness_extremes,1,0.0,3
secoffset,MID
seccontrol,,,, , , ,
!Side
sectype,2,shell,,side
secdata, thickness_center,1,0.0,3
secoffset,MID
seccontrol,,,, , , ,
!BOTTOM
sectype,3,shell,,bottom
secdata, thickness_extremes,1,0.0,3
secoffset,MID
seccontrol,,,, , , ,
k,1,0,0,0
k,2,Breadth/2,0,0
k,3,Breadth/2,Depth,0
k,4,0,Depth,0
k,5,0,0,Length
```

```
lat_mesh=Breadth/mesh_size/2
height_mesh=Depth/mesh_size
length_mesh=Length/mesh_size
l,1,2,lat_mesh
l,2,3,height_mesh
l,3,4,lat_mesh
l,1,5,length_mesh
Adrag,1,2,3,,,,4
Adrag,1,,,,,,2
asel,s,loc,z,-0.001,0.001,
Agen,2,all,0,0,0,0,Length,,0,
asel,all
lsel,all
AMESH,ALL

NUMMRG,all
!Bottom Plate
esel,s,cent,y,-0.001,0.001,
emodif,all,secnum,3
!TOP
esel,s,cent,y,Depth - 0.001,Depth + 0.001,
emodif,all,secnum,1
!SIDE
esel,s,cent,x,Breadth/2-0.001,Breadth/2+0.001,
emodif,all,secnum,2
!Bulkheads
esel,s,cent,z,-0.001,0.001,
emodif,all,secnum,2
esel,s,cent,z,Length-0.001,Length+0.001,
emodif,all,secnum,2
!Mass Calculation
esel,all
numb=0
vol=0
V_total=0
*get,numb,elem,,num,max
*do,i,1,numb,1
*get,vol,elem,i,volu
 V_total=vol+V_total
*enddo
```

```
 V_total=V_total-Breadth*Depth*thickness_center     !2/2=1 :)
Linear_Mass=V_total*dens*2/Length
!BOUNDARIES
!n_axis=Depth/2
n_axis=Depth/2
bb=node(0,n_axis,Length)
aa=node(0,n_axis,0)
nsel,s,loc,z,-0.001,0.001,
cerig,aa,all,all
D,aa, ,0, , , ux,uy,uz,roty,rotz
nsel,all
nsel,s,loc,z,Length-0.001,Length+0.001
cerig,bb,all,all
D,bb, ,0, , , ux,ux,uy,uz,roty,rotz
nsel,s,loc,x,0-0.00001,0+0.00001
nsel,u,loc,z,-0.001,0.001,
nsel,u,loc,z,Length-0.001,Length+0.001
D,all, ,0, , , ux,roty,rotz
nsel,all
!Moment Calculation
fnl_vh=1
fnl_vs=0.58*(Cb+0.7)/Cb
fm=1
f_p=1
fps=1
fsw=1
Cw=0.0856*Length
Wave_H_Moment=0.19*fnl_vh*fm*f_p*Cw*Length*Length*Breadth*Cb
Wave_S_Moment=-0.19*fnl_vs*fm*f_p*Cw*Length*Length*Breadth*Cb
SW_H_Moment=fsw*(171*Cw*Length*Length*Breadth*(Cb+0.7)*0.001-Wave_H_Moment)
SW_S_Moment=-0.85*fsw*(171*Cw*Length*Length*Breadth*(Cb+0.7)*0.001+Wave_S_Moment)
Moment=0
*if,-(SW_S_Moment+Wave_S_Moment),GT,(SW_H_Moment+Wave_H_Moment),then
Moment=(SW_S_Moment+Wave_S_Moment)*1000
*else
Moment=(SW_H_Moment+Wave_H_Moment)*1000
*endif
F,aa,Mx,-Moment/2
F,bb,Mx,Moment/2
esel,all
```

```
/SOL
/STATUS,SOLU
SOLVE
esel,s,cent,z,Length/2-2,Length/2+2
/post1
/EFACET,1
PLNSOL, S,EQV, 0,1.0
/GFORMAT,E,12,5,
/VIEW,1,1,1,1
/ANG,1
/REP,FAST
```

Appendix B - D-Optimal RSM applied to Simulations using Design Expert 8.

Step 1: The first step is to set the amount of numeric and categorical[14] factor. Numeric factors can be further divided into continuous or discrete factors and each categorical can have many levels (e.g. stiffener type A, type B, …). We don't have in our case, but constraints can be added in this step as well. Figure 1. Press "Continue".

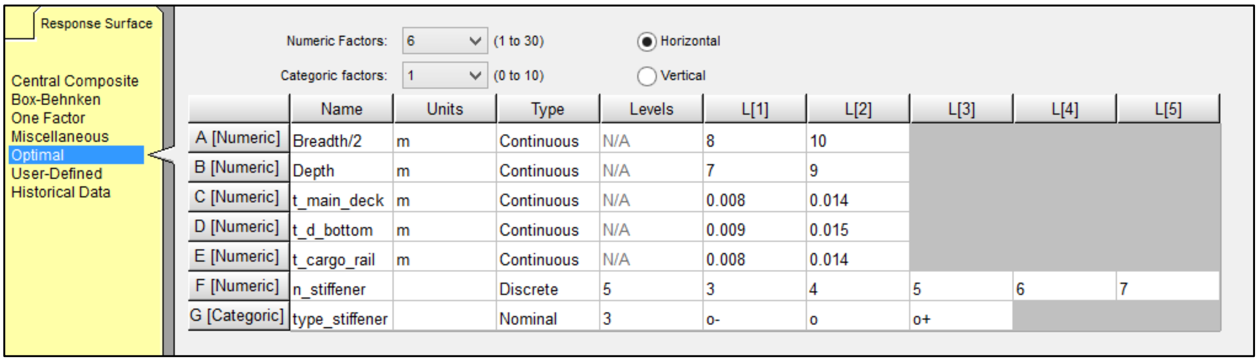

Figure 1: Selecting Factors

Step 2: Define Experimental Space according to user necessities. Figure 2.

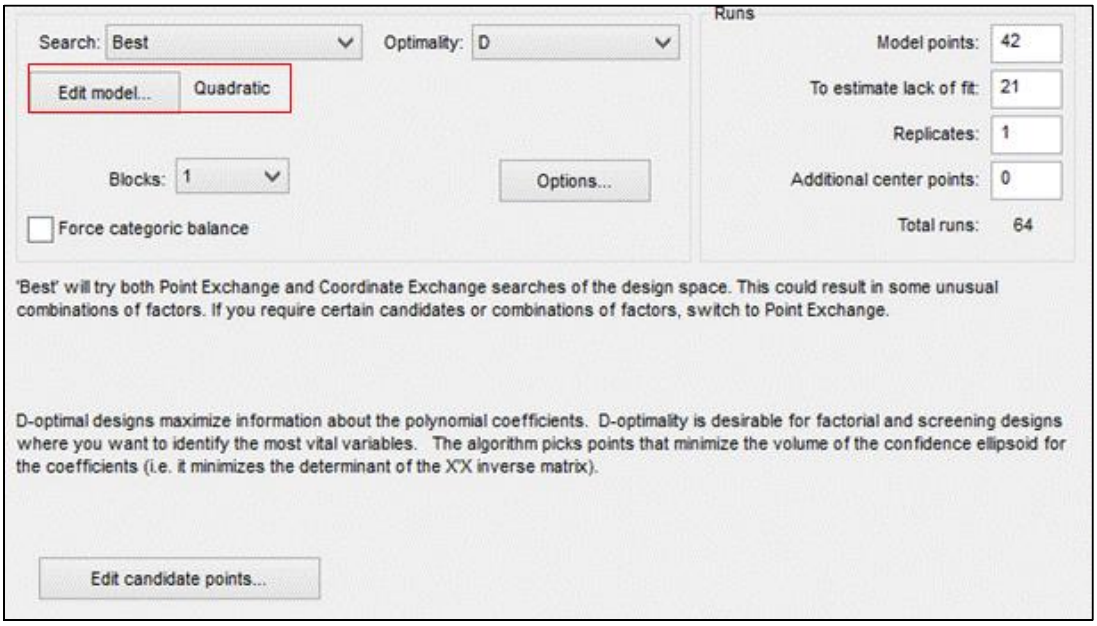

Figure 2: Selecting higher model type.

[14] Categorical factors are those who are not numbers, but labels, as colours for example or, in our case, stiffeners types.

Select the maximum model size for surface regression. Note that this does not mean that all models will have a quadratic polynomial regression, only that the number of points chosen are sufficient to create up to this order of regression. Quadratic regression is enough for our case.

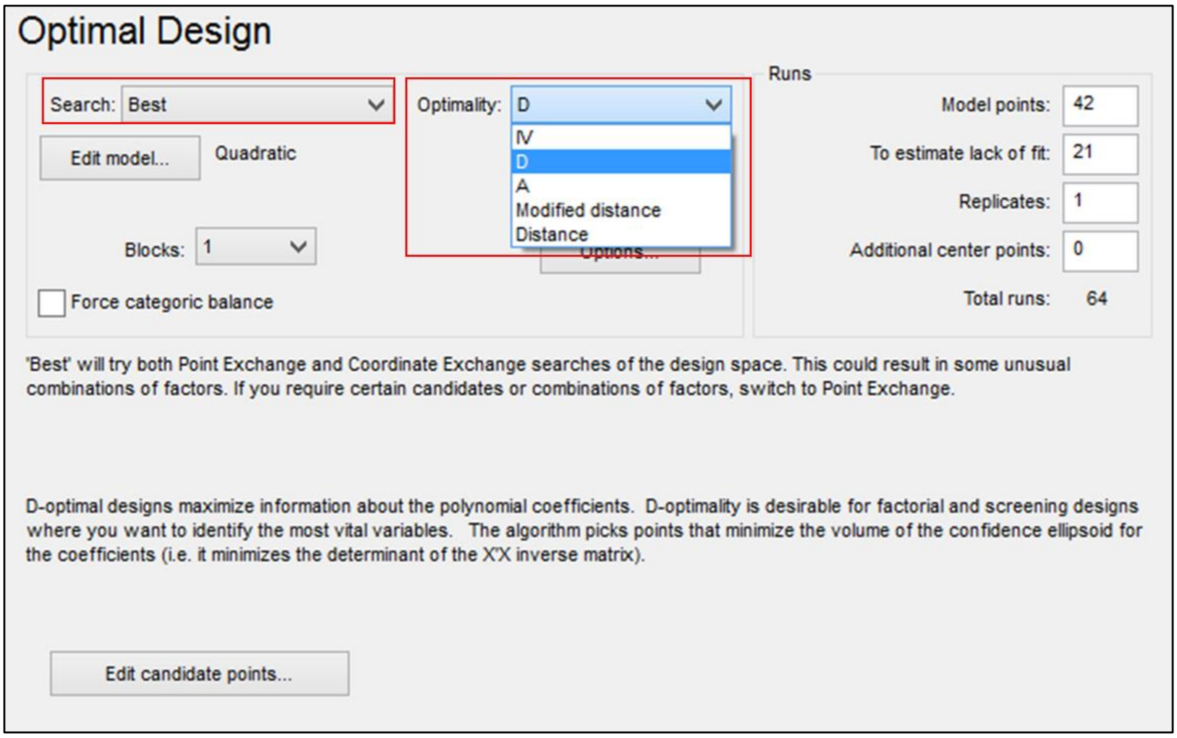

Figure 3: Search Method and D-Optimal.

Step 3: The standard method for the software to search for experiments points within the design space is called best (more information in Figure 3). And we set the Optimality to D, as it is the one best suited for our needs (Computer Simulation surface regression with more than 5 factors). This defines the minimal amount of model points, 42 in this case.

Step 4: Since we are implementing the Overestimated D-Optimal we still need to add at least 50% more experiments (21 points) using the minimal Euclidean distance method. This is done by manually setting the "to estimate lack of fit" input to 21. In addition to that we add one "replicate", which will track any possible change in the code. (Not likely to happen, but a safety measure against human error). Figure 4.

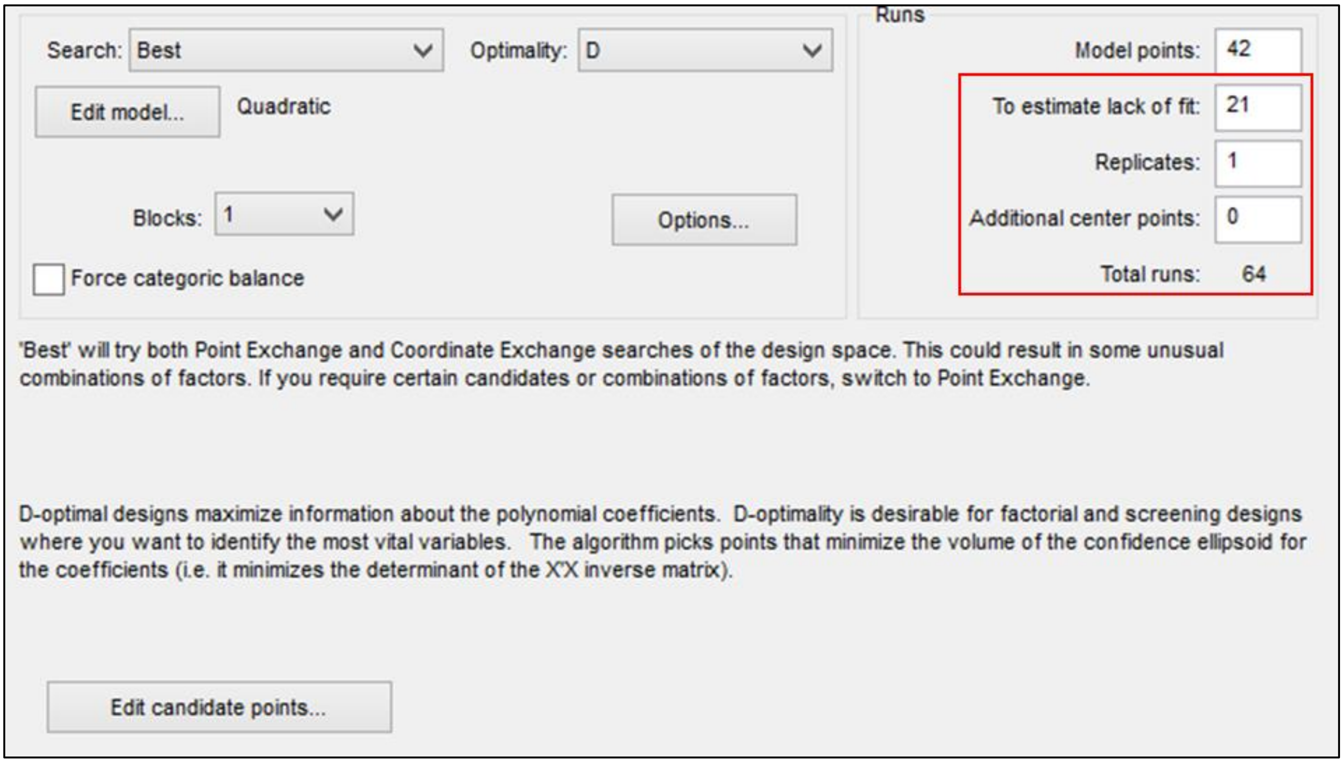

Figure 4: Model Points overestimation and replicate.

Press "Continue".

Step 5: Defining Responses. The number of responses wished is independent of the number of experiments, thus more can be added later if the user deems that the factors involved are significant and the model sufficient. Figure 5. Press "Continue".

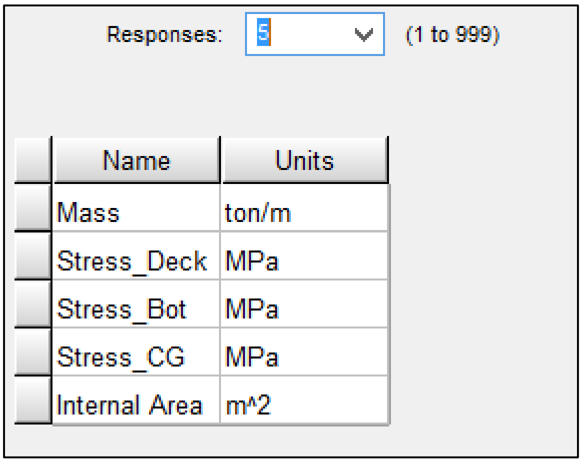

Figure 5: Adding Responses.

Appendix C – D-Optimal Experiments and Responses

Experiments Setup

	Main Factors						
Tests	**Breadth/2 (m)**	**Depth (m)**	**Main Deck Thickness (m)**	**Bottom Thickness (m)**	**Cargo Rail thickness (m)**	**Stiffener Number**	**Stiffener Type**
1	10	9	0.01	0.01	0.01	3	o-
2	8	8	0.01482615	0.01505	0.01	3	o-
3	9.45	7.1	0.0138	0.01005	0.0138	3	o-
4	8	9	0.02	0.02	0.0146511	3	o-
5	8.3	7	0.02	0.01	0.01765	3	o-
6	9.67	8.65	0.02	0.02	0.0182	3	o-
7	8	7	0.01	0.02	0.02	3	o-
8	10	7	0.0143	0.02	0.02	3	o-
9	8.82	9	0.01	0.01595	0.0148	4	o-
10	8	7	0.01	0.01	0.01	5	o-
11	10	7	0.02	0.02	0.01	5	o-
12	10	7.87	0.01555	0.01625	0.01525	5	o-
13	8	9	0.01525	0.01335	0.02	5	o-
14	8	7.958160372	0.011	0.017849807	0.01075	6	o-
15	10	7	0.02	0.01	0.02	6	o-
16	8	9	0.02	0.01	0.01	7	o-
17	9.25	9	0.01	0.02	0.01	7	o-
18	10	7	0.01	0.01425	0.014	7	o-
19	8.3	7	0.01555	0.0115	0.015	7	o-
20	8.75	8.25	0.01	0.01	0.02	7	o-
21	8	7	0.02	0.02	0.02	7	o-
22	10	9	0.02	0.02	0.02	7	o-
23	10	7	0.02	0.01	0.01	3	o
24	9.17	7	0.01	0.02	0.01	3	o
25	10	9	0.02	0.02	0.01	3	o
26	9.35	8.5	0.01525	0.01315	0.0126	3	o
27	8	9	0.01	0.01	0.0133	3	o
28	8	7	0.01	0.01	0.0164	3	o
29	10	9	0.01	0.01485	0.02	3	o
30	8	7.69	0.02	0.02	0.02	3	o
31	8	8.51	0.02	0.01525	0.012	5	o
32	9.82	9	0.01735	0.01525	0.0195	5	o
33	9.26	7	0.014	0.0133	0.02	5	o
34	8.93	7	0.01155	0.01495	0.01	6	o
35	8.587028	9	0.013074045	0.01005	0.0152452	6	o
36	10	8.32	0.01	0.01	0.01	7	o
37	8	7	0.02	0.01515	0.01	7	o

38	10	8.28	0.01995	0.01	0.01005	7	o
39	10	7	0.02	0.02	0.016818	7	o
40	8	7	0.01	0.01	0.02	7	o
41	8.82	9	0.02	0.01	0.02	7	o
42	8	9	0.01	0.02	0.02	7	o
43	8	9	0.02	0.01	0.01	3	o+
44	8	7	0.0155	0.02	0.012	3	o+
45	10	9	0.02	0.01	0.0197	3	o+
46	8.27	7.77	0.014557005	0.014153512	0.0198	3	o+
47	10	7	0.01	0.01	0.02	3	o+
48	10	7	0.02	0.0185	0.02	3	o+
49	8	9	0.01005	0.02	0.02	3	o+
50	10	8.47	0.01	0.02	0.0137	4	o+
51	8.56	8.123860551	0.014733158	0.0104	0.0101	5	o+
52	9.8	8.82	0.02	0.0147	0.0118	5	o+
53	8.992948	7.02	0.017567731	0.017505758	0.0135074	6	o+
54	8.608432	9	0.02	0.017139352	0.018382	6	o+
55	8.7	7	0.01	0.02	0.02	6	o+
56	9.41	7	0.017	0.01	0.01	7	o+
57	8	9	0.01	0.01275	0.01	7	o+
58	8	9	0.01	0.01275	0.01	7	o+
59	10	7	0.01	0.02	0.01	7	o+
60	8.36	9	0.02	0.02	0.01	7	o+
61	8	8.06	0.01455	0.02	0.0163	7	o+
62	10	9	0.01	0.01	0.02	7	o+
63	8	7.68	0.02	0.01	0.02	7	o+
64	9.9	7.98	0.0165	0.0135	0.02	7	o+

Responses

Test	Linear Mass (ton/m)	Bottom Stress (MPa)	Deck Stress (MPa)	Cargo Rail Stress (MPa)
1	19.05	45.36	42.73	70.59
2	19.66	49.84	45.13	83.80
3	17.67	41.98	45.82	81.55
4	20.15	42.24	43.30	78.28
5	18.21	38.14	28.78	49.96
6	21.78	36.49	32.61	57.77
7	20.15	30.93	26.09	45.34
8	17.41	51.72	34.02	69.00
9	19.28	34.08	28.06	47.69
10	18.99	45.75	32.49	60.98
11	19.33	36.26	34.57	59.73
12	22.00	33.71	28.85	48.69
13	19.38	44.71	33.13	60.77
14	18.39	58.74	49.36	93.46

15	20.11	31.98	27.26	45.95
16	19.99	42.78	37.59	70.29
17	22.40	31.92	32.86	53.34
18	18.32	38.88	32.30	54.79
19	21.28	41.52	27.66	50.18
20	19.12	38.75	27.93	52.91
21	21.52	29.25	27.17	44.98
22	22.06	40.18	32.77	62.63
23	19.36	36.93	35.84	59.92
24	18.31	50.84	38.74	72.53
25	18.63	40.89	37.99	70.15
26	21.10	38.25	38.98	67.26
27	17.40	48.20	38.96	70.85
28	20.73	37.15	29.66	51.30
29	19.44	55.85	35.66	73.06
30	21.91	31.36	32.22	52.36
31	20.67	42.76	32.82	56.70
32	20.30	43.94	48.20	85.77
33	18.16	44.69	35.14	67.74
34	19.96	43.67	37.71	68.33
35	19.63	36.54	23.45	42.49
36	19.08	37.70	31.97	60.46
37	21.44	30.56	28.82	47.83
38	19.51	48.08	30.24	62.19
39	17.98	51.49	34.70	69.90
40	20.35	29.39	29.09	47.61
41	20.32	34.31	26.29	45.51
42	22.67	33.28	28.10	49.49
43	20.88	40.21	29.74	51.95
44	18.08	59.56	52.33	98.12
45	18.63	39.10	30.38	52.41
46	22.44	32.04	32.67	53.05
47	19.89	29.48	29.76	48.49
48	20.21	41.22	32.50	55.98
49	17.72	45.34	33.64	65.98
50	18.64	43.59	29.78	59.75
51	20.31	39.42	34.46	64.78
52	21.67	32.63	36.84	59.08
53	19.42	47.79	40.77	76.49
54	20.09	34.13	30.66	54.25
55	20.66	43.71	32.93	59.22
56	17.86	48.25	36.71	70.40
57	20.86	35.22	32.37	53.80
58	19.52	37.79	34.26	63.71
59	21.97	40.43	37.07	68.85
60	20.45	53.24	34.91	71.08

61	18.55	47.64	30.96	63.17
62	22.56	34.40	31.48	55.47
63	22.21	26.71	20.80	35.84
64	22.21	26.71	20.80	35.84

Appendix D – Main Case Regression Models.

Mass Response Regression:

Stiffener Type o-	Stiffener Type o	Stiffener Type o+
Weight =	Weight =	Weight =
+3.46893	+3.47655	+3.55278
+0.35579 * Breadth/2	+0.36081 * Breadth/2	+0.36598 * Breadth/2
+0.71897 * Depth	+0.71917 * Depth	+0.71953 * Depth
-1.28497 * t_main_deck	-1.29376 * t_main_deck	-1.31703 * t_main_deck
+1.55583 * t_d_bottom	+3.33814 * t_d_bottom	+5.03401 * t_d_bottom
+110.74684 * t_cargo_rail	+110.77371 * t_cargo_rail	+110.88484 * t_cargo_rail
+0.15566 * n_stiffener	+0.19823 * n_stiffener	+0.23743 * n_stiffener
-1.10387E-004 * Breadth/2 * Depth	-1.10387E-004 * Breadth/2 * Depth	-1.10387E-004 * Breadth/2 * Depth
+15.62721 * Breadth/2 * t_main_deck	+15.62721 * Breadth/2 * t_main_deck	+15.62721 * Breadth/2 * t_main_deck
+31.26752 * Breadth/2 * t_d_bottom	+31.26752 * Breadth/2 * t_d_bottom	+31.26752 * Breadth/2 * t_d_bottom
+0.16133 * Breadth/2 * t_cargo_rail	+0.16133 * Breadth/2 * t_cargo_rail	+0.16133 * Breadth/2 * t_cargo_rail
-2.23845E-005 * Breadth/2 * n_stiffener	-2.23845E-005 * Breadth/2 * n_stiffener	-2.23845E-005 * Breadth/2 * n_stiffener
+0.23491 * Depth * t_main_deck	+0.23491 * Depth * t_main_deck	+0.23491 * Depth * t_main_deck
-0.096616 * Depth * t_d_bottom	-0.096616 * Depth * t_d_bottom	-0.096616 * Depth * t_d_bottom
+0.12174 * Depth * t_cargo_rail	+0.12174 * Depth * t_cargo_rail	+0.12174 * Depth * t_cargo_rail
+1.12421E-004 * Depth * n_stiffener	+1.12421E-004 * Depth * n_stiffener	+1.12421E-004 * Depth * n_stiffener
-9.69222 * t_main_deck * t_d_bottom	-9.69222 * t_main_deck * t_d_bottom	-9.69222 * t_main_deck * t_d_bottom
+36.04170 * t_main_deck * t_cargo_rail	+36.04170 * t_main_deck * t_cargo_rail	+36.04170 * t_main_deck * t_cargo_rail
-0.038940 * t_main_deck * n_stiffener	-0.038940 * t_main_deck * n_stiffener	-0.038940 * t_main_deck * n_stiffener
+28.80885 * t_d_bottom * t_cargo_rail	+28.80885 * t_d_bottom * t_cargo_rail	+28.80885 * t_d_bottom * t_cargo_rail
+4.10744 * t_d_bottom * n_stiffener	+4.10744 * t_d_bottom * n_stiffener	+4.10744 * t_d_bottom * n_stiffener
-0.020681 * t_cargo_rail * n_stiffener	-0.020681 * t_cargo_rail * n_stiffener	-0.020681 * t_cargo_rail * n_stiffener

Stress_Deck = +107.27338 +9.71244 * Breadth/2 -11.85952 * Depth -2131.58942 * t_main_deck -438.63762 * t_d_bottom -5007.86303 * t_cargo_rail -2.86917 * n_stiffener -0.37216 * Breadth/2 * Depth -135.82180 * Breadth/2 * t_main_deck -26.75474 * Breadth/2 * t_d_bottom -39.05402 * Breadth/2 * t_cargo_rail -0.023868 * Breadth/2 * n_stiffener +127.48817 * Depth * t_main_deck +5.16096 * Depth * t_d_bottom +240.45000 * Depth * t_cargo_rail +0.088959 * Depth * n_stiffener +10111.29035 * t_main_deck * t_d_bottom +55522.15132 * t_main_deck * t_cargo_rail +39.66465 * t_main_deck * n_stiffener +20691.86728 * t_d_bottom * t_cargo_rail -10.70401 * t_d_bottom * n_stiffener +67.72606 * t_cargo_rail * n_stiffener -0.095631 * Breadth/2^2 +0.40070 * Depth^2 +24063.45646 * t_main_deck^2 +5876.20827 * t_d_bottom^2 +43180.52397 * t_cargo_rail^2 +0.040179 * n_stiffener^2	Stress_Deck = +103.27409 +9.73421 * Breadth/2 -11.71272 * Depth -2059.43348 * t_main_deck -417.64595 * t_d_bottom -4943.03927 * t_cargo_rail -2.94300 * n_stiffener -0.37216 * Breadth/2 * Depth -135.82180 * Breadth/2 * t_main_deck -26.75474 * Breadth/2 * t_d_bottom -39.05402 * Breadth/2 * t_cargo_rail -0.023868 * Breadth/2 * n_stiffener +127.48817 * Depth * t_main_deck +5.16096 * Depth * t_d_bottom +240.45000 * Depth * t_cargo_rail +0.088959 * Depth * n_stiffener +10111.29035 * t_main_deck * t_d_bottom +55522.15132 * t_main_deck * t_cargo_rail +39.66465 * t_main_deck * n_stiffener +20691.86728 * t_d_bottom * t_cargo_rail -10.70401 * t_d_bottom * n_stiffener +67.72606 * t_cargo_rail * n_stiffener -0.095631 * Breadth/2^2 +0.40070 * Depth^2 +24063.45646 * t_main_deck^2 +5876.20827 * t_d_bottom^2 +43180.52397 * t_cargo_rail^2 +0.040179 * n_stiffener^2	Stress_Deck = +102.11023 +9.78070 * Breadth/2 -11.70422 * Depth -2039.99800 * t_main_deck -441.46525 * t_d_bottom -4892.44186 * t_cargo_rail -3.11318 * n_stiffener -0.37216 * Breadth/2 * Depth -135.82180 * Breadth/2 * t_main_deck -26.75474 * Breadth/2 * t_d_bottom -39.05402 * Breadth/2 * t_cargo_rail -0.023868 * Breadth/2 * n_stiffener +127.48817 * Depth * t_main_deck +5.16096 * Depth * t_d_bottom +240.45000 * Depth * t_cargo_rail +0.088959 * Depth * n_stiffener +10111.29035 * t_main_deck * t_d_bottom +55522.15132 * t_main_deck * t_cargo_rail +39.66465 * t_main_deck * n_stiffener +20691.86728 * t_d_bottom * t_cargo_rail -10.70401 * t_d_bottom * n_stiffener +67.72606 * t_cargo_rail * n_stiffener -0.095631 * Breadth/2^2 +0.40070 * Depth^2 +24063.45646 * t_main_deck^2 +5876.20827 * t_d_bottom^2 +43180.52397 * t_cargo_rail^2 +0.040179 * n_stiffener^2

Stress_Bot	=	Stress_Bot	=	Stress_Bot	=
+174.31561		+172.45578		+170.13565	
+6.81167	* Breadth/2	+6.82393	* Breadth/2	+6.91716	* Breadth/2
-20.42527	* Depth	-20.38213	* Depth	-20.29498	* Depth
-236.57212	* t_main_deck	-201.77036	* t_main_deck	-229.88599	* t_main_deck
-5593.54790	* t_d_bottom	-5552.06757	* t_d_bottom	-5460.61994	* t_d_bottom
-2142.25322	* t_cargo_rail	-2098.76656	* t_cargo_rail	-2126.45150	* t_cargo_rail
-1.86756	* n_stiffener	-1.93486	* n_stiffener	-2.09815	* n_stiffener
-0.26490	* Breadth/2 * Depth	-0.26490	* Breadth/2 * Depth	-0.26490	* Breadth/2 * Depth
-31.87901	* Breadth/2 * t_main_deck	-31.87901	* Breadth/2 * t_main_deck	-31.87901	* Breadth/2 * t_main_deck
-177.78084	* Breadth/2 * t_d_bottom	-177.78084	* Breadth/2 * t_d_bottom	-177.78084	* Breadth/2 * t_d_bottom
+3.93151	* Breadth/2 * t_cargo_rail	+3.93151	* Breadth/2 * t_cargo_rail	+3.93151	* Breadth/2 * t_cargo_rail
+0.023267	* Breadth/2 * n_stiffener	+0.023267	* Breadth/2 * n_stiffener	+0.023267	* Breadth/2 * n_stiffener
+20.40526	* Depth * t_main_deck	+20.40526	* Depth * t_main_deck	+20.40526	* Depth * t_main_deck
+314.89501	* Depth * t_d_bottom	+314.89501	* Depth * t_d_bottom	+314.89501	* Depth * t_d_bottom
+95.88269	* Depth * t_cargo_rail	+95.88269	* Depth * t_cargo_rail	+95.88269	* Depth * t_cargo_rail
+0.039358	* Depth * n_stiffener	+0.039358	* Depth * n_stiffener	+0.039358	* Depth * n_stiffener
+4174.06547	* t_main_deck * t_d_bottom	+4174.06547	* t_main_deck * t_d_bottom	+4174.06547	* t_main_deck * t_d_bottom
+14010.24166	* t_main_deck * t_cargo_rail	+14010.24166	* t_main_deck * t_cargo_rail	+14010.24166	* t_main_deck * t_cargo_rail
+1.37718	* t_main_deck * n_stiffener	+1.37718	* t_main_deck * n_stiffener	+1.37718	* t_main_deck * n_stiffener
+23783.06116	* t_d_bottom * t_cargo_rail	+23783.06116	* t_d_bottom * t_cargo_rail	+23783.06116	* t_d_bottom * t_cargo_rail
+39.67607	* t_d_bottom * n_stiffener	+39.67607	* t_d_bottom * n_stiffener	+39.67607	* t_d_bottom * n_stiffener
+13.22273	* t_cargo_rail * n_stiffener	+13.22273	* t_cargo_rail * n_stiffener	+13.22273	* t_cargo_rail * n_stiffener
-0.029189	* Breadth/2^2	-0.029189	* Breadth/2^2	-0.029189	* Breadth/2^2
+0.71537	* Depth^2	+0.71537	* Depth^2	+0.71537	* Depth^2
+1358.53467	* t_main_deck^2	+1358.53467	* t_main_deck^2	+1358.53467	* t_main_deck^2
+91730.41562	* t_d_bottom^2	+91730.41562	* t_d_bottom^2	+91730.41562	* t_d_bottom^2
+17013.60035	* t_cargo_rail^2	+17013.60035	* t_cargo_rail^2	+17013.60035	* t_cargo_rail^2
+0.031691	* n_stiffener^2	+0.031691	* n_stiffener^2	+0.031691	* n_stiffener^2

Stress_CG =		Stress_CG =		Stress_CG =	
+302.34725		+294.80008		+292.47606	
+16.85942	* Breadth/2	+16.91693	* Breadth/2	+17.07970	* Breadth/2
-41.89179	* Depth	-41.57991	* Depth	-41.50522	* Depth
-3285.73065	* t_main_deck	-3151.81858	* t_main_deck	-3163.29874	* t_main_deck
-3343.93371	* t_d_bottom	-3286.60956	* t_d_bottom	-3305.57120	* t_d_bottom
-8282.11756	* t_cargo_rail	-8177.44031	* t_cargo_rail	-8138.77205	* t_cargo_rail
-5.23322	* n_stiffener	-5.34526	* n_stiffener	-5.67395	* n_stiffener
-0.82949	* Breadth/2 * Depth	-0.82949	* Breadth/2 * Depth	-0.82949	* Breadth/2 * Depth
-203.58514	* Breadth/2 * t_main_deck	-203.58514	* Breadth/2 * t_main_deck	-203.58514	* Breadth/2 * t_main_deck
-108.66595	* Breadth/2 * t_d_bottom	-108.66595	* Breadth/2 * t_d_bottom	-108.66595	* Breadth/2 * t_d_bottom
-46.96567	* Breadth/2 * t_cargo_rail	-46.96567	* Breadth/2 * t_cargo_rail	-46.96567	* Breadth/2 * t_cargo_rail
-6.45779E-003	* Breadth/2 * n_stiffener	-6.45779E-003	* Breadth/2 * n_stiffener	-6.45779E-003	* Breadth/2 * n_stiffener
+227.92589	* Depth * t_main_deck	+227.92589	* Depth * t_main_deck	+227.92589	* Depth * t_main_deck
+220.02341	* Depth * t_d_bottom	+220.02341	* Depth * t_d_bottom	+220.02341	* Depth * t_d_bottom
+433.04871	* Depth * t_cargo_rail	+433.04871	* Depth * t_cargo_rail	+433.04871	* Depth * t_cargo_rail
+0.19583	* Depth * n_stiffener	+0.19583	* Depth * n_stiffener	+0.19583	* Depth * n_stiffener
+16412.30998	* t_main_deck * t_d_bottom	+16412.30998	* t_main_deck * t_d_bottom	+16412.30998	* t_main_deck * t_d_bottom
+81852.68203	* t_main_deck * t_cargo_rail	+81852.68203	* t_main_deck * t_cargo_rail	+81852.68203	* t_main_deck * t_cargo_rail
+53.74230	* t_main_deck * n_stiffener	+53.74230	* t_main_deck * n_stiffener	+53.74230	* t_main_deck * n_stiffener
+37688.15862	* t_d_bottom * t_cargo_rail	+37688.15862	* t_d_bottom * t_cargo_rail	+37688.15862	* t_d_bottom * t_cargo_rail
-1.03193	* t_d_bottom * n_stiffener	-1.03193	* t_d_bottom * n_stiffener	-1.03193	* t_d_bottom * n_stiffener
+94.71145	* t_cargo_rail * n_stiffener	+94.71145	* t_cargo_rail * n_stiffener	+94.71145	* t_cargo_rail * n_stiffener
-0.10240	* Breadth/2^{2}	-0.10240	* Breadth/2^{2}	-0.10240	* Breadth/2^{2}
+1.68520	* Depth^{2}	+1.68520	* Depth^{2}	+1.68520	* Depth^{2}
+31053.26819	* t_main_deck^{2}	+31053.26819	* t_main_deck^{2}	+31053.26819	* t_main_deck^{2}
+39969.18612	* t_d_bottom^{2}	+39969.18612	* t_d_bottom^{2}	+39969.18612	* t_d_bottom^{2}
+68123.59227	* t_cargo_rail^{2}	+68123.59227	* t_cargo_rail^{2}	+68123.59227	* t_cargo_rail^{2}
+0.071862	* n_stiffener^{2}	+0.071862	* n_stiffener^{2}	+0.071862	* n_stiffener^{2}

Internal Area =	Internal Area =	Internal Area =
-3.01045E-012	-1.98613E-012	-2.80169E-012
+2.12055E-01: * Breadth/2	+1.60977E-01: * Breadth/2	+1.81592E-01: * Breadth/2
-1.12398E-014 * Depth	+1.70037E-01‹ * Depth	-2.36018E-015 * Depth
+9.65690E-01' * t_main_deck	+6.28103E-01' * t_main_deck	+9.37608E-01' * t_main_deck
+1.27516E-01(* t_d_bottom	+1.18982E-01(* t_d_bottom	+1.27646E-01(* t_d_bottom
+7.33470E-01' * t_cargo_rail	+5.52876E-01' * t_cargo_rail	+7.01874E-01' * t_cargo_rail
+1.32119E-01: * n_stiffener	+9.18613E-01‹ * n_stiffener	+1.37654E-01: * n_stiffener
+2.00000 * Breadth/2 * Depth	+2.00000 * Breadth/2 * Depth	+2.00000 * Breadth/2 * Depth
-3.38714E-012 * Breadth/2 * t_main_deck	-3.38714E-012 * Breadth/2 * t_main_deck	-3.38714E-012 * Breadth/2 * t_main_deck
-6.50649E-012 * Breadth/2 * t_d_bottom	-6.50649E-012 * Breadth/2 * t_d_bottom	-6.50649E-012 * Breadth/2 * t_d_bottom
-5.81921E-012 * Breadth/2 * t_cargo_rail	-5.81921E-012 * Breadth/2 * t_cargo_rail	-5.81921E-012 * Breadth/2 * t_cargo_rail
-8.92527E-015 * Breadth/2 * n_stiffener	-8.92527E-015 * Breadth/2 * n_stiffener	-8.92527E-015 * Breadth/2 * n_stiffener
+1.23577E-01: * Depth * t_main_deck	+1.23577E-01: * Depth * t_main_deck	+1.23577E-01: * Depth * t_main_deck
-4.96105E-012 * Depth * t_d_bottom	-4.96105E-012 * Depth * t_d_bottom	-4.96105E-012 * Depth * t_d_bottom
+3.05772E-01: * Depth * t_cargo_rail	+3.05772E-01: * Depth * t_cargo_rail	+3.05772E-01: * Depth * t_cargo_rail
+6.74266E-01(* Depth * n_stiffener	+6.74266E-01(* Depth * n_stiffener	+6.74266E-01(* Depth * n_stiffener
-2.26518E-009 * t_main_deck * t_d_bottom	-2.26518E-009 * t_main_deck * t_d_bottom	-2.26518E-009 * t_main_deck * t_d_bottom
-2.34369E-009 * t_main_deck * t_cargo_rail	-2.34369E-009 * t_main_deck * t_cargo_rail	-2.34369E-009 * t_main_deck * t_cargo_rail
-1.52592E-012 * t_main_deck * n_stiffener	-1.52592E-012 * t_main_deck * n_stiffener	-1.52592E-012 * t_main_deck * n_stiffener
-6.70739E-010 * t_d_bottom * t_cargo_rail	-6.70739E-010 * t_d_bottom * t_cargo_rail	-6.70739E-010 * t_d_bottom * t_cargo_rail
-7.05265E-013 * t_d_bottom * n_stiffener	-7.05265E-013 * t_d_bottom * n_stiffener	-7.05265E-013 * t_d_bottom * n_stiffener
-2.95460E-012 * t_cargo_rail * n_stiffener	-2.95460E-012 * t_cargo_rail * n_stiffener	-2.95460E-012 * t_cargo_rail * n_stiffener

Appendix E – Scientific Paper

Parametric Structural Analysis for a Platform Supply Vessel at Preliminary Design Phase – A Sensitivity Study via Design of Experiments.

Sthéfano Lande Andrade*[1]; Henrique M. Gaspar[1]; Sören Ehlers[2]

1 Faculty of Maritime Technology and Operations, Norwegian University of Science and Technology, Aalesund, Norway

2 Hamburg University of Technology

* corresponding author - sthefano.lande@gmail.com

Parametric Structural Analysis for a Platform Supply Vessel at Preliminary Design Phase – A Sensitivity Study via Design of Experiments.

Parametric structural design analysis is a promising alternative to diminish the hull's structural mass, resulting in a vessel with higher payload capacity as well as lower construction and maintenance costs. The challenge of investigating a large space of alternatives, e.g. testing topology and materials, is caused by the high amount of engineering time required to model, analyse and evaluate each of the possible configurations. The objective of this paper is to demonstrate the application of a structural sensitivity study for a parametrically model global structure of a platform supply vessel, focused on mass reduction during the preliminary design phase. The methodology starts with the CAD/FEM creation of a parametric model, representing the vessel's middle sectional region. The focus on early design stages allows for simplifications in the structural model, gaining computational time when bypassing local details that would require finer mesh, which is not desirable for any kind of fast analyses procedures. Strength analyses are performed, following procedure of design of experiments methodology, which serves as a tool to understand mass efficiency based on the initially defined variables. The method gathers knowledge on impact of variables on various combined responses, and these are used to map the most efficient parameters and determine a viable solution space that better material usage in comparison to the original design.

Keywords: Parametric Model; Structural Sensitivity Analysis; Response Surface Methodology.

Introduction

Structural design of ships is a complex problem that invariably leads to a large amount of viable solutions, most of which are not optimal. It involves a diverse array of decisions, such as topology layout, plate thickness, material vs labour cost and main dimensions. However, by using response surface models combined with parametric finite elements methods, it is possible to investigate the effect of key vessel parameters based on their influence on the designer goal, be it stress reduction, material usage improvement or delimitate an ideal range for main parameters. In short, the methodology presented in this study can assist decision making at early design, when main parameters are still flexible at and new solutions can be considered.

Scope

As summarized in Figure 1, this structural sensitivity analysis at conceptual design stages is performed by studying results obtained through multi-response surface analyses applied to PSVs (Platform Supply Vessels).

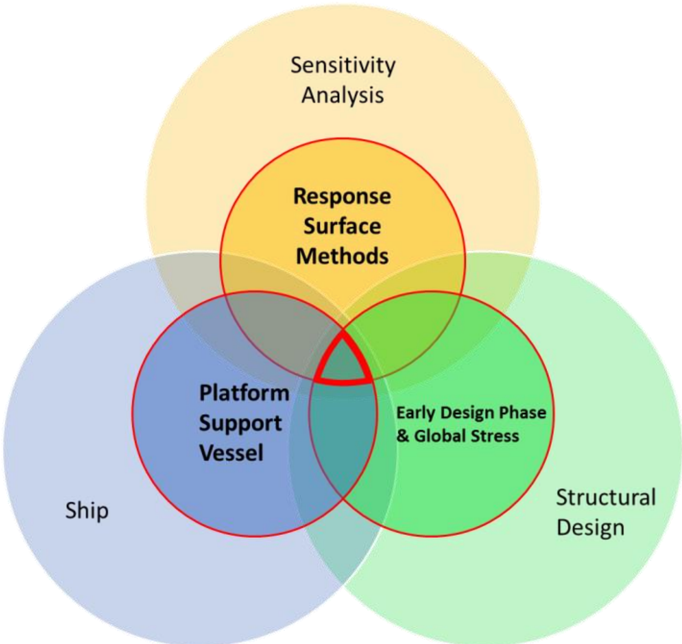

Figure 1: Scope Diagram.

Conceptual design is the first step of a ship's value chain. During this phase main dimensions, systems and volume arrangements are defined. Although many structural characteristics can be changed during detailing design, the freedom for changes is greatly reduced, because any major change would require more design time, resulting in increased cost.

As stated by (Andrews, 2011), after the definition of cost in the conceptual design phase, there is only a small margin of changes that can be done in the other phases as 70% of the total costs are assumed committed after the initial design is set. Thus the importance of optimizing key dimensional and structural parameters at an early stage, where changes are easier to make, cost less and allow for innovative designs.

Current Work on Structural Sensitivity Analysis

Two recent works related to structural sensitivity analysis are used as a starting point for this study. The first is “Basic Study on better Hull Beam Utilization for OCVs” (Brandt, 2015) showing that the vessels depth has a large influence on material utilization efficiency on Platform Supply Vessels when resisting to global bending moment, concluding that depth increments while decreasing breadth is far more beneficial than the opposite when aiming for better material use and stress reduction.

The second study, “Statistical Studies on the Influence of Primary and Secondary Structural Members on the Global Strength of Ship Structures“ (Diewald, 2015), has a similar goal, but focuses on structural elements sensitivity analysis. It defined which structural elements (or combination of) have a higher impact on the structure’s ability to resist to different load types.

Both works used experimentation procedure to generate statistical data. This can be done by applying design of experiments theory (as show by (Diewald, 2015)), where through input variation along an significant number of test we aim to obtain a model that describes the system studied along the desired defined space. Using the same idea, we can not only study how factors affect a single response, but a combination of them, stress, mass and internal space for example, and obtain improved solutions upon an original design. This is achieved with a Response Surface Method (RSM).

Methodology

The methodology for this structural sensitivity analysis starts with model creation, then the experiments are defined and each one of them is solved using FEA. After that, regression models are created and translated into surfaces that are used as visual representation of factorial response influence. Figure 2 shows this process, which is explained in detail in sequence.

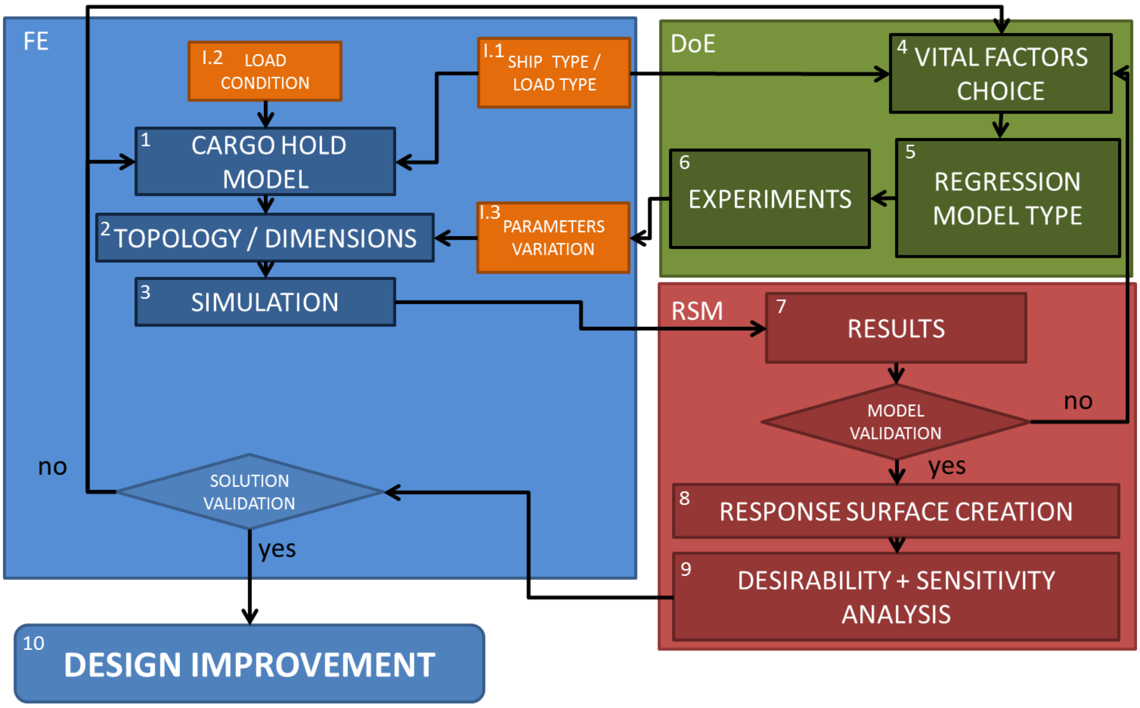

Figure 2: Structural Sensitivity Analysis Methodology.

Following the figure's logic, the first step of the procedure is to select ship type, loads to be applied and responses to study (step 1.1). This defines the parametric model creation directly (step 1). The load type defines the forces acting on the vessel that are studied as: global loads, local loads, bending moments, shear forces, torsional forces, etc. In this case the vertical bending moment is studied acting on a PSV cargo hold model based on the midship section. This process is done by writing an APDL script, which allows the creation of a parametric model, where inputs are changed at will and complex interaction between structural elements is solved using FEA.

The model topologies and dimensions can either be variable or fixed (step 2), but they are defined according to an input file containing all the initial parameters (step 2.1).

This file feeds the FE model (step 2) and allows for it to be solved (step 3). However, there are 3 different types of data that define this file:

1. Initial Parameter, which is the original case;
2. Fixed parameters, which are not going to be tested;
3. Variable Parameters, which are defined according to the design space and DoE methodology.

The design space[1] is contained within the case definition (step 1.1) and feeds into the design of experiments procedure, but only parameters that are expected to be the most influential to the response(s) can be selected and this is done by means of a screening process[2] (step 4). They are called vital factors, only vary within the design space and are fed into a DoE procedure (step 5). This procedure generates the experiments necessary to obtain a regression of the system's response(s) within the given design space (step 6). The vital factors definition for this study follows general conclusions from previous works and case related assumptions and the experiment generation is done according to a procedure for computer simulation responses documented by (Anderson & Whitcomb, 2005) called augmented D-Optimal.

Each experiment is different from the other in at least one of the factors and these changes are transferred to the model via an input file (step 2.1), which allows each experiment to generate a new model (step 2) and then be solved (step 3). Because of the uniqueness of each experiment, their total number also defines the amount of runs necessary for the FEA, thus the necessity of a simplified FE model, as complex iterative procedures with fine mesh discretization could require prohibitively long time to solve.

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[1] The design space is defined by the interval variation of each individual parameter.

[2] Note that this process was already performed by previous works.

The responses resulting from these simulations (step 7) are sent back to the design of experiments procedure and multifactorial regressions are obtained. These regressions significance should initially be validated for their statistical relevance and their ability to recreate the same responses obtained through the FEA. If deemed valid, they can then be represented in the form of surfaces using Response Surface Methods (step 8), if not, then either the factors chosen are insufficient, the number of experiments too few or the order of the regression not high enough, in any case the DoE procedure must be redone. To make multi-response model and obtain improved solutions for the system, desirability functions concept is implemented (step 9). This requires goals to be defined, for example: Minimization of a response and maximization of another. The method compares solution and grades each possible one according to their ability to achieve the defined goals. The best solutions are the ones that have the highest overall desirability. This also allows a response surface derived from the desirability function to be generated (step 9).

Besides obtaining improved design options, it should be possible to understand how changes in key factors affect the desirability by studying the many response surfaces. Moreover, all the best solutions obtained should be validated by comparing regression and simulation responses. If the responses do not agree, then either the DoE procedure must be altered or the model should be revisited from the beginning. Finally, the designer will have obtained a design that is more efficient and elegant in relation to the initial case.

The following sections detail 2 critical steps of this methodology, the FE model creation and the DoE approach for computer simulation.

FE Parametric Model (Step 1)

A PSV middle section drawing is modelled as a simplified parametric finite element model, illustrated in Figures 3.an and 3.b. Simplifications include disregarding small structural details (3), bilge curvature (4), non-continuous longitudinal elements (2) and discontinuities (1). This is done in order to avoid small finite elements and thus an overly fine mesh.

The frame is repeated until a cargo hold is formed, areas/lines are meshed using shell elements to which material and section properties assigned according to region and function. Most of this process is parametric, and initial inputs are sampled in a .csv input file, which is read by the ANSYS Parametric Design Language (APDL) routine at the start of each run.

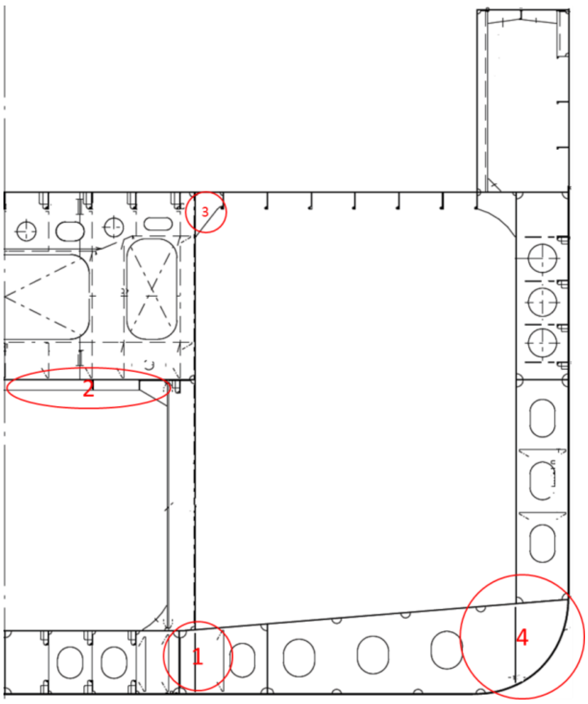

Figure 3.a: Typical PSV midship section drawing.

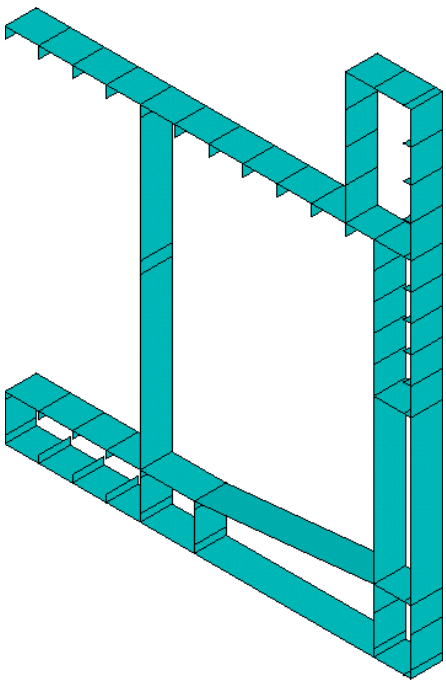

Figure 3.b: Section representation in ANSYS®.

Finite Elements Analysis (Steps 2 and 3 combined with I.1, I.2 and I3)

This study focuses on the analysis of vertical bending moment on the hull beam model:

(1) Hull vertical bending moment is determined according to classification society rules for conceptual design stages (Det Norske Veritas - Germanischer Lloyds, 2015) (International Association of Classification Societies, 2015).

(2) The model is constrained to vertical bending moment according to the IACS guidelines (International Association of Classification Societies, 2015). It determines that the model extremities bulkheads are rigid, thus the nodes are connected using rigid links to a single node at the section's Neutral Axis, where constraints and loads are also applied.

(3) Half of the ship is modelled using symmetry conditions along the centre line.

The equivalent von Misses stress is measured between the central frames of the model at key regions: Main Deck Plate, Bottom Plate and Cargo Rail Plate, Figure 4. Moreover, the model's total volume is measured and divided by its length, multiplied by the steel's specific mass, thus obtaining the. Additionally, we measure average linear mass and the section's internal area to measure material utilization and cargo space variation.

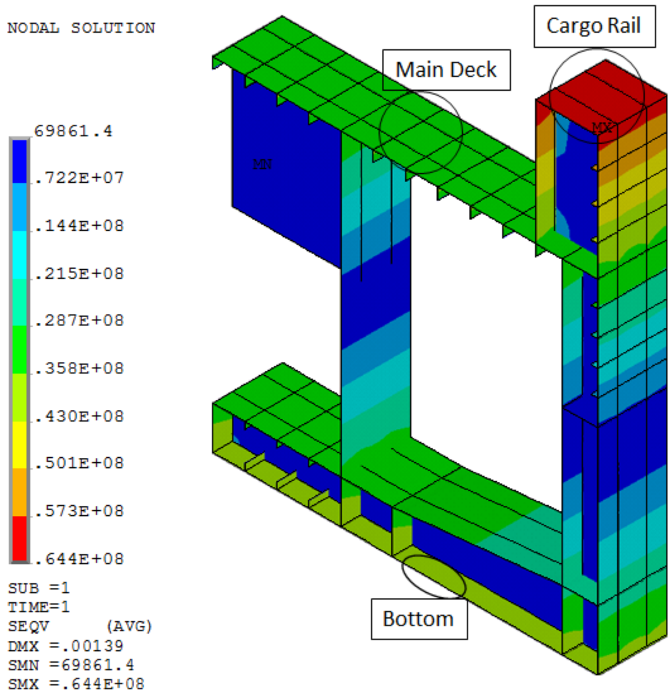

Figure 4: Stress measurement regions.

D-Optimal Overdetermined. (Steps 5 and 6 into I.3)

Determinant based Optimal Design is used to define the experiments, because it can handle a high number of factors while requiring a feasible number of experiments. It is assumed that a quadratic or lower models can describe any response involved in this analysis sufficient accuracy.

The second step is to add additional experiments with the objective improving the factor-response mapping, thus creating an improved regression surface. This is achieved by the distance based method, which scatters the extra experiment points across the factor space according to an algorithm that maximizes their Euclidian distance from all the other points already defined (Stat-Ease, Inc, 2011).

PX121 Case Study

Figure 5: PX121 PSV (Ulstein, 2016)

The finite element model of the case study is based on typical PSV midship section and the dimensions are based on the PX121 family, Figure 5. The principal dimensions for this vessel are: Length 79.5m, Breadth 18m, Depth (to Main Deck) 8m, Draught 6.7m. The following plate thickness distribution is assigned for the base case: General Plate Thickness is 11 mm, except Bottom and Tank Top Plate thickness, which have 12 mm. As for stiffeners, the following are used: General Stiffener Type HP 160x8, Main Deck Stiffener Type HP 260x12. The responses are shown in Table 1.

Table 1: Results for the base case.

Response	Value	Unit
Linear Mass	19.43	ton/m
Stress Deck	34.91	MPa
Stress Bottom	40.39	MPa
Stress Cargo Rail	61.82	MPa
Internal Area	144	m^2

Vital Factors and Design Interval

Vital factors for a global vertical bending moment on ships are: depth, breadth, main deck thickness, bottom plate thickness, cargo rail plate thickness, number of stiffeners and stiffener type. Since the number of stiffeners vary regionally, a general multiplier value that generates different numbers depending on the section's region (Main Deck or Bottom) is defined. Thus, 7 factors for a of total 64 different experiment setups.[3] The following design interval is defined:

- Half - Breadth (B/2): 8 to 10 m;
- Depth (D): 7 to 9 m;
- Deck thickness: 0.008 to 0.014 m
- Bottom thickness: 0.009 to 0.015 m
- Cargo Rail thickness: 0.008 to 0.014 m
- Stiffener Number Multiplier: 3 / 4 / 5 / 6 / 7
- Stiffener Type HP: Smaller (o-) / Standard (o) / Bigger (o+)

Table 2: Stiffener Types.

Location	Stiffener Type (o-)	Stiffener Type (o)	Stiffener Type (o+)
Main Deck	HP 240x10	HP 260x12	HP 280x12

[3] This procedure is done using a specialized software, Design Expert 8 (Stat-Ease, Inc, 2011), which generates experiments according to the desired procedure (e.g. D-Optimal) and maps the experiments responses to create regression surfaces.

Others	HP 180x10	HP 160x8	HP 140x8

Goals and Desirability

The main goal for this study is:

(1) The mass reduction is the main objective and this goal is defined with a **minimization** goal;
(2) All stresses have a **minimization** goal;
(3) The internal area is defined with the objective of improving or, at least, keeping it at the same level of the original case, which means a **maximization** goal with a lowest acceptable limit of **144 m^2**.

To combine a multi-response model into one function we use the concept of desirability (Anderson & Whitcomb, 2005). It combines many goals into a single function that is maximized to obtain the maximum desirability value within the solution space. This is done by grading each possible solution in the design interval in relation to their ability to achieve a certain objective. For example, for a mass minimization goal, the solution is assigned a grading of 1 if it has the lowest mass possible within the defined solution space, 0 if the highest or a proportional grade to other values. Then, each goal's desirability is combined into one function that is used to generate a response surface and can be maximized to obtain optimal solutions.[4]

$$D = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \qquad (1)$$

Results

The sensitivity analyses of the predetermined goals as now evaluated by a desirability function. The first 8 best solutions (highest desirability) have the following factor and response values:

[4] For a more complete definition refer to (Anderson & Whitcomb, 2005).

Table 3: Top 8 Solutions regarding desirability. This table present the top 8 best solutions and the original case with factors: A = Breadth/2 (m), B =Depth (m), C = Main Deck Thickness (mm), D = Bottom Thickness (mm), E = Cargo Rail Thickness (mm), F = Stiffeners' Number multiplier, G = Stiffener Type. Responses are: R1 = Linear Mass (ton/m), R2 = Main Deck Stress (MPa), R3 = Bottom Stress, R4 = Cargo Rail Stress (MPa), R5 = Internal Area (m^2), D = Desirability;

	Factors							**Responses**					
Solution	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**R1**	**R2**	**R3**	**R4**	**R5**	**D**
1	9.38	9	8.5	9.1	14	3	o-	19.363	32.061	40.817	55.077	168.763	0.641
2	9.37	9	8.1	9	14	4	o-	19.472	31.508	40.564	54.260	168.662	0.641
3	9.37	9	8.8	9	14	3	o-	19.376	31.774	41.024	54.767	168.656	0.641
4	9.37	9	8	9.3	14	3	o-	19.343	32.406	40.449	55.409	168.620	0.640
5	9.34	9	8.3	9.5	14	3	o-	19.427	32.062	39.924	54.786	168.176	0.640
6	9.28	9	8.5	9.1	14	3	o-	19.288	31.821	40.627	54.696	167.049	0.64
7	9.37	9	8	9	14	3	o	19.465	31.446	40.754	54.206	168.637	0.64
8	9.27	9	8.1	9	14	3	o	19.393	31.138	40.586	53.738	166.910	0.64
Original	9	8	11	12	11	3	o	19.4252	34.91493	40.39212	61.81656	144	-

The main trends noted for the factor are:

- Increase in Breadth, but still under the maximum limit (10 m) of the design space;
- Maximum use of Depth within the design interval;
- Decrease of Main Deck and Bottom Plate thicknesses;
- Increase in the Cargo Rail Plate thickness up to the design space limit;
- Generally, minimal use of stiffener numbers and smallest type, but not a necessity;

The following curves show the response variation for each solution in comparison to the base case.

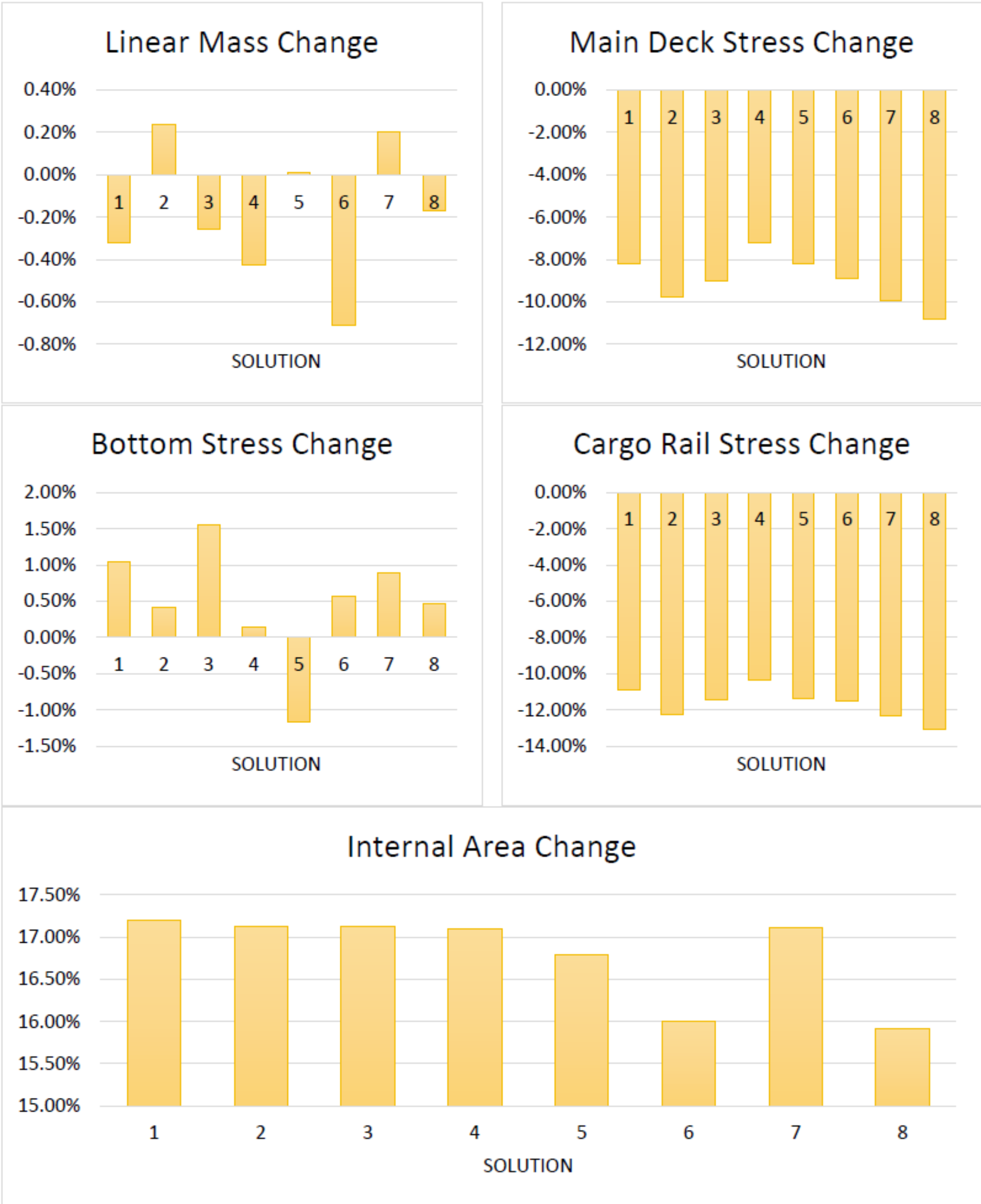

Figure 6: Response Variation for the base case.

Figure 6 shows that several improved solutions are obtained in relation to cargo hold capacity and strength, while maintaining the same amount of material usage, thus more efficient designs. Verification through Finite Elements Analysis (FEA) showed that the regression responses agreed with the simulated ones, since they presented less than 1% divergence for all solutions.

Factorial Sensitivity Analysis

Besides obtaining improved local solutions, the desirability response surface can be studied to understand how factors are affecting it.

Breadth versus Depth:

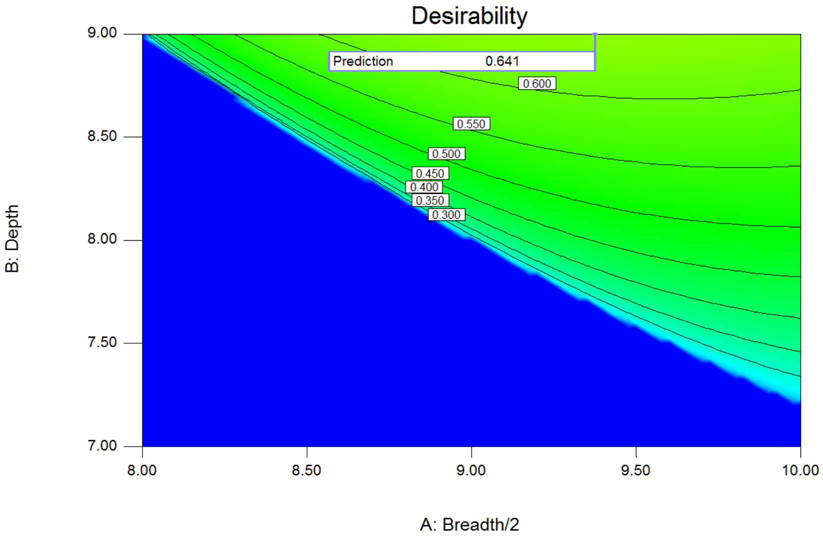

Figure 7: Breadth versus Depth Desirability Contour Plot.

Figure 7 shows that at lower desirability levels, both depth and breadth have a positive influence on the model, increasing the solution rating as they grow. However, as the depth values increase, so does its influence on the desirability, while the opposite response occurs for the breath.

Breadth versus Plate Thickness:

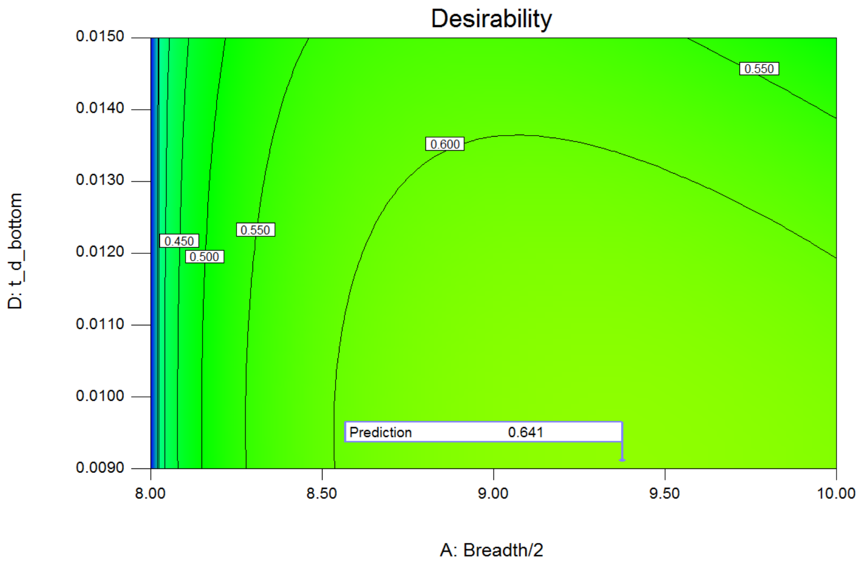

Figure 8: Breadth versus Cargo Rail Thickness Desirability Contour Plot.

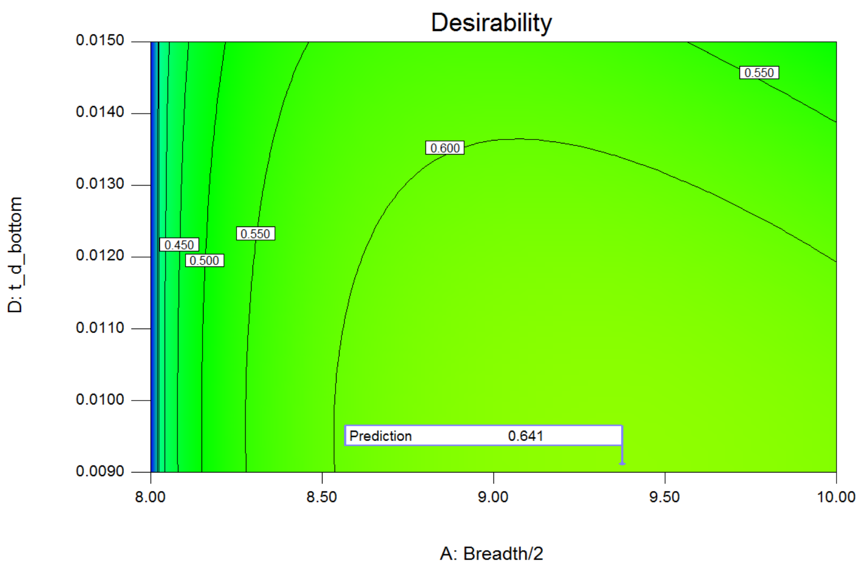

Figure8 shows that at lower desirability levels the cargo rail thickness has almost no influence over those values. But, as the desirability increases, so does the positive influence of the cargo rail plate thickness.

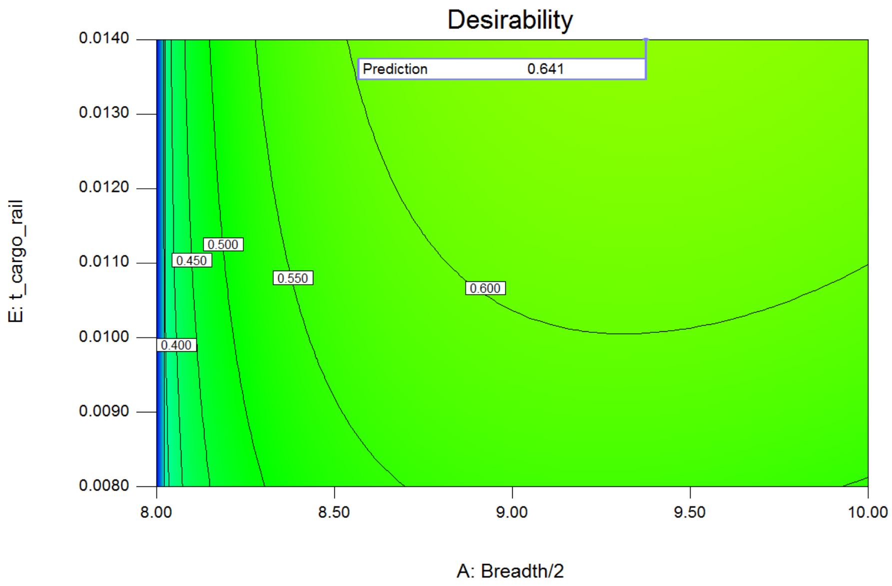

Figure 9: Breadth versus Bottom Thickness Desirability Contour Plot.

Figure 9 shows that the bottom plate thickness influences the desirability negatively in this case at high desirability levels.

It must be noted, that these comparisons are only examples, because many other possible factorial combinations can be analysed and used to plan important structural design decisions. While the optimization routine is a useful tool, it does not provide a complete picture, which is however represented via contour plots for factorial interactions and behaviour patterns of the multi-response goal model.

Conclusion

This study showed how design of experiments used for response surface generation can be applied to a parametric finite element model analysis to perform a multi-response sensitivity structural analysis. The results indicate that the presented procedure is a useful aid helping designers in defining critical parameters at conceptual design levels. The use of finite elements to this purpose allows for parametric model creation, different load configurations application, model robustness and it maps how complex structural elements interact to resist stress. However, this requires a good balance between structural discretization and model simplification, because reliable results shall be obtained minimal computational effort. Additionally, factor selection is crucial, since they directly influence on the experiments number, thus selecting non-crucial factors would only increase run time and would not provide meaningful information to the designer.

On the other hand, this approach can be used to decrease computational effort while maintaining good reliability in its results. Moreover, local optimization is not the only possible outcome, since the factor interaction and multi-response analyses generate important information for structural designers. In this case, the sensitivity study for one goals' set is performed, but it is possible to study any range of desired goals, given that they belong to the design interval. In addition to that, if the factor selection and finite element model are robust, more responses and parameters can be studied using the same structural model, e.g. local loads.

Acknowledgement

This article was partly supported by the EMIS Project, in cooperation with Ulstein International AS, who also provided a comparison case and information that allowed to delimitate a plausible design space for the study.

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