# An Integrated Framework for Conceptual Design Stage Structural Optimization of RoRo & RoPax Vessels

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# ABSTRACT

Structural Optimisation of RoRo & RoPax vessels during conceptual design stage –
As part of HOLISHIP Project

Optimization generally involve picking the optimum solution to a problem considering all the factors or design variables. HOLISHIP (HOLIstic optimisation of SHIP design and operation for life-cycle) is a European Union research project which is a system based approach aimed at developing optimized designs for the future, structure of which is divided into clusters and into several work packages (WP). Structural optimization of RoRo & RoPax vessels pose several challenges due to the unique design features of these type of vessels. This Thesis work concentrates on structural optimization of midship section transverse frame of RoRo & RoPax hulls for minimum weight thus achieving reduction of lightship weight which is one of the major technical requirements during conceptual design phase as part of WP4&WP7 of HOLISHIP project. Rule based tool called ‘STEEL’ by Bureau Veritas is used for the structural & load modeling and further structural analysis of the transverse frame and then optimization loop is established using ‘modeFRONTIER’ and ‘CAESES’ tools to study effect of different design variables. Also the structural optimization loop involving STEEL tool is to couple with a parametric hull in order to enable study of coupled structural analysis for different parametric hull variations. Structural weight is kept as the objective to minimize and design constraints are considered as per applicable Bureau Veritas rules for classification of steel ships. Then surrogate models are generated to replace the optimization loop using Response surface methodology and results obtained with different algorithms like polynomial regression, artificial neural networks etc. are studied further which would reduce complexity associated compared to conventional direct methods.

**Keywords** :HOLISHIP,Structural optimisation, Rule based analysis,RoRo, RoPax, Response Surface Methodology,Artificial neural Networks, Parametric Hull

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# ABBREVIATIONS AND LIST OF SYMBOLS

Generally references are given in square parentheses.

$\delta$ : Density of sea water, in $t/m^3$.
h1 : Reference values of the ship relative motions in the upright ship condition
h2 : Reference values of the ship relative motions in the upright ship condition
EU : European Union
HOLISHIP : HOLIstic optimisation of SHIP design and operation for life-cycle
WP4, WP7 : Work Package 4 & 7 of HOLISHIP Project
ULiege : University of Liege, Belgium.
$L_{PP}$ : Length between perpendiculars
$B_{mld}$ : Breadth moulded
T : Design draft
n : Navigation coefficient
$R_{eH}$ : Minimum Specified yield stress

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# 1. INTRODUCTION

## 1.1 GENERAL INTRODUCTION AND OVERVIEW

Nowadays, the majority of global trade is dominated by the international shipping industry. The growing shipping industry helps in the transport of goods necessary to cater the present world requirements possible. Hence it is also essential that maritime transport through ships need to be competent with other modes of transport.

Ships are generally built with a short lead time and also very few in number in a series compared to other modes of transport. Also different vessels usually will have varying design requirements due to different operating conditions. Hence it is essential that special care need to be taken during the initial phase to develop flexible designs which will cater to multiple requirements and also addressing the sustainability issues which are relevant in present world.

Since current design process are more based on contract requirements and also due to less available time, it doesn’t allow to consider these requirements which limit the developing of a flexible design. Also usually there is an overlap between different design phases in current design approaches which can limit things further. This points to the need for a more system based design approach which will address the inadequacy of present day design approaches, varying operating environments and also the future extended requirements. Hence using a system oriented multi objective and multi-disciplinary design optimization process which will integrate specific requirements of different subsystems of a ship like accommodation considering passenger comfort , propulsion, navigation, handling of cargo etc., and also considering overall life cycle requirements of a ship, better design can be developed which will address these requirements in a holistic way.

[1] HOLISHIP (HOLIstic optimisation of SHIP design and operation for life-cycle) project is a system based approach which aims at developing optimized lifecycle based design for the future addressing  above requirements by participating all stakeholders like shipyards, design houses, equipment suppliers, research organizations etc. to work on a design leading to optimal operational performance of a vessel.

In this thesis, the focus is to form a framework to perform structural optimization of main transverse frame during conceptual design phase based on the coupled internship performed by the Author at FRIENDSHIP SYSTEMS AG & University of Liege as part of the HOLISHIP Project taking RoRo & RoPax vessels as testcases.

Conceptual design phase forms one of the earliest stages in ship design where the focus is to develop preliminary design meeting client requirements. Structural analysis during conceptual design phase involve mainly rule based analysis in order to find key scantlings and strength behaviors.

An overview about HOLISHIP project is added next.

### [1] About HOLISHIP Project

HOLISHIP is a system based approach for product design and testing aimed at developing optimized solutions for the ever growing needs of the European maritime industry. The project was proposed in response to a 2015 call of the European Union’s Horizon 2020 Transport Research Programme by a team consists of 40 European maritime industry and research partners. Horizon 2020 is designed as the biggest EU Research and Innovation programme aimed at developing breakthroughs, discoveries and world-firsts by taking great ideas from the lab to the market and thus securing Europe's global competitiveness.

HOLISHIP project proposal was submitted aiming the same for the European maritime industry to reduce the complexity of European built ships and maritime structures as well as considering the growing number of rules and regulations based on a system based approach. Subsequently HOLISHIP was awarded approval and funding by the European Research Council.

HOLISHIP takes into account all the major components of ship design for the lifecycle including all steps of traditional design spiral based on multi-objective and multi-disciplinary optimization using integrated software tools and approaches. The HOLISHIP model utilizes modern CAE (Computer Aided Engineering) methods and integrates techno-economic databases together with software tools, calculation and optimization modules. Also by setting up of a virtual model, VVF (Virtual vessel Framework ) for the entire vessel, it allow the virtual testing prior to the actual construction starts which enables better evaluation of design goals and thus enabling to check for alternate product designs if required.

Accordingly HOLISHIP approach is divided into three main clusters as given below which are again subdivided into 8 work packages (WP).

Cluster 1: Tool development: It involves development of software tools and methods required for the automated design approach.

Cluster 2: Software Integration: It involves integration of software tools developed in Cluster 1 into HOLISHIP design platforms and the VVF.

Cluster 3: Application Cases/Demonstrators: The integrated tools from earlier cluster are applied to different ship cases for the design and operation and also demonstration of use of the VVF developed are included in this cluster.

The different clusters and work packages are shown in below figure;

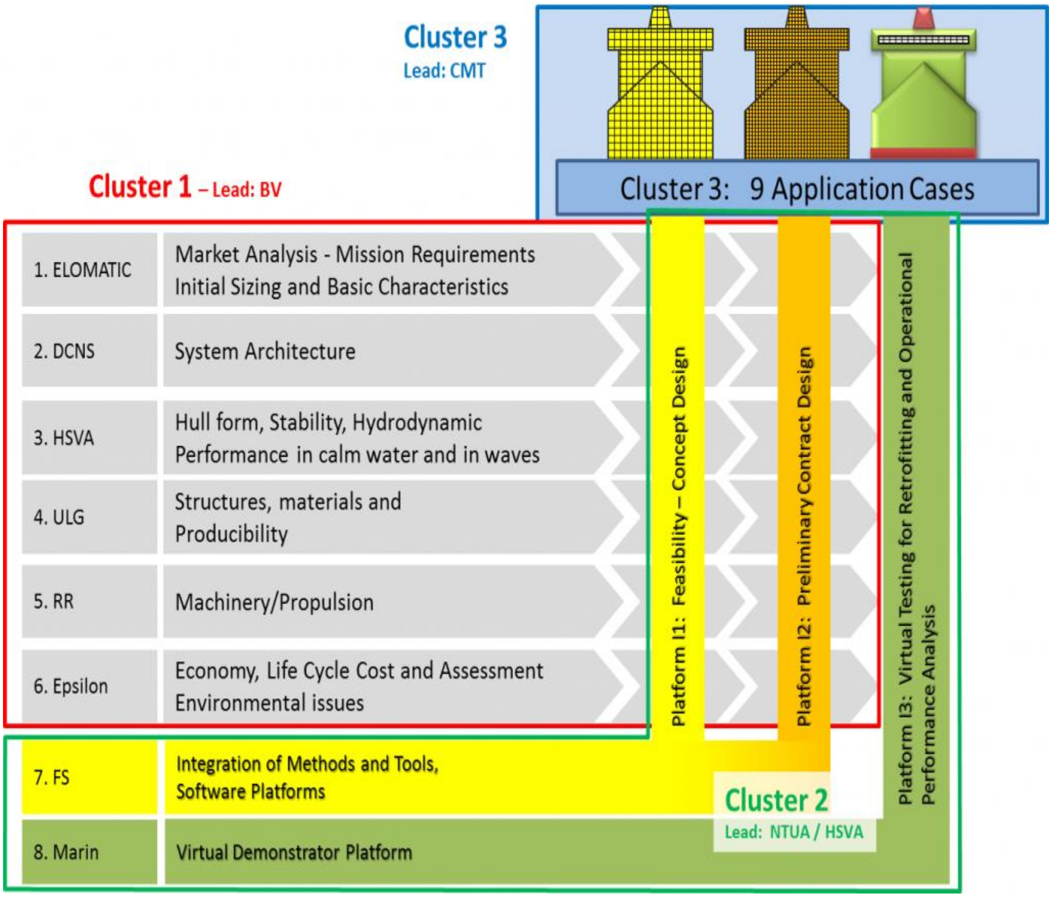

Figure 1 HOLISHIP structure showing different clusters &work packages

As shown in figure, each of the clusters involves different work packages (WPs) and are led by different European maritime industry leaders. Each of 8 WP concentrates on different components of ship design. Also figure 2 indicates a detailed view of the Application cases involved in Cluster 3.

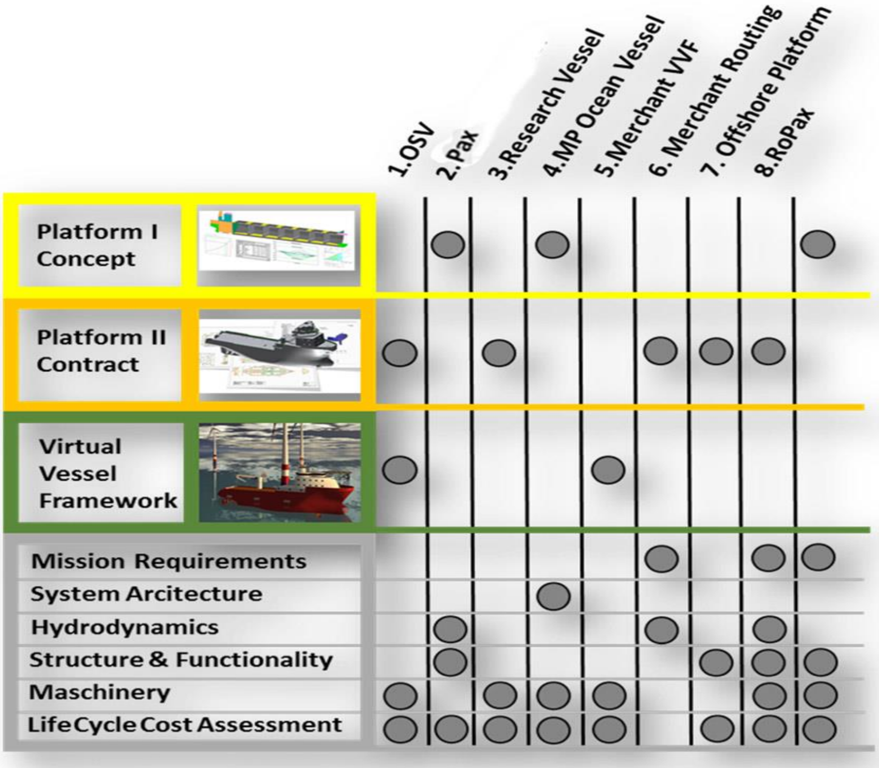

Figure 2 Details of Cluster 3 of HOLISHIP.

The above details were presented in order to provide a generalized view on structure of HOLISHIP and its approaches. The scope of Author's internship and this thesis is based only on WP4 and WP7 of the HOLISHIP structure in order to optimize the main transverse frame of midship structure considering a RoRo & RoPax vessel each as two testcases for various design variables. The detailed scope and methodology are discussed in following sections.

WP4 is led by ULiege (University of Liege, Belgium) and WP7 is led by FRIENDSHIP SYSTEMS AG, Germany as shown in figure 1.

## 1.2 OBJECTIVES AND SCOPE OF PROJECT

As mentioned earlier, the scope of the project comes within WP4 & WP7 of HOLISHIP Project. During Conceptual design phase,WP4 concentrates on minimising the ship's lightship weight by performing the structural optimisation of midship section of the testcases considered by utilizing Rule based/Simplified structural tools developed by Bureau Veritas.

Structural optimization of a midship section mainly involve rule based determination of optimum scantlings for main transverse frames, plates, longitudinal stiffeners etc. and associated structural analysis which adds minimum structural weight to ship's lightship weight. Structural analysis of plates and longitudinal stiffeners are done by using Rule based tool called BV MARS and transverse frames are analysed by a direct analysis tool called BV STEEL, both developed by the Bureau Veritas.

However as part of WP4, structural optimization of main transverse frames by integrating STEEL with other optimization tools is only considered within the scope of this thesis. Structural optimization of plates and longitudinal stiffeners using BV MARS and other optimization tools is being developed separately at University of Liege, which upon completion will be combined to the optimization loop developed by the Author to perform complete structural optimization of a midship section. Within WP4, testcase considered now is a RoRo hull for which the completed STEEL model of main transverse frame was already available at Univesity of Liege. This RoRo STEEL model was coupled with modeFRONTIER tool to form the optimization loop at University of Liege(STEEL-modeFRONTIER loop).

Also as mentioned earlier, WP7 within HOLISHIP project deals about integrating different methods, tools, software platforms using CAESES tool for the testcases considered. Structural& load modeling of the main transverse frame of the testcase2 which is a RoPax vessel was done by the author using the STEEL tool. A parametric hull of a RoPax vessel is already developed at FRIENDSHIP SYSTEMS using the CAESES tool in which the main dimensions are parameterized so that hull design can be altered by changing these parameters. Hence within WP7, the scope of this thesis involve coupling the STEEL tool with CAESES to establish optimization loop for the main transverse frame ( STEEL-CAESES loop) and then later to integrate this loop with the parametric hull of RoPax to establish the 'STEEL-CAESES-Parametric Hull loop' so that for each design iteration of the hull, corresponding structural analysis is performed for the modified midship section.

Also in order to replace optimization loops involving integration of different tools, feasibility of establishing surrogate models using response surface methodology will also be studied by considering different algorithms or methods such as polynomial regression, artificial neural networks etc.

## 1.3 METHODOLOGY / APPROACH

For the both testcases (RoRo & Ro-Pax vessels) considered, the approach followed is to perform structural optimisation of main transverse frame which can be a good starting point for the analysis further.

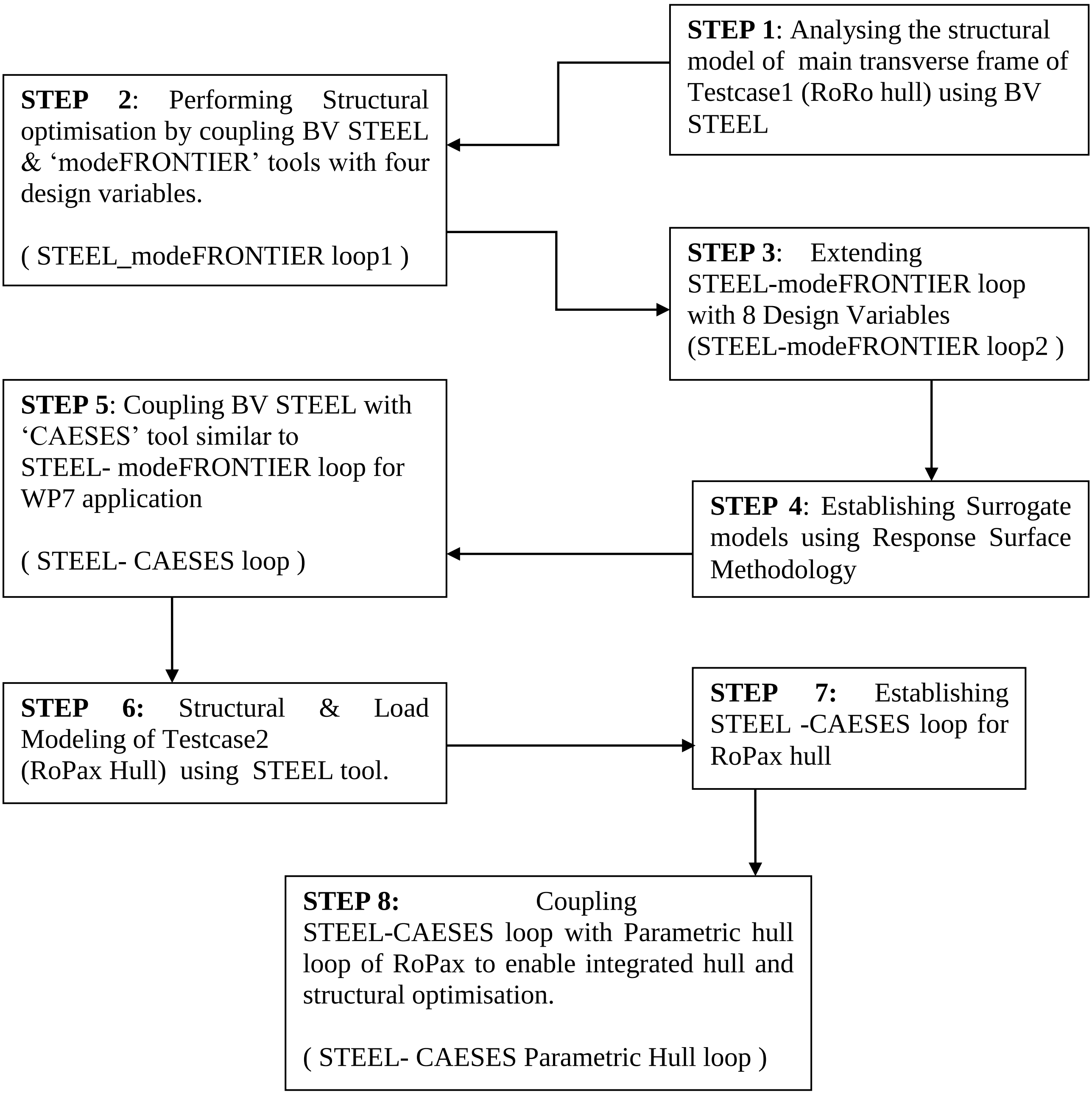

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Figure 3 Brief overview of general methodology adopted.

The different steps involved as part of the methodology are shown in figure 3.

For direct & rule based assessment of structural strength of midship sections, software tools developed by Bureau Veritas Classification society, STEEL and MARS are used, mainly as part of WP4 of HOLISHIP. As indicated earlier, the optimisation loop involving BV MARS tool for structural analysis of plates and ordinary stiffeners are developed separately at University of Liege.

Hence the Author's thesis focus only on integration of STEEL tool to enable structural analysis of main transverse frames using different optimisation tools and algorithms considered so that the remaining loops can be plugged into this loop for having the complete structural optimisation of midship section at later design stages.

In the first stages, an optimisation loop was established coupling STEEL model of RoRo hull and modeFRONTIER at University of Liege as part of WP4 of HOLISHIP. Initially four design variables are considered which are the beam scantlings of a deck. Then the loop is extended to accommodate total 8 design variables adding beam scantlings of another deck as well into design variables.

Then considering STEEL-modeFRONTIER loop as reference, similar optimisation loop is established for the RoPax vessel as well by coupling STEEL tool and CAESES which was done at FRIENDSHIP SYSTEMS asp part of WP7. Also the structural & load modelling was done for the RoPax hull. Finally STEEL-CAESES loop is integrated to parametric hull loop in CAESES platform as shown in figure 3. Also applications of response surface methodology in building reliable surrogate models for these applications are also analysed.

## 1.4 SOFTWARE/ TOOLS

Structural and load modelling of main transverse frame is done using BV STEEL tool.

Later STEEL tool is coupled with optimisation tool ESTECO modeFRONTIER to enable optimisation by analysing different design variables for the RoRo hull.

For the RoPax hull, STEEL model of main transverse frame of RoPax hull is coupled with CAESES® for performing structural optimisation and also later integrated with CAESES parametric hull of RoPax.

Within the optimisation process, an executable application developed by University of Liege specifically for this thesis will be used which gives the value of von mises stress of the entire web transverse frame modelled in STEEL tool based on the values of normal and shear stresses given by STEEL tool batch mode output file.

Finally response surface is established using CAESES and R tools and results are compared.

# 2. BIBILIOGRAPHY STUDY

Since the thesis was mainly focused on the structural optimisation of midship structure of RoRo or RoPax vessels, firstly the preference was given to better understand the general and structural characteristics of these type of vessels. Then emphasis was given in understanding structural design optimisation and the works done related to holistic optimisation of vessels utilizing integration of different tools.

Also as required by the objective of the internship, a study was performed in order to get sufficient details about Response Surface Methodology (RSM).The use and applications of recent developments of Artificial Neural Networks (ANN) for building surrogate models was also considered under study. The different methods available in CAESES for building response surface was also studied.

## 2.1 Structural Design of RoRo /RoPax Vessels and Integrated Optimisation

[2],[3].Generally a RoPax vessel can be considered as a combination of a passenger vessel and a RoRo vessel. RoPax vessels usually operate in a fixed schedule, regularly in between cities or islands where sufficient water side connectivity requirements are met.. A RoPax vessel is defines as “a passenger ship with RoRo cargo spaces or special category spaces” .Hence a RoPax vessel or RoRo passenger vessel can be considered as a vessel sailing across open waters, providing regular services between fixed ports, accommodating more than 12 passengers, carrying cars and commercial vehicles. [3].

A RoRo vessel is generally designed to carry wheeled cargo only unlike the RoPax vessels.

[4] deals about Risk based safety assessment and analysis of RoPax vessels which was published by IMO MSC , taking into account the work done by SAFEDOR integrated project as well. Also it discusses about the unique design features of RoPax vessels compared to other conventional commercial ship types according to the operational requirements. Some of the unique design features to be taken care while performing the structural design of the RoPax hulls are related to internal sub division, Cargo stowage and access requirements, low freeboard issues, fire prevention and other safety requirements etc. Usually the vehicle deck is located at the freeboard deck. For the easy movement and stacking of vehicles, the main deck which usually acts as the vehicle deck will not have pillars or bulkheads which form a major

design hurdle and pose damage stability problems. Also the cargo access doors at both ends form a potential weak spot as these are used as ramp as well. The paper also discuss about risk based analysis on collision and impact outcomes taking reference to a few RoPax vessels.

[5] Discuss about the general design aspects and multi criteria structural optimisation of a RoPax vessel as part of the IMPROVE project of EU. The paper also considered three alternate midship designs for the RoPax hull and two different configuration for the super structure. The different configuration of super structures was based on the number of tiers of superstructure and by altering the transverse position of the longitudinal bulkheads. Also it discuss about results from other calculations relevant (naval architectural calculations like stability, resistance, cargo capacity requirements etc.) for the different midship configurations considered. For each configuration, minimum freeboard depth requirements as per damage stability criteria were checked.

T. Richir et al [6] discuss about the multi criterion scantling design optimization done on a passenger ship considering minimum production cost, minimum weight and maximum moment of inertia as objectives using LBR-5 software considering IACS requirements. Though the structural design of RoPax will differ from passenger ships which is taken as reference in this paper, the study was helpful in understanding the mapping of entire pareto front on a problem involving multi criterion structural optimization, rule based structural constraints etc.

[7] Give details about holistic approach applied to ship design optimization. The paper describes about using advanced optimization tools for the computer-aided generation, exploration, and selection of optimal designs by defining the generic ship design optimization problem. Cargo and Naval ships are taken as reference for discussing the proposed methods related to multiple objectives which will lead to improved and partly innovative design features with respect to ships' economy, cargo carrying capacity, safety, survivability, comfort, required powering, environmental protection, or combat strength, as applicable. The paper considers Ship functions as two types namely payload functions and inherent ship functions and explains the same using the case of a Ro-Ro passenger ship. The payload functions are considered as those related to the provision of public and private accommodation spaces for the passengers and spaces and access equipment for the cargo handling (Ro-Ro decks, ramps, ventilation, etc.); while inherent ship functions are considered as those which enables safe transport of passengers and cargo from port to port with certain

speed, namely the ship as a system, consisting of ship's hull and all the sub systems. The paper also discuss about life cycle based design optimization using modeFRONTIER and also use of genetic algorithm as a design tool is also mentioned.

[8] Discuss about design optimization using first principle based methods and also how design competence will be achieved using the same taking the case of a RoPax vessel. The paper also analyses methods to increase the efficiency of RoPax vessels by considering several factors like increasing cargo capacity, operational parameters and shows how these factors will influence the hull and structure of the vessel.

[9] discuss about rule based structural design of wheel loaded decks in a RoRo vessel by taking main deck as an example. The rules from three different classification societies are compared in order to arrive at an improved design for the structural members thus saving significant reductions in lightship weight. A short sea RoRo ship is taken as the reference ship and wheel loads on the deck are calculated based on the wheeled load data available from the designer. For BV Class rules, it is considered that loads due to wheeled cargo are applied through the tyre centre taking a single lane width as 2.9m including the lashings. Both still water and inertial loads are considered. Based on the rule based scantling requirements, optimum scantlings are tried using the standard sections available in the market. Also a cost comparison is also done based on the weight savings achieved. Finally the rule based calculations are verified with an FEM analysis for the deck. The paper was helpful in understanding the wheeled load calculation based on BV Class rules.

Zaraphonitis et al [10] presents an in-depth review of the adopted formulation of SOLAS 2009 probabilistic damaged stability regulations which is applicable for passenger vessels as well. The paper discuss about new risk based formulation formed as part of EU project GOALDS for the assessment of damage stability of passenger vessels and it's impact on operational characteristics of RoRo passenger ships. Parametric modelling of RoPax vessel using the tool NAPA was done and design optimisation was analysed in order to study survivability of modified designs based on the regulation. The parametric transformation of hull utilized lackenboy transformation which is used for the parametric hull of RoPax vessel considered as part of this thesis as well. Also the reference vessels mentioned in the paper was a good starting point to study the general layout and characteristics of RoPax vessels.

Zeitz et al [11] discuss about coupling POSEIDON which is a ship structure modelling software with computer aided engineering system 'CAESES/FRIENDSHIP FRAMEWORK' (abbreviated as FFW) for ship structure optimisation problems. The paper was particularly interesting as it helps to understand use of CAESES platform in order to couple ship structure modelling tools .Both local and global hull girder loads were considered by the POSEIDON modeler and fatigue and buckling strength aspects were checked accordingly. Also the approach was applied to several test cases which includes simple barge and teo container vessels of different TEUs (1700 TEU and 7000 TEU capacity). With POSEIDON in batch mode, plate scantlings and stiffener arrangements given as inputs to the integrated framework. Sobol algorithm was used for the discrete optimisation and later a design engine like TSearch or NSGA2 was used for real and discrete variables with structural weight set as the objective function to minimise while considering global bending moment, shear force requirements along with local strength requirements.

## 2.2 Application of Response Surface Methodology (RSM)

[12] Response surface methodology (RSM) can be considered as a collection of mathematical and statistical techniques for empirical model building. The method was introduced by G. E. P. Box and K. B. Wilson in 1951

[13] describe about the basics of response surface methodology and it’s applications in multi objective optimization considering different design variables. With RSM, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables) through careful design of experiments. Hence “the field of response surface methodology consists of the experimental strategy for exploring the space of the process or independent variables, empirical statistical modelling to develop an appropriate approximating relationship between the yield and the process variables, and optimization methods for finding the values of the process variables that produce desirable values of the response”.

If input variables are represented by $\xi 1$, $\xi 2$ , $\xi 3$ ,..etc. and response as y, then the relationship can be shown as below;

$$y = f( \xi 1, \xi 2 , \xi 3 ,...... ) + \varepsilon ; \qquad \textbf{(1)}$$

where f is the true response function which is unknown and $\varepsilon$ is a term that represents other sources of variability not accounted for in f for the response.

Hence we need to find an approximate relation for response function f since it is unknown which depends on the independent input variables. Usually, a low-order polynomial in some relatively small region of the independent variable space is appropriate. In many cases, either a first-order or a second order model is used.[13].

[14], [15] Gives detailed view on working of Response surface methedology in modeFRONTIER software platform and its key features. Use of RSM within modeFRONTIER platform avoids the need of running large number of expensive simulations for achieving multi objective optimisation to a complex surface by generating meta- models and thereby enhancing the optimisation process. There are a rich set of algorithms necessary for creating the meta-models, thus helping in predicting the response of the system for different operating variables.

[16] Provides simplified information on meta-model-based design optimization (MBDO) and some relevant references in understanding the same. Simplified models which provide an efficient representation of detailed and costly product are called surrogate models. A model is called meta-model if it is surrogate for a detailed simulation model. Meta-models are generated by a mathematical expression depending on the input dataset and the corresponding output from the simulation model. Hence the type of meta-model or the mathematical expression would depend on the input dataset and intended application. So different meta-models will be created accoriding to different dataset of input variables. Design of Experiment (DOE), which is an underlying tool in the modeFRONTIER platform is the process of controlling placing of data points in the design space.

Figure 3 below shows the concept of meta modelling applied to a given set of input design variables.

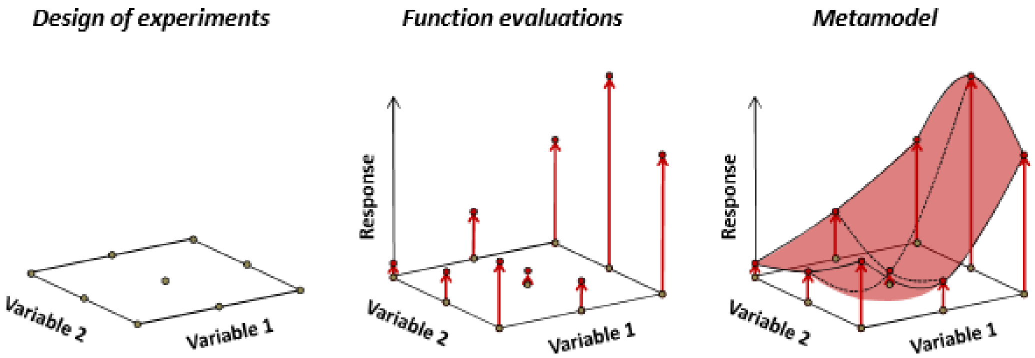

Figure 4 Metamodeling of response for two design variables (Source [16])

[17] discuss about multidisciplinary multi objective design of heavier –than- water underwater vehicle ( HUV) which is a new concept of autonomous underwater vehicles(AUV). Multidisciplinary design optimization (MDO) method is used for the multiple objective design of HUV. Also in the MDO process, All-in-one (AIO) is adopted with Non Sorting Genetic Algorithms ( NSGA)-II and surrogate models are built utilizing a kriging model for finding global optimization as well. The surrogate models are used in order to replace the expensive CFD simulations which are required to predict the hydrodynamic characteristics of the HUV accurately. The paper discuss use of response surface models in obtaining approximation models with less CFD simulation runs.

For this purpose, different types of Design of Experiments (DOE) are tried like full factorial design, The computation time for running full factorial designs for creating the approximate model increase exponentially with number of design parameters. Hence optimal Latin hyper cube design is suggested as the method for DOE which ensure that design points are spread evenly in the design space thus increasing the accuracy of the surrogate models.

Kriging method is then used to build the surrogate model which combines a global model and local components as below;

$$y(x) ) = f(x) + z(x) \tag{2}$$

where $f(x)$ is the global model similar to a polynomial response surface model and $z(x)$ is the local component which show the deviations from global model.

## 2.3 Surrogate models using Artificial Neural Networks (ANN):

This is relatively a new development to be applied in the marine structural problems though it has a rich history in other applications. The method can be applied for the structural optimisation of ships and other marine assets.

[18] Discuss about necessity for the application of neural network in engineering problems and history of developments on its application to various fields. Though it gives reliable results, the time consuming nature and complexity associated with the application of FEM has resulted in development of artificial neural networks which was introduced by Warren McCulloch and Pitts (1943).Later it was introduced in structural engineering applications on

1991 by Hajela and Berke by using the artificial neural network to represent the force–displacement relationship in static structural analysis. Also Shao and Murotsu (1997) have applied ANN to predict the reliability of structures. Also from around 2000, the method was used in marine and offshore structural fields as well which includes structural reliability analysis by Papadrakakis et al. (1996). The analysis of results had shown that an ANN-based response surface method (RSM) is more accurate and efficient than conventional polynomial-based RSM in structural reliability analysis.

[19] Was referred for getting more basic and simplified understanding of ANN methods and application in engineering applications though subject of application of the ANN method mentioned in the paper was out of scope of this thesis. The paper define ANN as a structure built by many interconnected basic elements called artificial neurons which resembles the natural tissues in brain consisting from many nervous cells. The ANN method was developed by and is inspired from observation of the natural neurons behaviour thus uncovering its basic operation principles and interesting properties. The first idea of creating modern artificial neuron was done by Rosenblatt is called simple perceptron, which may be considered as a transducer giving only one output for many input signals .For nonlinear applications, more than one neurons are grouped into many layers thus forming multi layer perceptrons (MLP). Layers between the input and output layer are called hidden layers and this class of artificial neural network can be used for majority of problems due to the ability to extend non-linear model applications. Also using genetic algorithm tools, number of layers in multi layer perceptrons and number of artificial neurons in hidden layers can be optimised as otherwise could result in overfitting.

[20] Provide information about use of response surface methods for marine structural applications. However as a more efficient and less time consuming alternative, Lee et al., 2013a has constructed a framework for optimal design based on the Neuro-Response Surface Method (NRSM). The application of the framework in structural and hydrodynamic performance analysis was checked using a case study. The framework was constructed using a MATLAB code. The design alternatives for performance analysis were generated using an orthogonal array table (Ross, 1996) and commercial software codes were used for performance analysis. The optimal design Framework using NRSM was consisted of a few phases, which represented generation of geometry, generation of response surface method for prediction of system performance using Back- Propagation Artificial Neural network

(BPANN , which is considered as NRSM) and performing NRSM for optimisation of system geometry.

Cilimkovic [21] gives details about basic structure of artificial neural network and it's analogy with human brain layout consisting of neurons. The paper discuss logic behind the popular back propagation neural network algorithm and describe in detail about the different layers of neural network, weights transferred in each layer and about activation function etc. Generally a BPNN consist of three layer namely input layer which contain the input variables, output layer which contain the output or response variable and hidden layers in between these two layers as shown in below figure. The number of hidden layers and number of neurons in each layer are usually iterated. The paper define working of a BPNN as a method in which output from the neural network is checked against the desired input or with the training set. Then if the relative error is large, connection (weights) between the different layers are modified so that process is repeated till the value of error function reaches within acceptable limits. Hence the running of a neural network includes two pass namely forward and backward passes. Outputs are calculated and relative error with desired output is checked in the forward pass while weights are modified according to the error obtained until it become low enough in the backward pass.

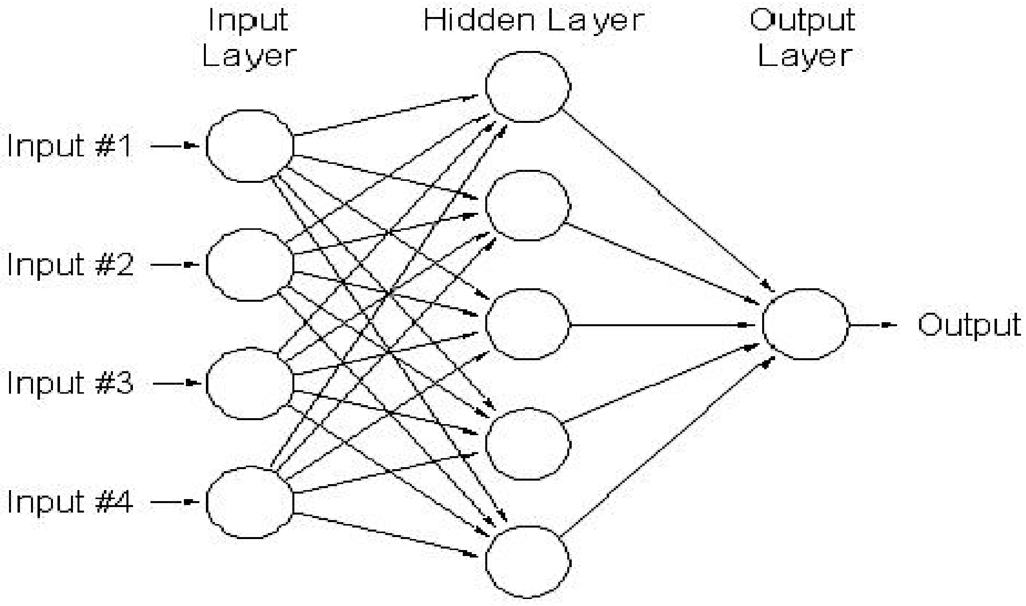

Figure 5 Structure of simple neural network (Source [21])

## 2.4 RSM With CAESES Tool

Advanced response surface options are avaiable in CAESES using the inbuilt DAKOTA optimisation package. [22][23] DAKOTA is a toolkit developed by the Sandia National Laboratories and it provides a flexible and extensible interface between simulation codes and iterative analysis methods.

[22][23] There are three types of surrogate based models available in DAKOTA which are data fits, multifidelity, and reduced-order model surrogates. Based on the data (response values,gradients, and Hessians) or results available from original truth model, data fitting methods involve building an approximation or surrogate model accordingly. Based on the number of points used for generating the data fit, data fitting methods can be further classified as local, multipoint, and global approximation techniques. As the name indicates, global methods involve many design points spread over the parameter ranges of interest.

Some of the key global methods which are often referred to as response surface methods and available in CAESES for building the surrogate models are discussed below;

**Polynomial Regression**: First-order (linear), second-order (quadratic), and third-order (cubic) polynomial response surfaces are available in DAKOTA which can be computed using linear least squares regression methods.

For each point x, a linear polynomial model is approximated by

$$f(x) \approx c_0 + \sum_{i=1}^{n} c_i x_i \tag{3}$$

The form of quadratic polynomial model is shown below;

$$f(x) \approx c_0 + \sum_{i=1}^{n} c_i x_i + \sum_{j \geq i}^{n} c_{ij} x_i x_j \tag{4}$$

Where f(x) is the response of the polynomial model or the gives the value of objective function.

If n is the number of design parameters, then $x_i$, $x_j$ etc. are the components of the n-dimensional design parameter values; and $c_0$ , $c_i$ $c_j$, $c_{ij}$ terms are the polynomial coefficients.

The number of coefficients, nc depends on the order of polynomial model and the number of design parameters. Also for solving the polynomial coefficients and to form a full determined linear system, there must be at least nc data samples.

For the linear polynomial model, $n_{c,linear} = n+1$ (5)

For Quadratic polynomial model, $n_{c,quad} = \frac{(n+1)\,(n+2)}{2}$ (6)

**Gaussian Process (GP) or Kriging Interpolation :** Kriging interpolation ( or also known as gaussian processes) which is available in the Surfpack sub-package of DAKOTA use the Gaussian correlation function with parameters that are selected by Maximum Likelihood Estimation (MLE).

Establishing a Kriging model typically involves below steps;

- Choice of a trend function,
- Choice of a correlation function, and
- Estimation of correlation parameters.

The response function or the Kriging emulator, f(x) generally consists of a trend function (usually a least squares fit to the data, $g(x)^T\ \beta$ ) and a gaussian process error model, $\varepsilon$ (x), which is used to correct the trend function.

$$f(\underline{x}) = \underline{g}\ (\underline{x})^T\ \underline{\beta} + \varepsilon\ (\underline{x}) \quad (7)$$

**Artificial Neural Networks:** Stochastic layered perceptron (SLP) neural network model developed by Prof. D. C. Zimmerman of the University of Houston is implemented in DAKOTA other than the general back propagation neural network models available in other platforms and it is intended to have a lower training (fitting) cost comparatively.

Apart from the models briefed above, there are further more models available in DAKOTA like Multivariate Adaptive Regression Splines ( MARS) , Radial basis functions (RBF) etc which are also global models for building the surrogates.

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# 3. ESTABLISHING THE STEEL-MODEFRONTIER LOOP FOR PERFORMING STRUCTURAL OPTIMISATION OF RORO HULL

As indicated in the previous section (Methodology), initial task was to analyze the STEEL model available for the RoRo hull (testcase1). The STEEL model of RoRo hull with structural and load modeling of the main transverse frame completed was already available at ANAST-University of Liege and the same was made available for this thesis.

Hence the initial task was to study the RoRo STEEL model in order to couple the same with optimization tools used, for which the tool ESTECO modeFRONTIER was used at University of Liege as part of HOLISHIP WP4.

## 3.1 Analysing The RoRo STEEL Model

### 3.1.1 About STEEL Tool and Coordinate System Followed

[24] BV STEEL is a 3D Beam analysis tool. Using the graphical user interface, it is possible to define the main nodes and then nodes are interconnected to form the beams. The six degrees of freedom (3 translational and 3 rotational) of each node can be defined manually. Then a suitable beam type like I Section, bulb or Angle section etc. can be assigned to each beam. After defining nodes and beams, the loads can be modeled either as node loads or beam loads.

Accordingly labels are given for the nodes, beams and beam loads.

With respect to a global axes system defined (X,Y,Z), a local coordinate axes system is also followed in order to represent beams. Local coordinate axis x is defined as from start of a beam to the end of a beam while other local coordinate axes y &z are defined in the perpendicular directions to x accordingly so that together forming a dextrose trihedron.

The local axes y and z are the reference axes for defining the beam stiffness characteristics and for the applied beam loads.

### 3.1.2 Understanding The RoRo STEEL Model

The structural modeling and load modeling of RoRo hull was already completed in the STEEL model of the main transverse frame of the RoRo hull.

The reference drawings with which STEEL model was completed were not available for developing this thesis due to restrictions from the vessel owner. Hence this STEEL model was used only as reference to understand modeling the main transverse frame using BV STEEL tool and to study the parameters needed to define in order to couple STEEL tool with the optimization tools and thereby to perform the structural optimization of main transverse frame under consideration.

Approximate vessel dimensions of the RoRo hull used are added below for reference;

Table 1 Vessel Dimensions - RoRo Hull

| | |
|---|---|
| $L_{OA}$ | ~ 211 m |
| $L_{PP}$ | ~ 196 m |
| $L_{Rule}$ (96% LWL) | ~ 193 m |
| $B_{mld}$ | ~ 32.2 m |
| Scantling Draft, T | ~ 8.2 m |
| Material of Construction | Steel AH36 |

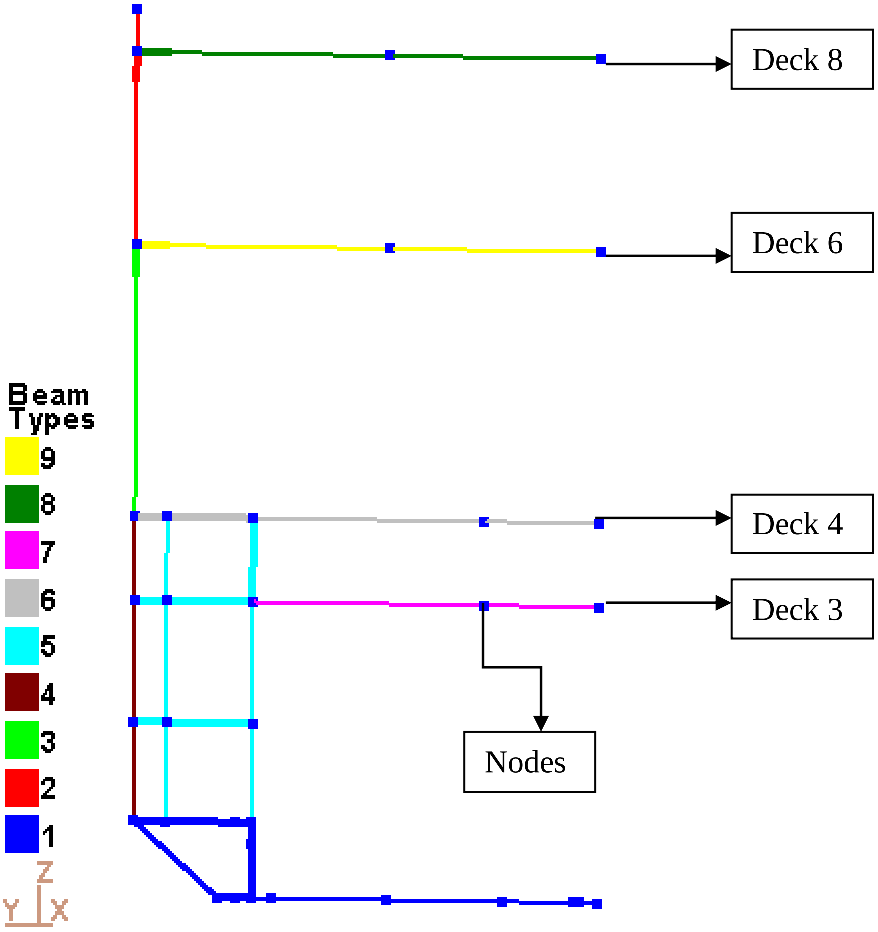


Figure 6 BV STEEL model of RoRo Vessel (Source:RoRo Hull STEEL model)

As shown figure 6, nodes are connected together to form the beams. Figure also represents the beam types assigned to each beam with reference to table 2.

The structural members are represented with the plating to which they are connected in a 3D beam model according to the BV Class rules applicable, with elements are modeled with their net scantlings. Then each beam is assigned with either of below beam types accordingly. All the members are modeled with standard I Section type beams for which the beam characteristics like area of cross section, moment of inertia are then calculated directly by the STEEL tool.

Table 2 Beam types from RoRo STEEL model- Initial Configuration

| Sl No. | Beam Type (Name) | Section Type | Material Grade | $B_f$ (in m) | $H_w$ (in m) | $B_P$ (in m) | $T_f$ (in mm) | $T_w$ (in mm) | $T_P$ (in mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Floor | I Sec | AH36 | 2.400 | 1.700 | 2.400 | 14 | 12 | 12.5 |
| 2 | Upper Side shell | I | AH36 | 0.650 | 1.200 | 1.250 | 19.5 | 13.5 | 7.5 |
| 3 | Mid Side shell | I | AH36 | 0.500 | 1.200 | 2.400 | 19.5 | 11.5 | 8.5 |
| 4 | Lower Side shell | I | AH36 | 0.150 | 0.650 | 0.800 | 14.5 | 15.5 | 10 |
| 5 | Long. BHD | I | AH36 | 0.150 | 0.600 | 0.800 | 14.5 | 15.5 | 9.5 |
| 6 | Deck 4 | I | AH36 | 0.300 | 1.000 | 2.400 | 19.5 | 9.5 | 14 |
| 7 | Deck 3 | I | AH36 | 0.120 | 0.290 | 2.400 | 9.5 | 5.5 | 5.5 |
| 8 | Deck 8 | I | AH36 | 0.380 | 0.980 | 2.463 | 19.5 | 9.5 | 11 |
| 9 | Deck 6 | I | AH36 | 0.350 | 1.030 | 2.463 | 19.5 | 9.5 | 11 |

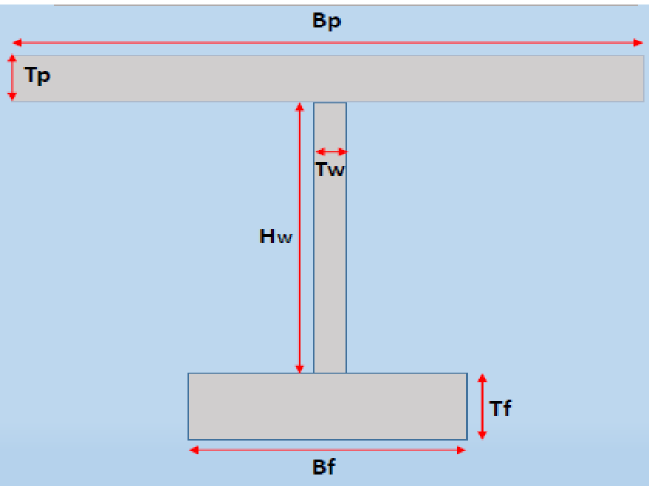


Figure 7 Typical Representation of a Beam Section Considered

In the current RoRo STEEL model, total seven load cases are defined according to the Classification rules applicable. For each load cases, the sea pressure loads and wheeled loads are applied to the beams as shown below. Below a sample loading condition for load case a+ (Which refers to load case a in upright conditions with wave crest as per BV Class rules) is given. All the load cases were pre defined in the RoRo STEEL model available.

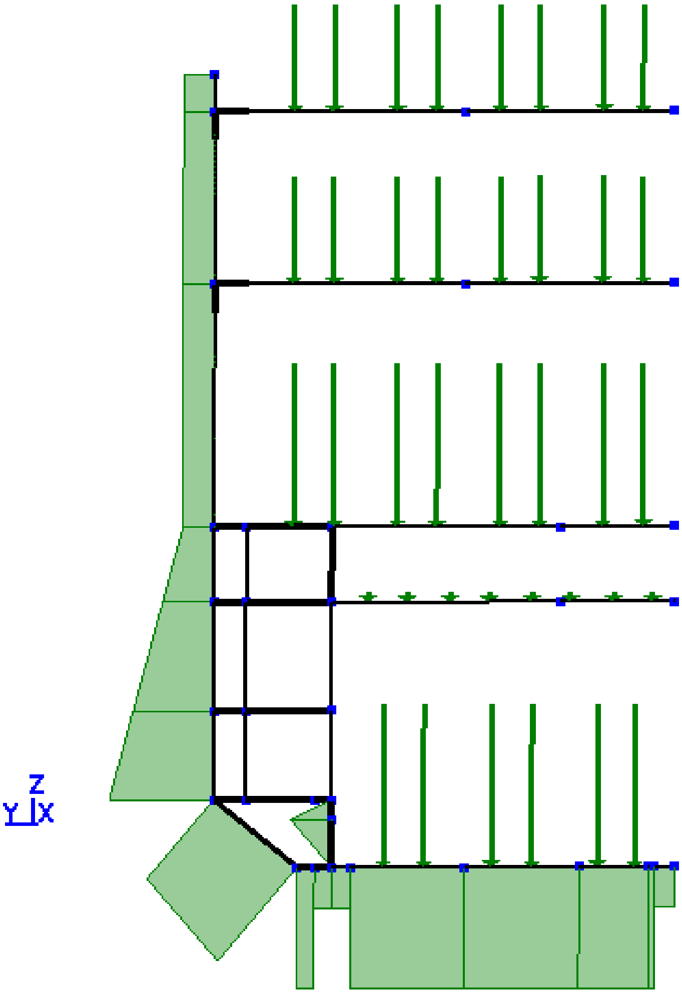


Figure 8 Representation of Load Case a+ for RoRo Hull

(Source:RoRo Hull STEEL model)

### 3.1.3 Understanding the stresses and other checks

As described in earlier sections, structural modeling and load modeling completed, the model can be checked for applicable stresses generated in the structure. STEEL tool indicates an overall Von mises stress distribution on all beams which can be referred to identify critically stressed regions as shown below.

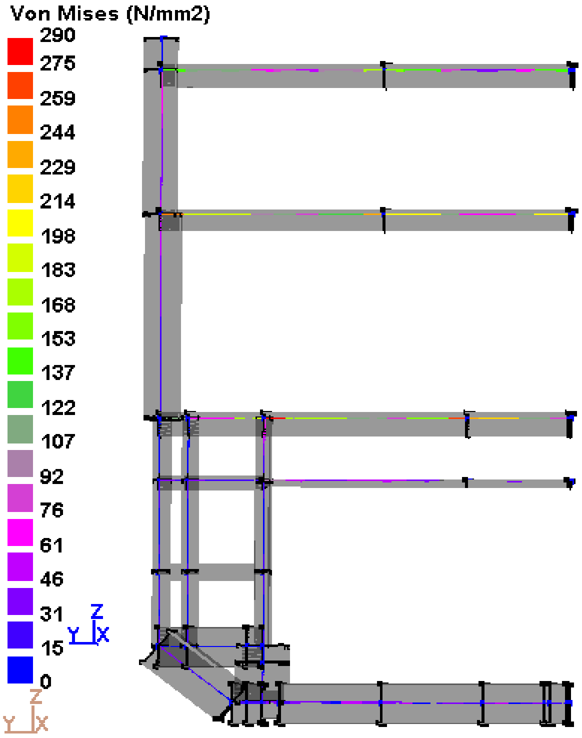
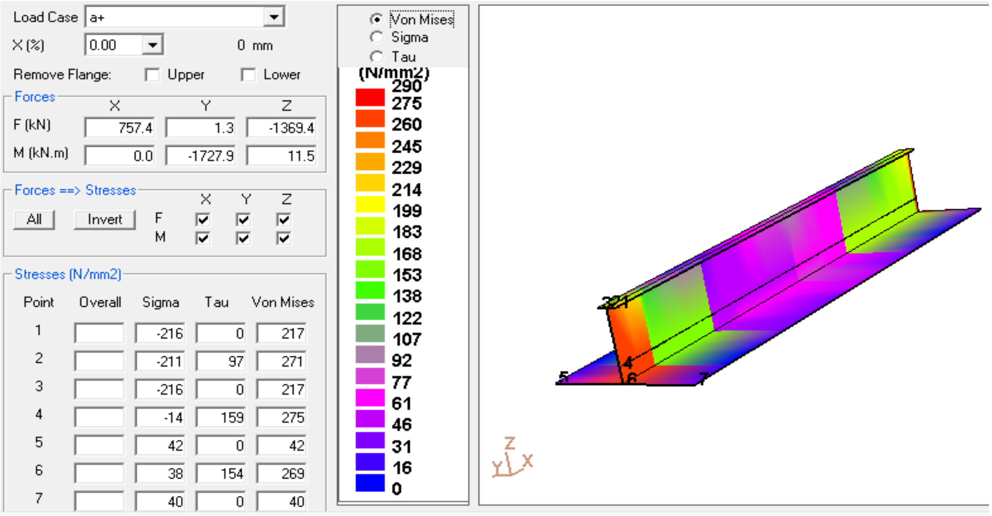


Figure 9 Von mises stress distribution of load case a+ for RoRo hull

(Source:RoRo Hull STEEL model)

Figure 7 indicates the overall Von mises stress distribution when the structure was checked for load case a+ as defined within the RoRo STEEL model. Load case a+ represent load case a with a wave crest considered as per defined in BV Class rules.

Also the stress distribution along a beam can be studied as well as indicated below.



Load Case a+

X (%) 0.00 0 mm

Remove Flange: ☐ Upper ☐ Lower

Forces

|  | X | Y | Z |
|---|---|---|---|
| F (kN) | 757.4 | 1.3 | -1369.4 |
| M (kN.m) | 0.0 | -1727.9 | 11.5 |

Forces ==> Stresses

|  | X | Y | Z |
|---|---|---|---|
| F | ☑ | ☑ | ☑ |
| M | ☑ | ☑ | ☑ |

Stresses (N/mm2)

| Point | Overall | Sigma | Tau | Von Mises |
|---|---|---|---|---|
| 1 |  | -216 | 0 | 217 |
| 2 |  | -211 | 97 | 271 |
| 3 |  | -216 | 0 | 217 |
| 4 |  | -14 | 159 | 275 |
| 5 |  | 42 | 0 | 42 |
| 6 |  | 38 | 154 | 269 |
| 7 |  | 40 | 0 | 40 |

● Von Mises
○ Sigma
○ Tau

Figure 10 Von mises Stress distribution along a beam span - RoRo Hull

(Source:RoRo Hull STEEL model)

The STEEL tool calculates the bending stress, shear stress and the Von mises stress at seven points across a beam section as shown in figure 9.

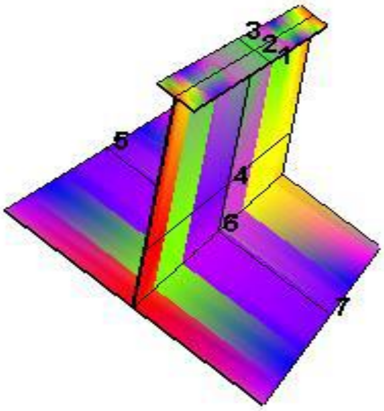


Figure 11 Stress distribution on a beam cross section - RoRo Hull

(Source:RoRo Hull STEEL model)

## 3.2 Coupling BV STEEL with modeFRONTIER for performing Structural Optimisation

The next task is to perform structural optimization of the main transverse frame of the RoRo hull using the output from STEEL tool studied in earlier section and by integrating the STEEL tool with an optimization platform so that structural analysis can be studies for varying beam scantlings.

A short description about modeFRONTIER tool is added below which was used as the optimization platform at ULiege for HOLISHIP WP4 application in order to couple with the STEEL tool for performing the structural optimization.

### 3.2.1 About modeFRONTIER Tool

ESTECO modeFRONTIER is an optimization tool in which a predefined output can be studied for varying design variables defined by the user. Also different software can be integrated together for this purpose.

In modeFRONTIER, Different input design variables defined are connected to the output variables using script nodes like a DOS batch script node, calculator node or a Python node etc. Then a scheduler is set up which controls the optimization process. Scheduler consists of two nodes which are DOE (Design of Experiments) and Scheduler which act as the design engine for running the optimization. DOE helps to generate different design configurations of the input design variables initially as per the selected algorithm and the required optimization strategy is applied accordingly through the Scheduler node.

### 3.2.2 Coupling STEEL Tool And modeFRONTIER with four design variables

As indicated earlier, it is required to define the design variables initially in order to set up the optimization loop. Since in our case beam scantlings are varied, the scantlings of a required beam section were defined as the input design variables.

A workflow was created within modeFRONTIER in order to set up the optimization loop as shown below.

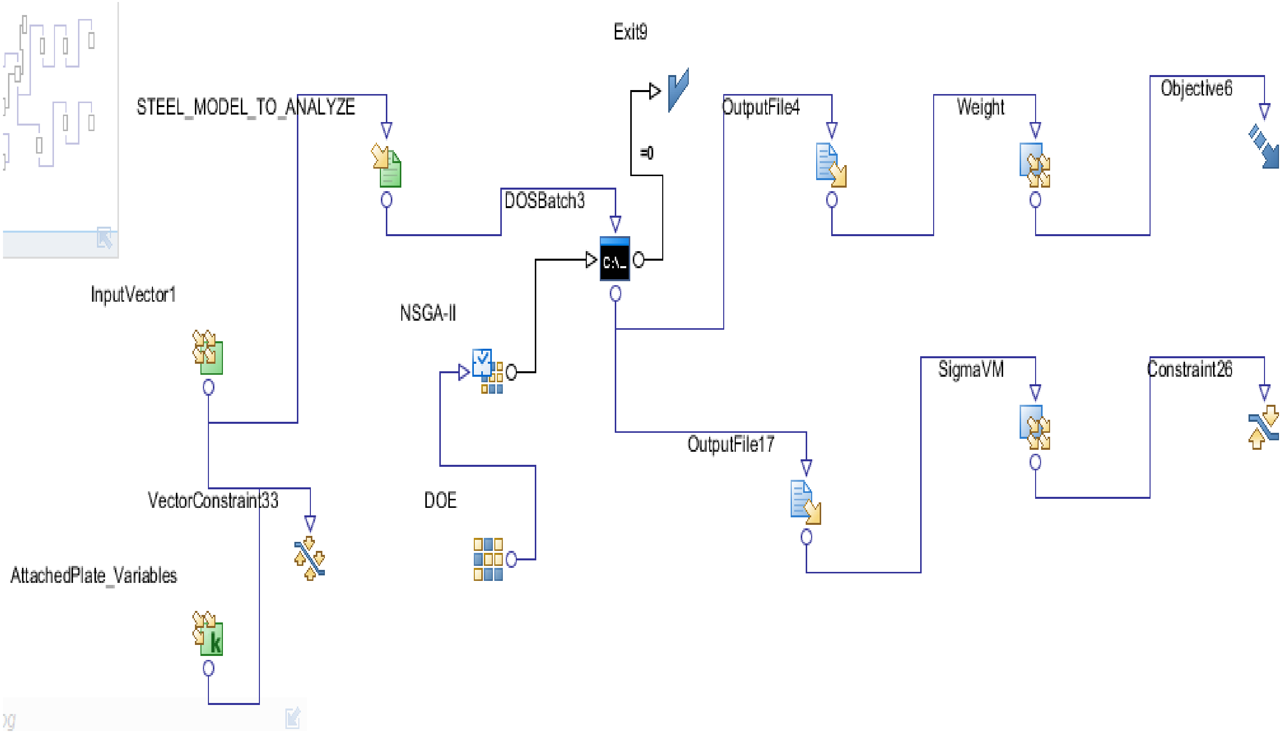


Figure 12 Workflow Created For STEEL-modeFRONTIER Optimisation loop

In Figure 12;

**InputVector1** : Indicates the Input design variables defined which are the beam scantlings.

**InputVector32** : Contains the Attached plate Scantlings for the beam type considered.

**STEEL_MODEL_TO_ANALYZE** : STEEL tool Input file for the model considered.

**OutputFile4** : Output file generated by STEEL Tool in batch mode

**OutputFile17** : Output File generated by STEELBeamStressExtractor Tool showing Von mises Stress for the loadcase considered.

**VectorConstraint33** : Geometrical Constraints related to beam and attached plate scantlings.

**Weight** : Give the value for output variable which is the structural weight of entire main transverse frame section and is set as the objective using the node Objective6.

**SigmaVM :** Indicate the value of maximum Von mises stress for the entire section and is set as a constraint for yield check.

With reference to figure 5 shown earlier, initially four design variables were selected as the scantlings of beam section of Deck 6. The scantlings of attached plating were kept constant as it will be determined by the BV MARS tool as described earlier.

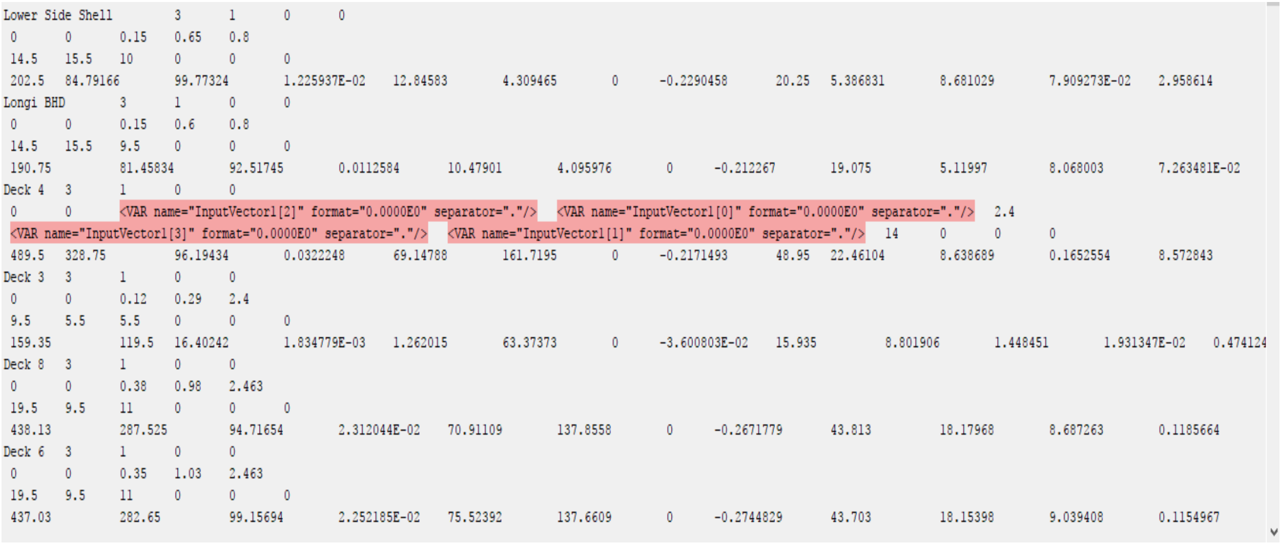
The list of design variables defined with their range of values considered are listed in the next table. Since attached plate scantlings will be determined by the BV MARS loop as mentioned earlier, they are kept as constant.

Table 3 Input Design Variables for STEEL-modeFRONTIER Loop 1

| Design Variable | Description | Min. Value | Max. Value |
|---|---|---|---|
| Hw_Deck6 | Web Height of Deck6 Beam section | 0.800 m | 1.2 m |
| Tw_Deck6 | Web Thickness of Deck6 Beam Section | 7 mm | 12 mm |
| Bf_Deck6 | Flange Width of Deck6 Beam Section | 0.250 m | 0.500 m |
| Tf_Deck6 | Flange Thickness of Deck6 Beam Section | 15 mm | 25 mm |

Web height and Flange width were given in meters, while thickness is mentioned in mm as required by the STEEL tool.

The beam scantlings were marked as design variables within the STEEL input file as shown below.

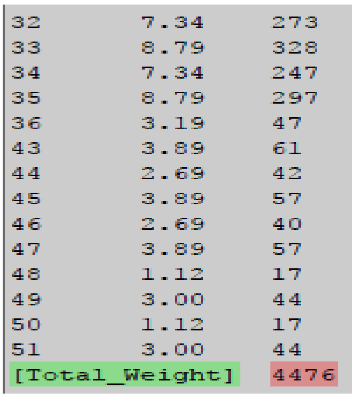


```
Lower Side Shell        3       1       0       0
 0       0       0.15    0.65    0.8
 14.5    15.5    10      0       0       0
 202.5   84.79166        99.77324        1.225937E-02    12.84583        4.309465        0       -0.2290458      20.25   5.386831        8.681029        7.909273E-02    2.958614
Longi BHD       3       1       0       0
 0       0       0.15    0.6     0.8
 14.5    15.5    9.5     0       0       0
 190.75          81.45834        92.51745        0.0112584       10.47901        4.095976        0       -0.212267       19.075          5.11997         8.068003        7.263481E-02
Deck 4  3       1       0       0
 0       0       <VAR name="InputVector1[2]" format="0.0000E0" separator="."/>   <VAR name="InputVector1[0]" format="0.0000E0" separator="."/>   2.4
 <VAR name="InputVector1[3]" format="0.0000E0" separator="."/>   <VAR name="InputVector1[1]" format="0.0000E0" separator="."/>   14      0       0       0
 489.5   328.75          96.19434        0.0322248       69.14788        161.7195        0       -0.2171493      48.95   22.46104        8.638689        0.1652554       8.572843
Deck 3  3       1       0       0
 0       0       0.12    0.29    2.4
 9.5     5.5     5.5     0       0       0
 159.35          119.5   16.40242        1.834779E-03    1.262015        63.37373        0       -3.600803E-02   15.935          8.801906        1.448451        1.931347E-02    0.474124
Deck 8  3       1       0       0
 0       0       0.38    0.98    2.463
 19.5    9.5     11      0       0       0
 438.13          287.525         94.71654        2.312044E-02    70.91109        137.8558        0       -0.2671779      43.813          18.17968        8.687263        0.1185664
Deck 6  3       1       0       0
 0       0       0.35    1.03    2.463
 19.5    9.5     11      0       0       0
 437.03          282.65          99.15694        2.252185E-02    75.52392        137.6609        0       -0.2744829      43.703          18.15398        9.039408        0.1154967
```

Figure 13 Assigning the Input design Variables within modeFRONTIER

### 3.2.3 Defining Objective Function and Constraints for Optimization

The weight of main transverse frame is shown in the output file generated by STEEL tool in batch mode. Hence the weight of main transverse frame was selected as the objective function which will be minimized during the optimization process.



```
32          7.34      273
33          8.79      328
34          7.34      247
35          8.79      297
36          3.19      47
43          3.89      61
44          2.69      42
45          3.89      57
46          2.69      40
47          3.89      57
48          1.12      17
49          3.00      44
50          1.12      17
51          3.00      44
[Total_Weight]        4476
```

Figure 14 Assigning the Output Variable to set as objective function within modeFRONTIER

**Figure 14**: Assigning the Output Variable to set as objective function within modeFRONTIER

The output file shows the beam numbers, beam length and weights in the table as shown in above figure along with the total weight of the entire STEEL model and hence an output variable is created within the modeFRONTIER workflow which is set to be minimized within the optimization process.

The constraints required to be defined within the optimization process was defined as per Bureau VERITAS Class rules applicable.

Since here the primary transverse supporting members are analyzed, below constraints are considered according to BV Rules applicable when the structural members are analyzed using a 3D Beam model.

### a) Criteria for the Von Mises Stresses & Yield Check

As per BV Rules NR 467, Pt.B, Ch7, App.1,[5.2.2] , the Von Mises equivalent Stress($\sigma_{\mathrm{VM}}$) on a beam is to calculated as

$$\sigma_{VM} = \left(\sigma_1{}^2 + 3\tau_{12}{}^2\right)^{1/2} \tag{8}$$

where ;

$\sigma_1$ : Normal stress acting in the direction of beam axis.

$\tau_{12}$ : Shear Stress acting in the direction of the local loads applied to the beam.

Only Yield check is considered as applicable since structural modelling of transverse frames are only considered. According to BV Rules NR 467, Pt.B, Ch7, Sec 3,[4.3.3] , the Von

Mises Equivalent stress calculated as per (8) above needs to be less than the value shown below.

$$\sigma_{VM} \leq \frac{R_y}{\gamma_R \gamma_m} \tag{9}$$

Where;

$Ry$ = 355 MPa (Yield Stress of the material of construction considered )

$\gamma_m$ = 1.02 (Material Factor as defined in BV Rules NR 467, Pt.B, Ch7, Sec 3, Table 2)

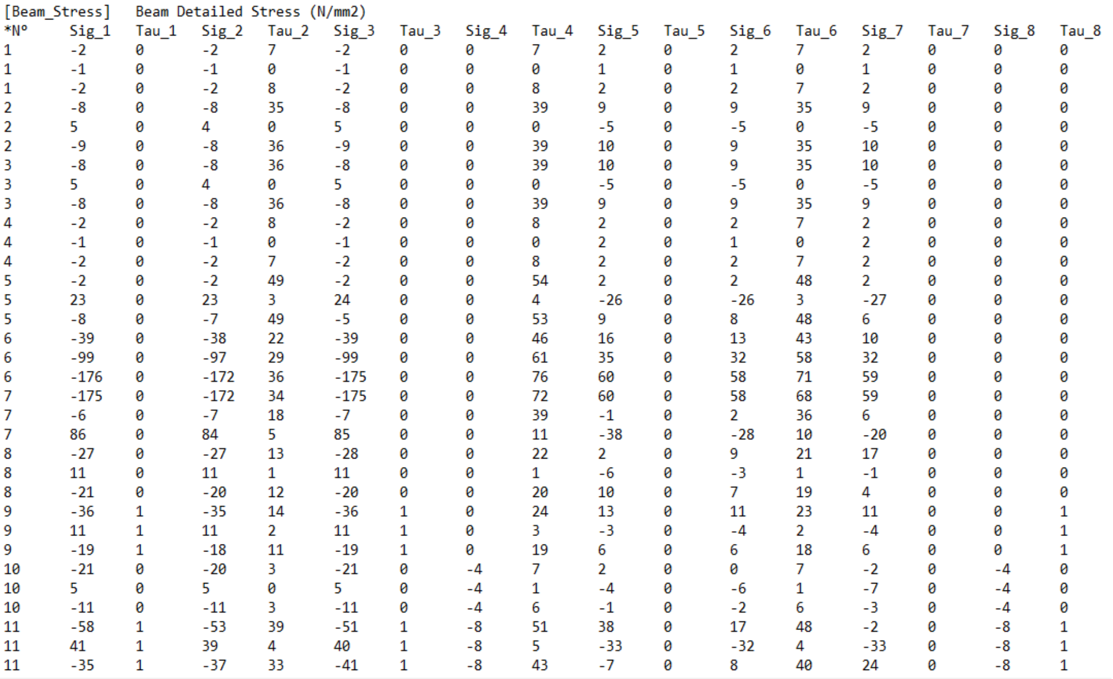
$\gamma_R$ = 1.2 (Resistance Partial Safety Factor as defined in Rules NR 467, Pt.B, Ch7, Sec 3, Table 5 for 3D beam models)

Substituting the values, $\sigma_{VM} \leq \frac{355}{1.02*1.2}$

$$\leq 290 \text{ MPa}$$

Hence this Yield Check criterion for the Von mises stress is defined as one of the Constraints within the optimisation loop.(In Figure 12, Constraint26 defines the yield check within modeFRONTIER.)

By analysing the output file generated by the STEEL tool in Batch mode, it is noted that beam deflections, reactions and beam stresses are shown within this output file. But however only beam bending stresses and shear stresses at predefined points on a cross section of beam are shown in the output file, even though the Von mises stresses are shown in the Graphic user interface of STEEL tool.



```
[Beam_Stress]   Beam Detailed Stress (N/mm2)
*N°     Sig_1   Tau_1   Sig_2   Tau_2   Sig_3   Tau_3   Sig_4   Tau_4   Sig_5   Tau_5   Sig_6   Tau_6   Sig_7   Tau_7   Sig_8   Tau_8
1       -2      0       -2      7       -2      0       0       7       2       0       2       7       2       0       0       0
1       -1      0       -1      0       -1      0       0       0       1       0       1       0       1       0       0       0
1       -2      0       -2      8       -2      0       0       8       2       0       2       7       2       0       0       0
2       -8      0       -8      35      -8      0       0       39      9       0       9       35      9       0       0       0
2       5       0       4       0       5       0       0       0       -5      0       -5      0       -5      0       0       0
2       -9      0       -8      36      -9      0       0       39      10      0       9       35      10      0       0       0
3       -8      0       -8      36      -8      0       0       39      10      0       9       35      10      0       0       0
3       5       0       4       0       5       0       0       0       -5      0       -5      0       -5      0       0       0
3       -8      0       -8      36      -8      0       0       39      9       0       9       35      9       0       0       0
4       -2      0       -2      8       -2      0       0       8       2       0       2       7       2       0       0       0
4       -1      0       -1      0       -1      0       0       0       2       0       1       0       2       0       0       0
4       -2      0       -2      7       -2      0       0       8       2       0       2       7       2       0       0       0
5       -2      0       -2      49      -2      0       0       54      2       0       2       48      2       0       0       0
5       23      0       23      3       24      0       0       4       -26     0       -26     3       -27     0       0       0
5       -8      0       -7      49      -5      0       0       53      9       0       8       48      6       0       0       0
6       -39     0       -38     22      -39     0       0       46      16      0       13      43      10      0       0       0
6       -99     0       -97     29      -99     0       0       61      35      0       32      58      32      0       0       0
6       -176    0       -172    36      -175    0       0       76      60      0       58      71      59      0       0       0
7       -175    0       -172    34      -175    0       0       72      60      0       58      68      59      0       0       0
7       -6      0       -7      18      -7      0       0       39      -1      0       2       36      6       0       0       0
7       86      0       84      5       85      0       0       11      -38     0       -28     10      -20     0       0       0
8       -27     0       -27     13      -28     0       0       22      2       0       9       21      17      0       0       0
8       11      0       11      1       11      0       0       1       -6      0       -3      1       -1      0       0       0
8       -21     0       -20     12      -20     0       0       20      10      0       7       19      4       0       0       0
9       -36     1       -35     14      -36     1       0       24      13      0       11      23      11      0       0       1
9       11      1       11      2       11      1       0       3       -3      0       -4      2       -4      0       0       1
9       -19     1       -18     11      -19     1       0       19      6       0       6       18      6       0       0       1
10      -21     0       -20     3       -21     0       -4      7       2       0       0       7       -2      0       -4      0
10      5       0       5       0       5       0       -4      1       -4      0       -6      1       -7      0       -4      0
10      -11     0       -11     3       -11     0       -4      6       -1      0       -2      6       -3      0       -4      0
11      -58     1       -53     39      -51     1       -8      51      38      0       17      48      -2      0       -8      1
11      41      1       39      4       40      1       -8      5       -33     0       -32     4       -33     0       -8      1
11      -35     1       -37     33      -41     1       -8      43      -7      0       8       40      24      0       -8      1
```

Figure 15 Sample Output file showing Beam Stresses generated by STEEL Tool in Batch Mode

Figure 15 shows a sample output file generated by STEEL tool when coupled with an optimisation platform in batch mode. The output file lists the normal and shear stresses at predefined points on a beam section as shown. Also it shows these stress values at three locations along the beam span, at start point, midspan and end point on the beam.

Hence in order to calculate the Von mises stress from the normal stress and shear stress provided within the Batch mode output file, an executable application called “SteelBeamStressExtractor” was developed at University of Liege for this purpose. The application reads the normal and shear stress at each point on the beam section for the load case considered at the three locations and in turn calculates the corresponding Von Mises stress. Then the application finally gives an output file showing the maximum Von Mises Stress of all the beams in the entire Transverse frame section modelled in STEEL, which then kept as a Constraint to be within the Yield check Criteria for the Von Mises Stress as mentioned earlier((Denoted as Constarint26 in Figure 12).

**b) Criteria for the Geometrical properties**

The geometrical Constraints were defined as per BV Rules NR 467, Pt B, Ch4, Sec3, [4]

$$\mathrm{A_a} \geq \mathrm{T_f} * \mathrm{B_f} \tag{10}$$

$$\frac{\mathrm{H_w}}{\mathrm{T_p}} \geq 10 \tag{11}$$

$$\frac{\mathrm{H_w}}{\mathrm{T_f}} \geq 10 \tag{12}$$

where ;

$\mathrm{A_a}$ : Net Sectional Area of the Attached Plating in mm$^2$

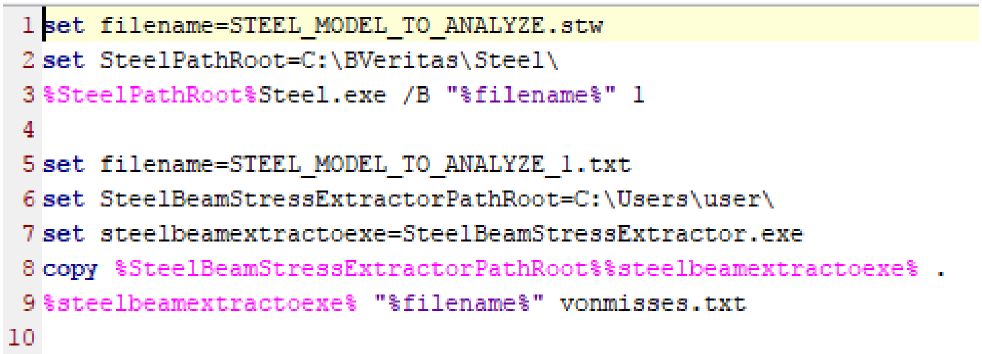
$\mathrm{H_w}$ : Web Height of the beam section under consideration in mm

$\mathrm{T_f}$, : Flange thickness of beam section under consideration in mm

$\mathrm{T_p}$ : Thickness of Attached Plating in mm

Hence accordingly these constraints were defined within STEEL-modeFRONTIER loop using the vector constraints. (Denoted as VectorConstarint33 in Figure 12)

Below Bach mode command was incorporated in the DOS Script Node in order to couple STEEL tool with modeFRONTIER.



```
set filename=STEEL_MODEL_TO_ANALYZE.stw
set SteelPathRoot=C:\BVeritas\Steel\
%SteelPathRoot%Steel.exe /B "%filename%" 1

set filename=STEEL_MODEL_TO_ANALYZE_1.txt
set SteelBeamStressExtractorPathRoot=C:\Users\user\
set steelbeamextractoexe=SteelBeamStressExtractor.exe
copy %SteelBeamStressExtractorPathRoot%%steelbeamextractoexe% .
%steelbeamextractoexe% "%filename%" vonmisses.txt

```

Figure 16 Command Script for coupling STEEL in Batch Mode with modeFRONTIER

Within the batch command, first two lines are meant for calling STEEL tool in batch mode and it creates a batch mode output file named as “STEEL_MODEL_TO_ANALYZE_1.txt” Within the project folder for each iterations considered.

Using this output file, ‘SteelBeamStressExtractor’ generates an output file named as “Vonmisses.txt” showing the maximum Von mises stress for the entire model as explained earlier. Accordingly the STEEL- modeFRONTIER loop was set up and optimisation was performed analysing several design iterations.

SOBOL algorithm was chosen as the DOE and MOGA (Multi Objective Genetic Algorithm) as the Design Engine/Scheduler for the optimisation run. Since here the objective is the structural weight only, it reduces to a single objective optimisation problem. Then total of around 200 iterations were run in modeFRONTIER.

As listed below, the output table lists design variables, objective function, values of the constraints and feasibility of the designs considered. Initial designs according to DOE is used to detect key trends on the design variable range. Then the design engine/scheduler will run in the areas where the feasibility to get a successful iteration is higher, thus increasing the probability to find feasible iterations minimising the objective function.

Table 4 Sample Results from modeFRONTIER with 4 Design Variables

| Design ID | Category | $B_P$_ Deck4 | $T_P$_Deck4 | $H_W$_ Deck4 | $T_W$_Deck4 | $B_f$_Deck4 | $T_f$_Deck4 | $\sigma_{VM}$ (MPa) | Weight (Tonnes/ 100) | C1 ( in $mm^2$) | C2 | C3 | Feasibility |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | SOBOL | 2.4 | 14 | 0.8 | 7 | 0.25 | 15 | 493.6345 | 4343 | 29850 | 57.143 | 53.333 | false |
| 1 | SOBOL | 2.4 | 14 | 0.9 | 10.75 | 0.4375 | 22.5 | 271.932 | 4469 | 23756 | 64.286 | 40.000 | true |
| 2 | SOBOL | 2.4 | 14 | 1.1 | 8.25 | 0.3125 | 17.5 | 304.8409 | 4407 | 28131 | 78.571 | 62.857 | false |
| 3 | SOBOL | 2.4 | 14 | 1.15 | 11.375 | 0.28125 | 18.75 | 216.5063 | 4455 | 28327 | 82.143 | 61.333 | true |
| 4 | SOBOL | 2.4 | 14 | 0.95 | 8.875 | 0.40625 | 23.75 | 311.7691 | 4451 | 23952 | 67.857 | 40.000 | false |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | MOGA2 | 2.4 | 14 | 0.825 | 11.3803 | 0.36317 | 18.125 | 289.2525 | 4425 | 27018 | 58.929 | 45.517 | true |
| 24 | MOGA2 | 2.4 | 14 | 0.9174 | 11.3764 | 0.429738 | 20.1806 | 256.3435 | 4464 | 24928 | 65.529 | 45.460 | true |
| 100 | MOGA2 | 2.4 | 14 | 1.0346 | 9.7289 | 0.33247 | 17.2007 | 275.39609 | 4423 | 27881 | 73.897 | 60.146 | true |
| 101 | MOGA2 | 2.4 | 14 | 1.102 | 8.89625 | 0.26575 | 17.1055 | 289.25247 | 4405 | 29054 | 78.708 | 64.419 | true |
| 191 | MOGA2 | 2.4 | 14 | 0.9869 | 10.0163 | 0.25414 | 15.8383 | 289.2525 | 4399 | 29575 | 70.492 | 62.310 | true |
| 193 | MOGA2 | 2.4 | 14 | 1.0116 | 10.277 | 0.250003 | 17.1307 | 275.3961 | 4409 | 29317 | 72.255 | 59.050 | true |

In the table, C1,C2 and C3 indicate the geometrical constraints applied to the Deck4 beam scantlings as explained earlier. Hence Constraint C1 calculates the net difference between net sectional area of attached plating and flange for each iteration while C2 & C3 calculates the ratio between web height with thickness of attached plating and flange thickness.

Figure below indicates the history chart for the objective function, which is the weight of the transverse frame modelled in STEEL tool. Each Design ID given in the X-axis represent each iteration.

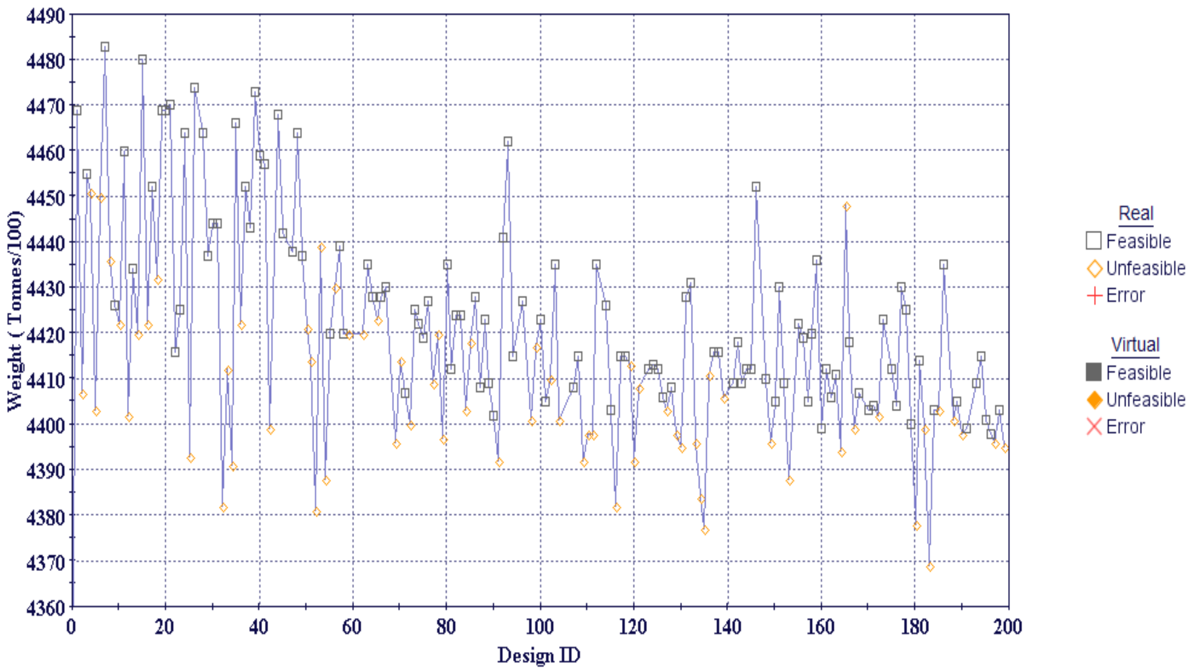


Figure 17 History Chart-Weight with 4 Variables from STEEL-modeFRONTIER loop

The figures show both feasible and unfeasible designs. Even though Sobol gave many unfeasible design s initially, later sufficient feasible designs were obtained with MOGA2 design engine. With different algorithms chosen for DOE and design engine, the percentage of feasible designs and ranges of values considered for the whole iterations will differ to above values obtained now.

### 3.2.4 Extending STEEL-modeFRONTIER Optimisation Loop for 8 Design Variables

Similar to as done earlier, beam scantlings from one more deck of the RoRo hull was considered as design variables, thus making total 8 design variables. The design variables considered, and details of the design algorithm chosen are tabulated below.

Table 5 Details of STEEL-modeFRONTIER loop with 8 Design Variables

|  | DOE | Design Engine |
|---|---|---|
| Chosen Type | SOBOL | MOGA |
| No. Of designs Generated | 40 | 25 |
| Total No. of Iterations | 1000 |  |

| Design Variable | Description | Min. Value | Max. Value |
|---|---|---|---|
| Hw_Deck4 | Web Height of Deck4 Beam section | 0.800 m | 1.2 m |
| Tw_Deck4 | Web Thickness of Deck4 Beam Section | 7 mm | 12 mm |
| Bf_Deck4 | Flange Width of Deck4 Beam Section | 0.250 m | 0.500 m |
| Tf_Deck4 | Flange Thickness of Deck4 Beam Section | 15 mm | 25 mm |
| Hw_Deck6 | Web Height of Deck6 Beam section | 0.800 m | 1.2 m |
| Tw_Deck6 | Web Thickness of Deck6 Beam Section | 7 mm | 12 mm |
| Bf_Deck6 | Flange Width of Deck6 Beam Section | 0.250 m | 0.500 m |
| Tf_Deck6 | Flange Thickness of Deck6 Beam Section | 15 mm | 25 mm |

As shown in the table, range of values for deck 6 are also kept similar to deck 4 as chosen earlier. Total of 1000 iterations were run and results obtained are shown below.

During the optimization process, design variables were chosen as the free variables so that values are not limited to integers since there was no requirements provided from the shipyard in this regard at this stage. It will be possible to run the design iterations with discrete design variables as well if required at a later stage.

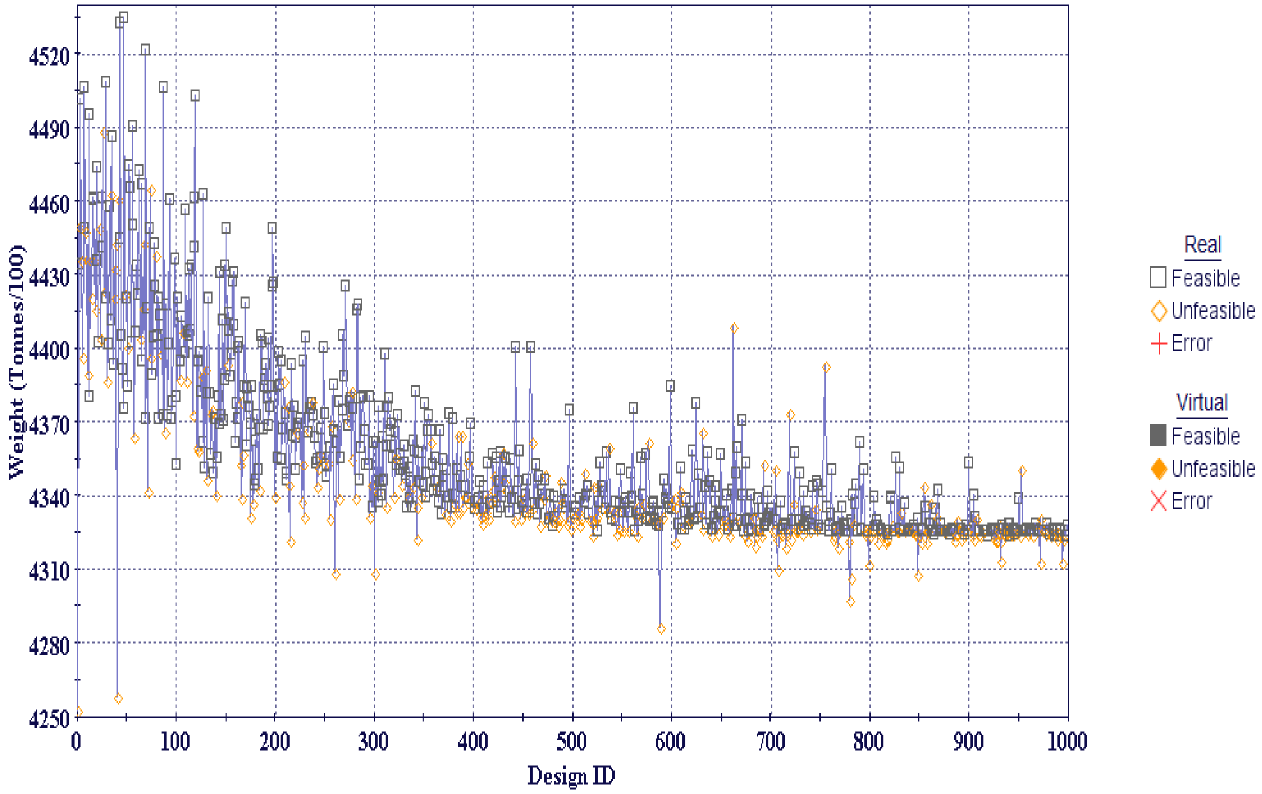


Figure 18 History Chart-Weight with 8 Variables from STEEL-modeFRONTIER loop

As indicated in figure 18, the weight of main transverse frame section decreases as the iterations are progressed, which shows the advantage of coupling STEEL tool with an optimisation platform like modeFRONTIER while satisfying the constraints defined as well.

# 4. GENERATING RESPONSE SURFACE AND REVIEW OF RESULTS

Response-Surface Methodology (RSM) is usually used for determining objective function values for some design data range on which experimental or actual optimisation results are not available or to find a near accurate fit to optimisation results so that actual optimisation loop doesn’t need to run which may be complex, time consuming or expensive.

The main objective to use response surface methodology in this thesis was to check feasibility and applicability of RSM for analysing ship structural problems which could be a resource for the later stages within HOLISHIP project itself especially when BV MARS and STEEL optimization loops are integrated together thereby increasing the number of design variables to be considered.

Hence different algorithms available as part of RSM within different platforms like R Tool, CAESES were analysed and results obtained were studied. The steps taken for establishing the response surface are also discussed. The different factors which affect the accuracy of a surrogate model or response surface are also discussed.

The suitable options available in different tools to build surrogate models for this thesis scope are discussed next.

## 4.1 RSM Using ‘R’ Tool.

### 4.1.1 About R

[25] R is an integrated suite of software facilities for data manipulation, calculation and graphical display. Among other things it has

- an effective data handling and storage facility,
- a suite of operators for calculations on arrays, in particular matrices,
- a large, coherent, integrated collection of intermediate tools for data analysis,
- a well developed, simple and effective programming language

The R enviornment has several packages which are intended for different data analyzing purposes, including various packages for data analysis using Response surface methodology as well. The optimization results obtained from STEEL-modeFRONTIER loop were further analyzed using these packages in order to establish reliable surrogate models.

### 4.1.2 Normalizing the Data

When building a response surface, the data range available for different input variables might be within non uniform ranges of values. Hence normalization of data is critical in order to keep all the variables within a specified range of values and it plays a key role in getting an accurate response fit for the response variable as well.

As mentioned earlier, the input to the program for building the surrogate model is the tabular results obtained from STEEL-modeFRONTIER loop after performing design optimization imported in ASCII format, with titles given for design variables and the output/ Response variable similar to as shown in below example.

| A | B | C | D | E |
|---|---|---|---|---|
| 0.9 | 10.75 | 0.4375 | 22.5 | 4453 |
| 1.1 | 8.25 | 0.3125 | 17.5 | 4392 |
| 1.15 | 11.375 | 0.28125 | 18.75 | 4439 |
| 0.95 | 8.875 | 0.40625 | 23.75 | 4435 |
| 0.85 | 10.125 | 0.34375 | 16.25 | 4387 |
| 1.05 | 7.625 | 0.46875 | 21.25 | 4434 |

Data shows 4 input or predictor variables A,B,C & D (beam scantings) and a response variable E (structural weight). Data are stored in coded form similar to below formulas in order to normalize the variables. x1, x2, x3 & x4 here represent the normalized variables which are coded so that all the variables come within a range of [-1,1].

```
x1 ~ (A - 0.975)/0.175
x2 ~ (B - 9.1875)/2.1875
x3 ~ (C - 0.38126)/0.10311625
x4 ~ (D - 19.6875)/4.6875
```

The design variables are the beam scantlings as explained earlier and output variable is the weight of the main transverse section modeled in STEEL for the RoRo hull.

### 4.1.3 RSM using Polynomial Regression

[26] R environment has a package called ‘rsm’ which can be used for standard response-surface methods in order to analyze data using first or second order polynomial regression models. Multiple-response optimization is not covered in this package. In case of problems involving multiple response variables, response surface is established separately for each of the variables using the same design data available.

Based on the optimization results available for the response variable which is the weight if the transverse section in our case, rsm package is used to establish a polynomial expression involving the design variables used for getting the desired values for the response variable. Appropriate coding is an important element of response-surface analysis using R.

The full design data table used for establishing Response surface with 8 design variable is added in Appendix A3. The maximum and minimum values of each column are found out for normalizing the data.

After normalizing the data, the package available within the R environment called 'rsm' is used to find the polynomial relation between design variables and output variable, which is the weight of the entire transverse frame in this case.

The R code used for running the 'rsm' package is shown in Appendix A4 for the below results data considered. After running the code, the package returns an output similar to as shown in below;

Table 6 Sample output from R tool for rsm with 8 variables

```
              Estimate      Std. Error      t value    Pr(>|t|)
(Intercept) 4447.024883   1.131944    3928.6625 < 2.2e-16 ***
x1          20.861899     1.331937    15.6628    2.203e-15 ***
x2          25.620005     1.301943    19.6783    < 2.2e-16 ***
x3          29.432390     0.550625    53.4527    < 2.2e-16 ***
x4          22.062829     1.152441    19.1444    < 2.2e-16 ***
x5          22.610280     1.977199    11.4355    4.602e-12 ***
x6          24.341768     1.034397    23.5323    < 2.2e-16 ***
x7          32.250878     1.088770    29.6214    < 2.2e-16 ***
x8          24.222521     1.112111    21.7807    < 2.2e-16 ***
x1:x2        5.039888     0.614015     8.2081    6.200e-09 ***
x1:x4       -2.021143     0.861742    -2.3454    0.026321 *
x3:x4        5.634134     1.150612     4.8966    3.679e-05 ***
x5:x6        6.455664     1.986638     3.2495    0.003003 **
x7:x8       12.109894     2.180388     5.5540    6.116e-06 ***
x1^2        -0.648640     0.311000    -2.0857    0.046242 *
```

The result as shown above lists all the design variables and their correlation with each other with respect to the output variable. Only the significant terms with p value(Pr(>|t|)) less than 5% from the output obtained is  shown above.

Then the polynomial relation between design variables and weight is established by taking into account the significant variables together with their coefficients as shown below.

$$\mathbf{Weight} = 4447.024883 + 20.861899{*}x_1 + 25.620005{*}x_2 + 29.43239{*}x_3 + 22.062829{*}x_4 + 22.61028{*}x_5 + 24.341768{*}x_6 + 32.250878{*}x_7 + 24.222521{*}x_8 + 5.039888{*}x_1{*}x_2 + 5.634134{*}x_3{*}x_4 + 6.455664\,x_5{*}x_6 + 12.109894{*}x_7{*}x_8 \quad (13)$$

Where x1,x2,x3…….x8 are the 8 normalized design variables . Using this polynomial relation, the weight of the main transverse frame was calculated and compared with the values given by the STEEL tool.

Table 7 Comparison between Weight obtained from rsm using ‘R’ & STEEL tool with 8 Design Variables

| Weight from STEEL | Weight from RSM | Difference (%) |
|---|---|---|
| 4435 | 4434.91 | 0.002 |
| 4502 | 4499.25 | 0.061 |
| 4449 | 4449.87 | -0.020 |
| 4507 | 4505.59 | 0.031 |
| 4434 | 4432.87 | 0.025 |
| 4470 | 4468.9 | 0.025 |
| 4443 | 4442.02 | 0.022 |
| 4431 | 4432.16 | -0.026 |
| 4503 | 4501.77 | 0.027 |
| 4482 | 4485.14 | -0.070 |
| 4446 | 4444.07 | 0.043 |
| 4435 | 4435.22 | -0.005 |
| 4450 | 4449.96 | 0.001 |
| 4475 | 4476.39 | -0.031 |
| 4410 | 4414.04 | -0.092 |
| 4445 | 4446.78 | -0.040 |
| 4421 | 4422.83 | -0.041 |
| 4404 | 4407.23 | -0.073 |
| 4495 | 4495.13 | -0.003 |
| 4446 | 4444.05 | 0.044 |
| 4439 | 4438.62 | 0.009 |

Results are added in table 10 for a few cases which show the relative difference between the value of weight obtained from the optimisation results (using STEEL tool) and the corresponding values from the RSM given by the R tool. It is observed that the difference between both results is in good relation as percentage error is of the order of 10E-3 which is negligible.

This show that response surface could be helpful in replacing the optimisation loop with reliable surrogate models like obtained.

However if there are more design variable, suitability of polynomial regression models need to be verified.

### 4.1.4 RSM Using Artificial Neural Networks

[27] Like rsm package, there are a few dedicated packages available for artificial neural networks in the 'R' environment depending on the type of artificial neural network mechanism used. A package called 'neuralnet' is available which is based on the popular back propagation neural network model. The neural network is constructed with an interconnected group of nodes, which involves the input, connected weights, processing element, and output. Neural networks can be applied to many areas, such as classification, clustering, and prediction. To train a neural network in R, 'neuralnet' package is used which is built to train multilayer perceptron in the context of regression analysis, and contains many flexible functions to train feed forward neural networks.

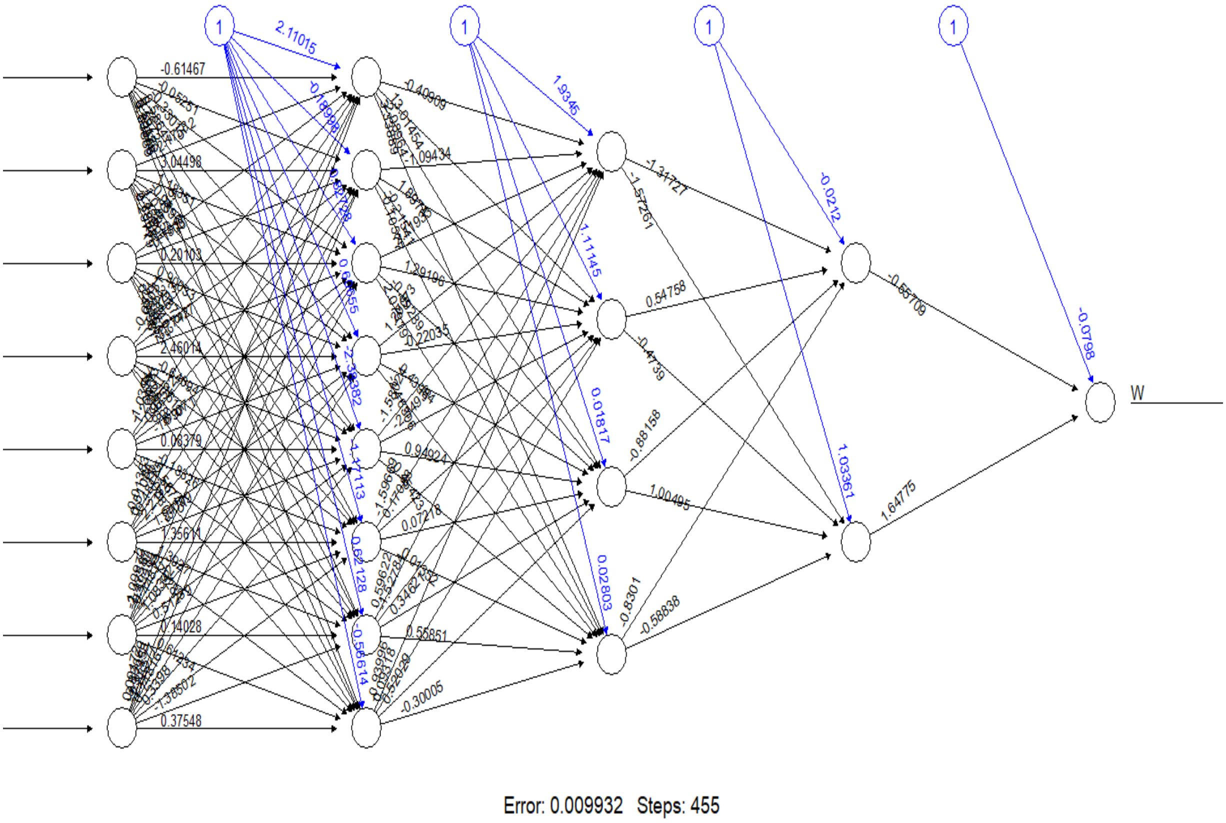


Figure 19 Neural network model obtained for 8 design variables

The iterations are run until the error function reaches below .01 which is the threshold. Figure 19 above shows the neural network model obtained from R based on the results obtained running optimisation with 8 variables using the STEEL-modeFRONTIER loop with total around 400 iterations were considered. Three hidden layers were considered with each containing 8,4 & 2 neurons respectively as shown in the figure. The first layer contain the input variables which are the beam scantlings and the single neuron in the last layer represent the response variable or the structural weight.

Based on this neural network model obtained, when tried to predict the structural weight for the database given in Appendix A4, the relative error was found to be within acceptable limits (maximum percentage of relative error obtained was around 0.2 %).

The R code used for building the above neural network is added in Appendix A6 for reference.

## 4.2 RSM Using CAESES

CAESES has inbuilt features for Response Surface Methodology with different algorithms. Response surface can be established by using DAKOTA Global optimization using CAESES. But since here we are concerned about establishing a Surrogate model using the results already available from the optimization process, a different approach is required.

[28] For this purpose the RSM feature available within CAESES has been used. Using this method, a response surface can be established easily without manual coding. The Result table is saved in the project folder and then by choosing appropriate algorithm with which response surface needs to be set up, surrogate models can be established. When the value of output variable or objective function is needed for a specific set of input variables, then the response surface already set up in CAESES using the initial database provide the result without needing to run the optimisation loop again and thus saving significant amount of time.
Also response surface to find the objective function can be established using more than one type of RSM algorithm like polynomial regression, kriging, radial basis functions, neural networks etc and then CAESES indicate the best algorithm/method which give the result with most reliable fit to the initial dataset. Then as a further step, the results obtained from RSM are compared with values provided by STEEL tool in order to verify accuracy of the results.
Based on the ‘export_model’ option in Dakota and running a polynomial quadratic surrogate model using the RSM feature available in CAESES tool, a polynomial second order empirical relation was established between the input variables and the output variable W. Below the polynomial second order relation established using the optimisation results obtained from STEEL-modeFRONTIER loop with 4 design variables for the RoRo hull is shown.

**Weight, W** = $4205.65 - 3.864 * x_1 + 5.874 * x_1^2 + 12.461 * x_1 x_2 + 6.480 * x_1 x_3 - 0.5429 * x_1 x_4 + 0.1929 * x_2 + 0.0003 * x_2^2 + 0.4970 * x_3 + 0.0031 * x_3^2 + 1.798 * x_3 x_4 + 0.1127 x_4$

$+ 0.0007 * x_4^2$ (14)

Where x1,x2,x3&x4 are the design variables which are the beam scantlings of deck 4 of RoRo hull . Using this polynomial relation, the weight of the main transverse frame was calculated and compared with the values given by the STEEL tool.

Below was the result obtained using polynomial quadratic global surrogate model available with DAKOTA-CAESES platform and the same was extracted using Export Model option. The results obtained using polynomial model and that given by the STEEL tool are found to be in good relation with relative difference as low as .002%.

Table 8 Comparison of results from RSM using CAESES & STEEL tool for the RoRo hull

| $H_W$ ( in m) ($x_1$) | $T_W$ ( in mm) ($x_2$) | $B_f$ ( in m) ($x_3$) | $T_f$ ( in mm) ($x_4$) | W From RSM | W from STEEL | Difference (%) |
|---|---|---|---|---|---|---|
| 0.9 | 10.75 | 0.4375 | 22.5 | 4453 | 4453 | -0.002 |
| 1.1 | 8.25 | 0.3125 | 17.5 | 4391.65 | 4392 | 0.008 |
| 1.15 | 11.375 | 0.28125 | 18.75 | 4439.03 | 4439 | -0.001 |
| 0.95 | 8.875 | 0.40625 | 23.75 | 4435.12 | 4435 | -0.003 |
| 0.85 | 10.125 | 0.34375 | 16.25 | 4387.19 | 4387 | -0.005 |
| 1.05 | 7.625 | 0.46875 | 21.25 | 4434.03 | 4434 | -0.001 |
| 1.075 | 11.0625 | 0.359375 | 24.375 | 4466.76 | 4467 | 0.005 |
| 0.834032 | 7.08765 | 0.31628 | 17.4508 | 4352.86 | 4353 | 0.003 |
| 0.823344 | 7.9113 | 0.319575 | 17.3752 | 4360.79 | 4361 | 0.005 |
| 0.9 | 7.38835 | 0.43878 | 22.5004 | 4416.05 | 4416 | -0.001 |

The polynomial quadratic surrogate model exported from CAESES is also added in Appendix A7. Also the entire result table showing feasible results taken from the STEEL-modeFRONTIER loop with 4 design variables with which the response surface was established, is added in Appendix A8 for reference.

# 5. APPLICATION TO ROPAX HULL

Testcase 2 considered was a RoPax hull which is a HOLISHIP Application case within WP7. Similar to STEEL-modeFRONTIER loop established for Testcase1 (RoRo hull), an optimization loop was established for Testcase2 (RoPax hull) as well. For this structural & load modeling of the RoPax hull was done by the Author based on the available information and then later the optimization loop was formed. Based on the results obtained from the optimization, feasibility was checked to establish polynomial regression based response surface using CAESES.

## 5.1 Structural Modeling And Description Of Load Cases

### 5.1.1 Available Data

A typical sketch showing details of web transverse frame was provided by CETENA, a design partner within WP7 of HOLISHIP Project.

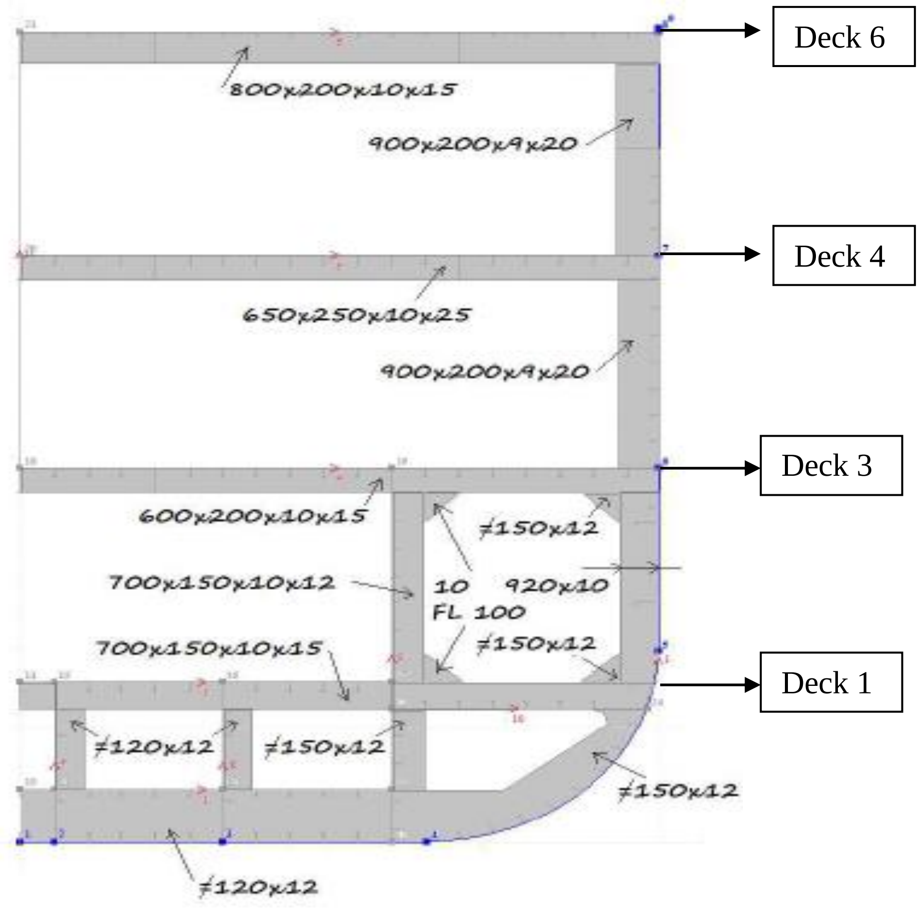


Figure 20 Typical sketch of Web Frame. (Source: CETENA)

The sketch indicated the dimensions of web frame to be considered while defining the beam scantlings using STEEL.

Also a model made with BV MARS tool showing position of nodes for the decks and longitudinal bulkheads was also available. Using these information, modeling was done in BV STEEL tool by the Author. The midship section is considered as symmetrical with respect to the centerline.

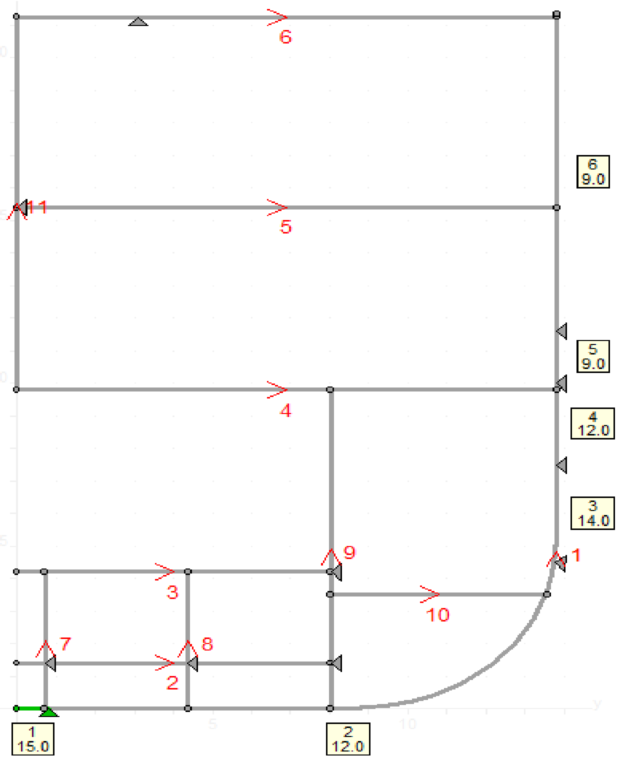


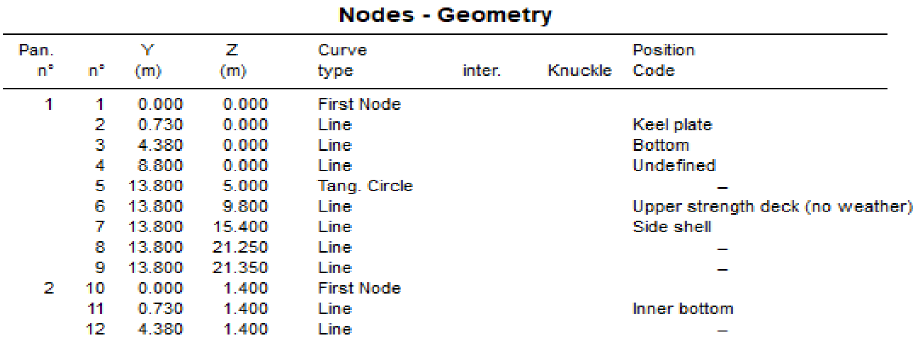
Figure 21 Midship section modeled in BV MARS ( Source : CETENA)

In the MARS tool, Panels like decks, outer shell, inner decks, longitudinal bulkheads etc are created connecting the nodes together. The above figure indicates plate thickness modeled for the different strakes of the outer shell panel. Similarly the thickness of attached plating of other panels are also extracted from the MARS model. It also indicates position and scantlings of longitudinal stiffeners in the model which are however not required within the scope of this project.

Basic vessel data of the RoPax hull is added in table

Table 9 Basic Vessel Data - RoPax Hull with Initial Configuration ( Source: BV MARS model)

| | |
|---|---|
| Scantling Length | 162.845 m |
| $B_{mld}$ | 27.6 m |
| Scantling Draft, T | 7.1 m |
| Block Coefficient | 0.6 |



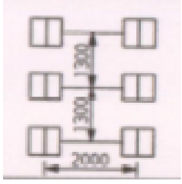
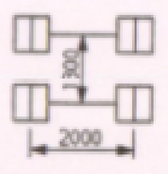
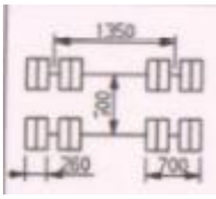
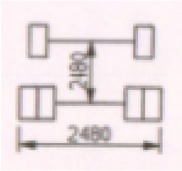
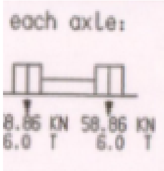
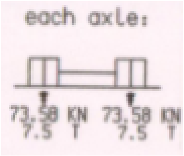
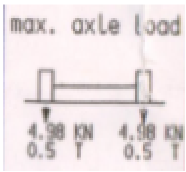
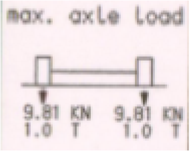
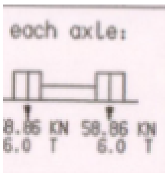
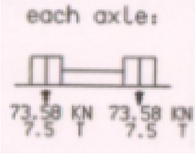
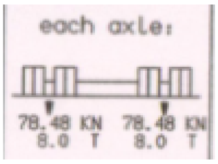
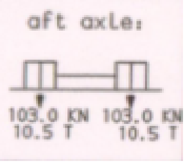
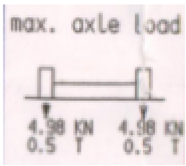
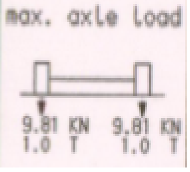
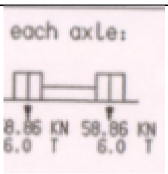
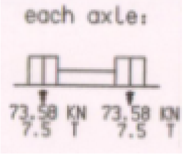
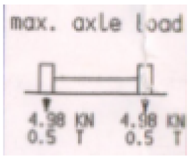
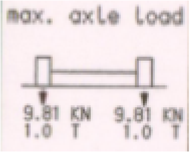
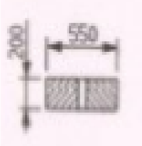
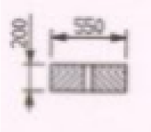
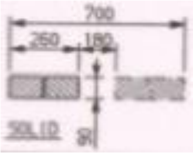
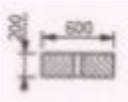
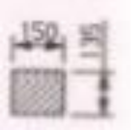
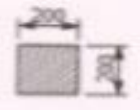
**Nodes - Geometry**

| Pan. n° | n° | Y (m) | Z (m) | Curve type | inter. | Knuckle | Position Code |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.000 | 0.000 | First Node | | | |
| | 2 | 0.730 | 0.000 | Line | | | Keel plate |
| | 3 | 4.380 | 0.000 | Line | | | Bottom |
| | 4 | 8.800 | 0.000 | Line | | | Undefined |
| | 5 | 13.800 | 5.000 | Tang. Circle | | | – |
| | 6 | 13.800 | 9.800 | Line | | | Upper strength deck (no weather) |
| | 7 | 13.800 | 15.400 | Line | | | Side shell |
| | 8 | 13.800 | 21.250 | Line | | | – |
| | 9 | 13.800 | 21.350 | Line | | | – |
| 2 | 10 | 0.000 | 1.400 | First Node | | | |
| | 11 | 0.730 | 1.400 | Line | | | Inner bottom |
| | 12 | 4.380 | 1.400 | Line | | | – |

Figure 22 Sample Node Positions extracted from MARS model (Source : CETENA)

The distribution of wheeled cargos onboard is indicated in below table.

Table 10 Details of Wheeled loads (Source : NTUA)

| **Deck** | **Road Trailor Max. 45 Ton** | | **MAFI Trailor Payload 40 Ton** | **Tug Master Max. 26 Ton** | **Private Car Max. 1.7 Ton** | **Private Car Max. 3.5 Ton** |
|---|---|---|---|---|---|---|
| | **Triple Axle** | **Double Axle** | | | | |
| |  |  |  |  |  |  |
| **Deck1** |  |  | | |  |  |
| **Deck3** |  |  |  |  |  |  |
| **Deck4** |  |  | | |  |  |
| **Tyre Print** |  |  |  |  |  |  |

As indicated the Table, wheeled loads are distributed in Deck1, Deck 3 & Deck4. A simple sketch showing these distribution of wheeled loads were provided by National Technical University of Athens (NTUA) who are also one of the design partner within WP7 of HOLSHIP project. In the table, type of vehicles loaded on each decks together with axle load details and tyre print dimensions are shown.

Passenger area is located at Deck 6 as noted from the preliminary General Arrangement drawing made available for this project. Hence Accommodation loads are assumed at Deck 6 according to BV Class rules applicable.

### 5.1.2 Structural Modeling of the Main Transverse Frame using BV STEEL

For modeling the main transverse frame in STEEL tool, the scantlings of web and flange of all beam sections were taken in accordance with the typical web frame sketch shown in Figure 20.

The scantlings of attached plating together with longitudinal stiffeners are usually modeled with BV MARS tool. Hence scantlings mentioned in BV MARS model for the attached plate were used while defining the beam types within the STEEL tool.

Taking the node positions indicated in the MARS model as a reference, and referring to the typical web frame sketch provided, nodes were modeled in STEEL tool. Then nodes are connected to form beams and beam types were defined in accordance with provided data and based on BV Class rules applicable.

For a ship with rule length L, if $120 < L \leq 170$, then structural modeling of primary supporting members including transverse frames need to be modeled with a 3D beam structural model like as done in STEEL tool. Hence structural modeling was done according to applicable rules specified for 3D structural models in the BV Rules.

The grade of material of construction is assumed as Steel grade AH36 with a minimum specified Yield stress, $R_{eH}$= 355 MPa similar to the RoRo hull.

[29] The structural model to represent the main transverse frame is to be modeled with the plating to which it is attached according to BV Rules, Pt B, NR 467, Ch 7, App 1, [3.1]

Also the net scantlings considered while doing the modeling according to BV Rules, Pt B, NR 467, Ch 7, App 1, [3.1.2]

According to the BV Class rules applicable, Generally nodes are given in the 3D Beam model to represent below main members for the analysis of Primary supporting members like main transverse frame modeled here using STEEL tool;

Ramps and supporting members are not considered now. Even though brackets are not modeled, rigid end beams are considered to connect ends of the various primary supporting members, such as floors and side vertical primary supporting members according to the BV rules applicable(Pt B, Ch 7, App 1) and as per figure 20.

The net thickness of plating which forms the webs of primary supporting members is to be not less than the value obtained, in mm, from the following formulae according to BV Rules NR 467, Ch 7, Sec 3 [2.1]

$$\mathbf{t_{MIN} = 3{,}7 + 1{,}8 * k^{1/2} \text{ for } L \geq 120 \text{ m}} \qquad \mathbf{(15)}$$

where k is the material factor defined as per Pt B, Ch 4, Sec 1, [2.3],for steel which depends on the minimum specified yield stress $R_{eH}$

Since $R_{eH}$= 355 MPa in this case for the material of construction considered, Material Factor, k = 0.72
Hence $t_{MIN}$ = 5.23 mm
So the minimum thickness of web of any beam section to be modeled on the main transverse frame in STEEL tool need to be more than $t_{MIN}$ as obtained.

For Deck 4 &Deck6, in order to avoid large unsupported beam span, an additional node is considered at 6.8 m off centerline assuming a pillar or suspension deck support at that point similar to the wheeled load decks of RoRo hull STEEL model .Apart from these two nodes, all other nodes are modeled according to the BV MARS model provided by CETENA as mentioned earlier.

Preliminary structural model with Beam numbers are shown in Figure 23. Bema types assigned to each of the beams are also indicated with reference to table 13.

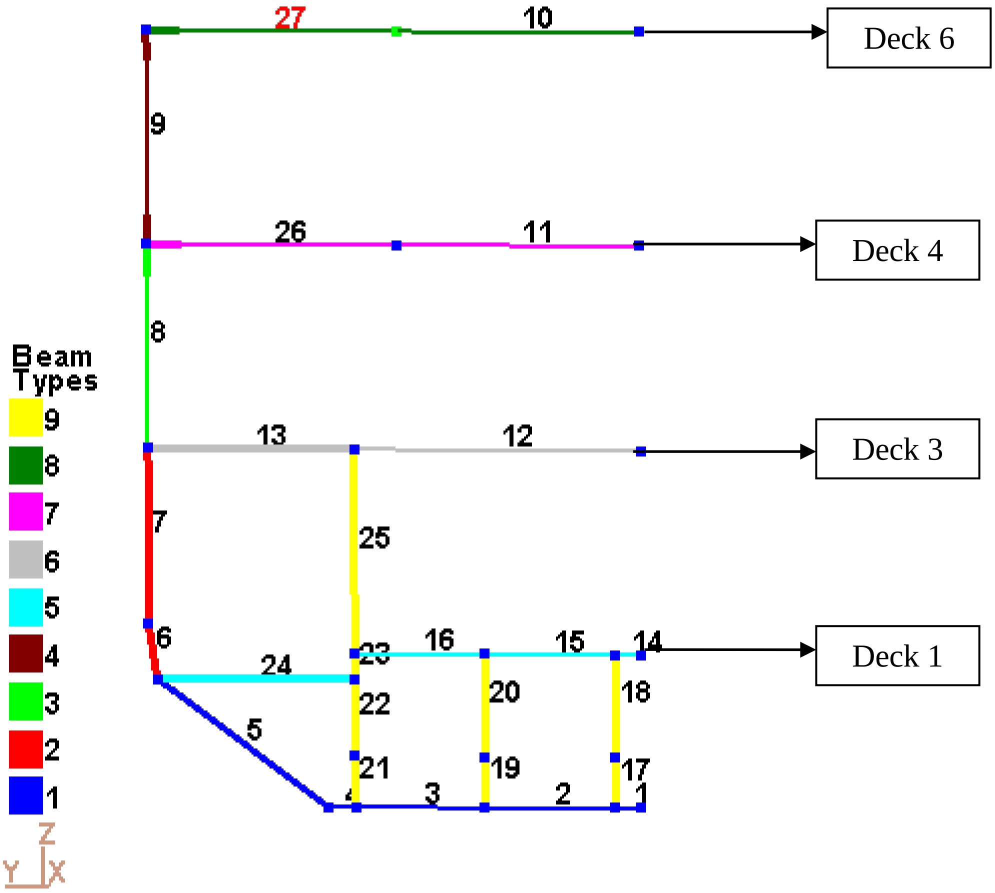


Figure 23 RoPax STEEL model with beam numbers & beam types indicated

Figure 24 below shows the 3D view of final structural model for the RoPax hull as per the given details. I sections are considered for all the beams with dimensions as shown in Table 13 for all the beams modeled.

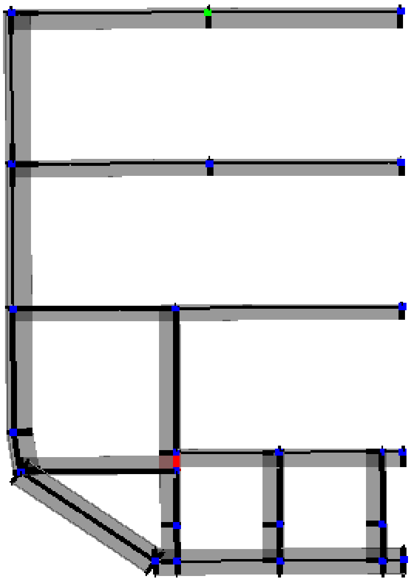
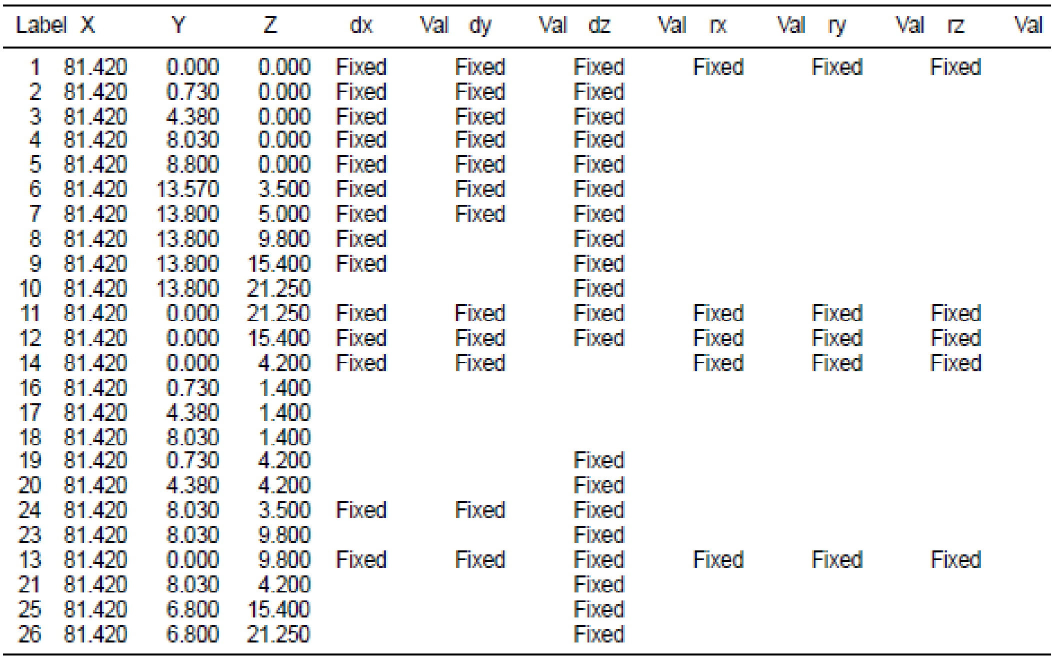


Figure 24 3D view of RoPax STEEL model

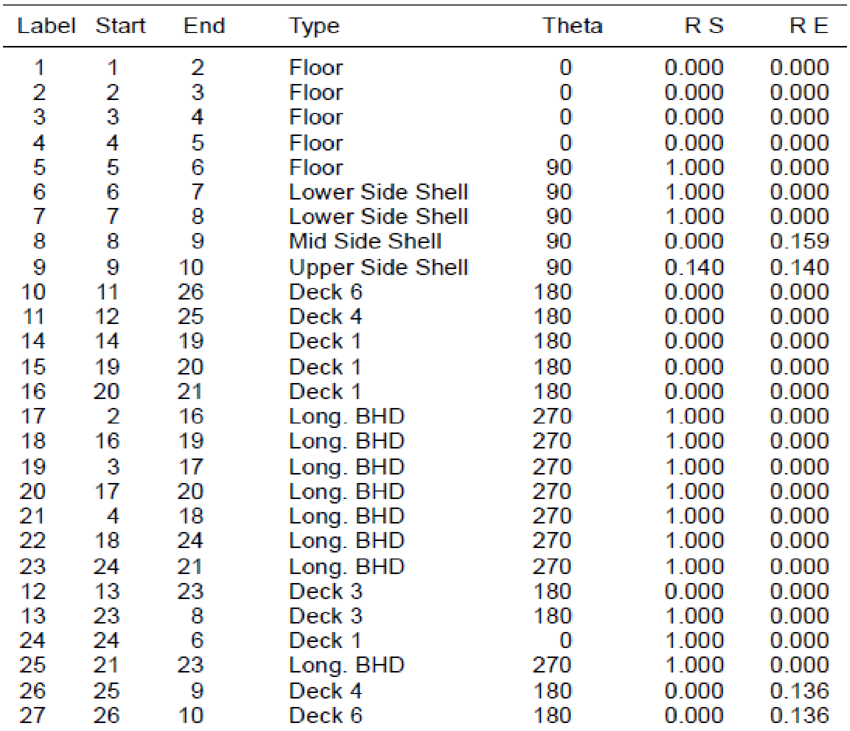
Table 11 Details of Node Positions extracted from RoPax STEEL model



| Label | X | Y | Z | dx | Val | dy | Val | dz | Val | rx | Val | ry | Val | rz | Val |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 81.420 | 0.000 | 0.000 | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | |
| 2 | 81.420 | 0.730 | 0.000 | Fixed | | Fixed | | Fixed | | | | | | | |
| 3 | 81.420 | 4.380 | 0.000 | Fixed | | Fixed | | Fixed | | | | | | | |
| 4 | 81.420 | 8.030 | 0.000 | Fixed | | Fixed | | Fixed | | | | | | | |
| 5 | 81.420 | 8.800 | 0.000 | Fixed | | Fixed | | Fixed | | | | | | | |
| 6 | 81.420 | 13.570 | 3.500 | Fixed | | Fixed | | Fixed | | | | | | | |
| 7 | 81.420 | 13.800 | 5.000 | Fixed | | Fixed | | Fixed | | | | | | | |
| 8 | 81.420 | 13.800 | 9.800 | Fixed | | | | Fixed | | | | | | | |
| 9 | 81.420 | 13.800 | 15.400 | Fixed | | | | Fixed | | | | | | | |
| 10 | 81.420 | 13.800 | 21.250 | | | | | Fixed | | | | | | | |
| 11 | 81.420 | 0.000 | 21.250 | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | |
| 12 | 81.420 | 0.000 | 15.400 | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | |
| 14 | 81.420 | 0.000 | 4.200 | Fixed | | Fixed | | | | Fixed | | Fixed | | Fixed | |
| 16 | 81.420 | 0.730 | 1.400 | | | | | | | | | | | | |
| 17 | 81.420 | 4.380 | 1.400 | | | | | | | | | | | | |
| 18 | 81.420 | 8.030 | 1.400 | | | | | | | | | | | | |
| 19 | 81.420 | 0.730 | 4.200 | | | | | Fixed | | | | | | | |
| 20 | 81.420 | 4.380 | 4.200 | | | | | Fixed | | | | | | | |
| 24 | 81.420 | 8.030 | 3.500 | Fixed | | Fixed | | Fixed | | | | | | | |
| 23 | 81.420 | 8.030 | 9.800 | | | | | Fixed | | | | | | | |
| 13 | 81.420 | 0.000 | 9.800 | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | | Fixed | |
| 21 | 81.420 | 8.030 | 4.200 | | | | | Fixed | | | | | | | |
| 25 | 81.420 | 6.800 | 15.400 | | | | | Fixed | | | | | | | |
| 26 | 81.420 | 6.800 | 21.250 | | | | | Fixed | | | | | | | |

Table 11 indicates the node positions within the RoPax STEEL model. dx, dy& dz indicate the translational degree of freedom of the nodes while rx, ry & rz indicate the rotational degree of freedom with reference to the local coordinate axes system as described earlier.

Table 12 Details of beams extracted from RoPax STEEL model



| Label | Start | End | Type | Theta | R S | R E |
|---|---|---|---|---|---|---|
| 1 | 1 | 2 | Floor | 0 | 0.000 | 0.000 |
| 2 | 2 | 3 | Floor | 0 | 0.000 | 0.000 |
| 3 | 3 | 4 | Floor | 0 | 0.000 | 0.000 |
| 4 | 4 | 5 | Floor | 0 | 0.000 | 0.000 |
| 5 | 5 | 6 | Floor | 90 | 1.000 | 0.000 |
| 6 | 6 | 7 | Lower Side Shell | 90 | 1.000 | 0.000 |
| 7 | 7 | 8 | Lower Side Shell | 90 | 1.000 | 0.000 |
| 8 | 8 | 9 | Mid Side Shell | 90 | 0.000 | 0.159 |
| 9 | 9 | 10 | Upper Side Shell | 90 | 0.140 | 0.140 |
| 10 | 11 | 26 | Deck 6 | 180 | 0.000 | 0.000 |
| 11 | 12 | 25 | Deck 4 | 180 | 0.000 | 0.000 |
| 14 | 14 | 19 | Deck 1 | 180 | 0.000 | 0.000 |
| 15 | 19 | 20 | Deck 1 | 180 | 0.000 | 0.000 |
| 16 | 20 | 21 | Deck 1 | 180 | 0.000 | 0.000 |
| 17 | 2 | 16 | Long. BHD | 270 | 1.000 | 0.000 |
| 18 | 16 | 19 | Long. BHD | 270 | 1.000 | 0.000 |
| 19 | 3 | 17 | Long. BHD | 270 | 1.000 | 0.000 |
| 20 | 17 | 20 | Long. BHD | 270 | 1.000 | 0.000 |
| 21 | 4 | 18 | Long. BHD | 270 | 1.000 | 0.000 |
| 22 | 18 | 24 | Long. BHD | 270 | 1.000 | 0.000 |
| 23 | 24 | 21 | Long. BHD | 270 | 1.000 | 0.000 |
| 12 | 13 | 23 | Deck 3 | 180 | 0.000 | 0.000 |
| 13 | 23 | 8 | Deck 3 | 180 | 1.000 | 0.000 |
| 24 | 24 | 6 | Deck 1 | 0 | 1.000 | 0.000 |
| 25 | 21 | 23 | Long. BHD | 270 | 1.000 | 0.000 |
| 26 | 25 | 9 | Deck 4 | 180 | 0.000 | 0.136 |
| 27 | 26 | 10 | Deck 6 | 180 | 0.000 | 0.136 |

Table 12 represent the details of beam modeled showing the beam type associated to each beam, orientation angle (Theta) and the rigidity at start and end positions of beam span.

Each beams are to be defined with a beam type which determine the scantlings of beam sections. In this model, standard I sections are chosen as the beam types for all beams as per the data available from the designer as shown in Figure 20.

Table 13 below lists different beam types defined and shows the material of construction together with the scantlings.

$B_f$, $B_p$ represent the width of flange and attached plating while $H_w$ indicate the web height of each beam types defined. Similarly $T_f$, $T_w$ & $T_p$ represent the thickness of flange, web& attached plating respectively.

Based on the beam scantlings defined, STEEL tool calculates the beam characteristics such as area of cross section, moment of inertia etc which are required to calculate the weight and stress values for the beams.

Table 13 Details of Beams Types from RoPax STEEL Model

| Beam Type | Section Type | Material | $B_f$ (in m) | $H_w$ (in m) | $B_p$ (in m) | $T_f$ (in mm) | $T_w$ (in mm) | $T_p$ (in mm) |
|---|---|---|---|---|---|---|---|---|
| Floor | I | AH36 | 2.235 | 1 | 2.235 | 14 | 12 | 12 |
| Lower Side shell | I | AH36 | 0.2 | 0.920 | 2.235 | 15 | 10 | 8 |
| Mid Side shell | I | AH36 | 0.2 | 0.900 | 2.235 | 20 | 9 | 9 |
| Upper Side shell | I | AH36 | 0.2 | 0.900 | 2.235 | 20 | 9 | 9 |
| Deck 1 | I | AH36 | 0.15 | 0.700 | 2.235 | 15 | 10 | 10 |
| Deck 3 | I | AH36 | 0.2 | 0.600 | 2.235 | 15 | 10 | 12 |
| Deck 4 | I | AH36 | 0.25 | 0.650 | 2.235 | 25 | 10 | 12 |
| Deck 6 | I | AH36 | 0.2 | 0.800 | 2.235 | 15 | 10 | 12 |
| Long. BHD | I | AH36 | 0.15 | 0.700 | 2.235 | 12 | 10 | 12 |

### 5.1.3 Load Modeling

Generally Local loads and Global hull girder loads are to be considered for load modelling and structural analysis of transverse frames. However as mentioned earlier, Hull girder loads are determined by the MARS loop as mentioned earlier. Hence only local loads are considered in this project.

[29] Generally below load cases are to be considered for doing the structural analysis when analysed through 3D beam models as mentioned in BV Rules NR 467, Pt B, Ch 5, Sec 4.

- Loadcases at Upright Conditions : Load case a & Load case b. (ie, when ship is at rest or having surge, heave or pitch motions)
- Loadcases at Inclined Conditions: Load case c & Load Case d ( ie, when ship is having sway, roll and yaw motions)

**Load case a &b :** Load case a is considered when ship is at rest and encountered with a wave which produces a relative motion of the sea waterline (both positive and negative) which is symmetric on both sides. For Load case b, it is considered that heave and pitch motions are induced as well.

Hence still water and wave pressure loads are to be considered for load case a while inertial loads will also be applicable in case of load case b.

**Load case c &d :** As mentioned earlier, these load cases are considered when encountered with a wave that induces sway, roll and yaw motions and also a relative motion of the sea waterline which is anti-symmetric on the ship sides. Hence still water loads, wave pressure loads and inertial loads will need to be considered for these load cases. Also when a wave crest is considered at one side of ship, there will have negative sea waterline at the other side of ship in these load cases.

Hence based on whether the wave causes positive or negative sea waterline at the ship side under consideration, these load cases are further divided as below;

- Load case a+: Load case a when produces a positive relative motion of sea waterline with a relative increase in height h1 from the still waterline. ( ie, when encountered with a wave crest)

- Load case a- : Load case a when produces a negative relative motion of sea waterline with a relative decrease in height h1 from the still waterline. ( ie, when encountered with a wave trough)

- Load case b : Load case b when produces a positive relative motion of sea waterline with a relative increase in height 0.5h1 from the still waterline.

- Load case c+ : Load case c when produces a positive relative motion of sea waterline with a relative increase in height h2 from the still waterline. ( ie, when encountered with a wave crest at the ship side under consideration)

- Load case c-: Load case c when produces a negative relative motion of sea waterline with a relative decrease in height h2 from the still waterline. ( ie, when encountered with a wave trough at the ship side under consideration)

- Load case d+: Load case d when produces a positive relative motion of sea waterline with a relative increase in height 0.5h2 from the still waterline. ( ie, when encountered with a wave crest at the ship side under consideration)

- Load case d-: Load case d when produces a negative relative motion of sea waterline with a relative increase in height 0.5h2 from the still waterline. ( ie, when encountered with a wave trough at the ship side under consideration)

Values of h1, h2 are defined in later sections.

Also below types of local loads are to be considered as per BV Class rules NR 467 Pt B, Ch.7

- the still water sea pressure.
- the still water internal loads for the various types of cargoes and for ballast.
- the wave pressure, for each load case “a”, “b”, “c” and “d” mentioned earlier.
- the inertial loads, for the various types of cargoes and for ballast, and for each load case “a”, “b”, “c” and “d”.

But as the availability of detailed load distribution of ballast and other cargo load details were limited at this design stage, only below major types of local loads like sea pressure loads and wheeled cargo loads are considered for the structural analysis at design draft within the scope of this thesis. Also since passenger area is located at Deck 6, accommodation loads as per the BV Rules applicable are considered at Deck 6.

### a) Sea Pressure Loads

Sea pressure loads consists of loads due to Still water pressure and Wave pressure.

**Still Water Pressure :**

As mentioned in BV Class rules NR 467, Pt B, Ch 5, Sec 5, Still water distribution is shown in figure 28 and it is calculated according to below relation;

Still water pressure ,$\mathbf{P}_S = \rho g (T_1 - z)$ , on points at or below waterline **(16)**

$$P_S = 0 \qquad \text{, at points above waterline} \qquad \mathbf{(17)}$$

Where;

$\rho$ : is the sea water density taken as 1.025 t/m$^3$

$T_1$ : is the draught in m.

z : is the vertical height measured from ship's base line

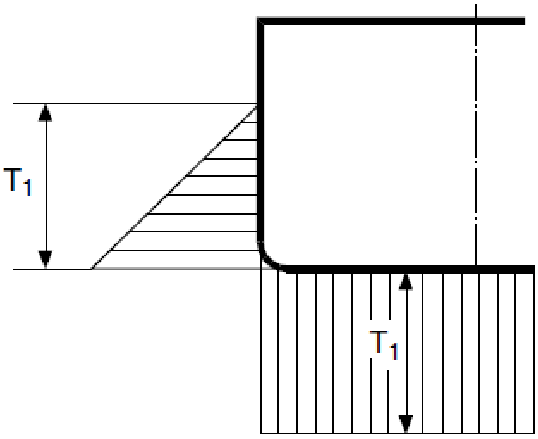


Figure 25Still water pressure distribution (Source:[29] )

Wave pressure is also calculated according to BV Class rules NR 467, Pt B, Ch 5, Sec 5 for each load cases.

**<u>Wave Pressure for Load Cases a &b ( in kN/ m$^2$ ):</u>**

Table 14 Wave Pressure on sides & bottom for Load Cases a &b [29]

| Location | Wave Pressure, $P_W$ ( in kN/ m$^2$) | |
|---|---|---|
| | With Wave Crest | With Wave Trough |
| At bottom & Sides below waterline | $\rho\, g\, h\, exp^{\frac{-2\pi(T_1-z)}{L}}$ | $-\rho\, g\, h\, exp^{\frac{-2\pi(T_1-z)}{L}}$ |
| At above waterline | $\rho\, g\, (T_1+h-z)$, without being taken less than $0.15\, \varphi 1\, \phi 2\, L$ | 0 |

Table 14 shows the empirical relation to find wave pressure at bottom and sides as per defined in BV Class rules as mentioned earlier.

Where ;

$h = C_{F1}\, h_1$ , with $C_{F1} = 1$ for load case a and $C_{F1} = 0.5$ for load case b **(18)**

$h_1 = 0{,}42\ n\ C\ (C_B + 0{,}7)$ as per BV Rules NR 467, Pt B Ch 5, Sec 3. **(19)**

n = 1. (Navigation coefficient as per Pt B, Ch 5, Sec 1, [2.6] for unrestricted navigation)

$$C = 10.75 - \left[\frac{(300-L)}{100}\right]^{1.5} \quad \text{for } 90 < L < 300 \qquad \textbf{(20)}$$

Values of $\varphi_1$& $\varphi_2$ are considered according to BV Rules applicable.

L is considered as 162.845 m

Substituting these values, wave pressure was calculated accordingly.

**Wave Pressure for Load Cases c &d :**

Similarly wave pressure was calculated using the empirical relation as defined in below table for load cases c &d as well. Only loads in z direction are considered in the present STEEL model. In order to consider conservative loading condition, only loads at $y \geq 0$ are considered.

Table 15 Wave Pressure on sides & bottom for Load Cases c &d [29]

| Location | Wave Pressure, $P_W$ ( in kN/ m$^2$) |
|---|---|
| | $y \geq 0$ |
| At bottom & Sides below waterline | $\beta\ C_{F2}\rho g \left[ \frac{y}{B_W} h_1\ exp^{\frac{-2\pi(T_1-z)}{L}} + A_{Ry}\ exp^{\frac{-\pi(T_1-z)}{L}} \right]$ |
| At above waterline | Not being taken less than $0.15\ \varphi_1\ \varphi_2\ L$ |

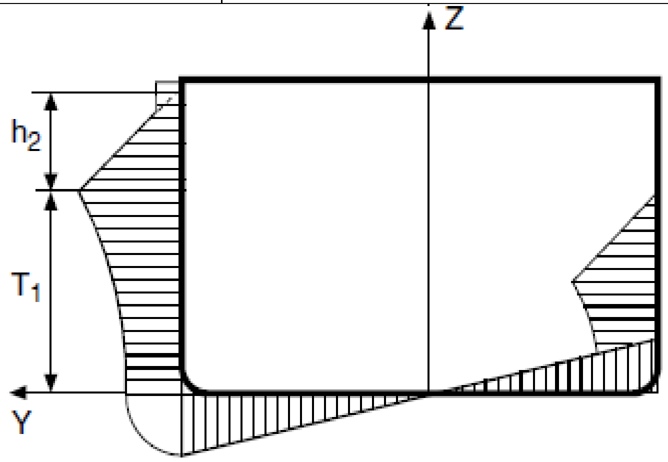


Figure 26 Wave pressure distribution for load case c (Source: [29] )

Where;

$C_{F2}$ is the combination factor. $C_{F2} = 1$ for load case c and $C_{F2} = 0.5$ for load case d
$\beta$ is taken as 1 as per the BV Rules applicable.
$B_w = 27.6$ m (Moulded breadth) .
y is considered in accordance with above figure from centre line.

$A_R = 0.35$, is the Roll Amplitude & is considered as per BV Rules Pt B Ch 5, Sec 3 [2.4].

Hence using these relations, wave pressure for all beams were calculated. Depending on the node coordinates of beam under consideration, y & z were taken.

Finally total loads due to sea pressure ,$\mathbf{F_{SP}}$ at each beam is calculated based on below relation;

$$\mathbf{F_{SP}\ (in\ kN/m) = (P_{SW} + P_W)*S} \qquad \mathbf{(21)}$$

Where S is the spacing of the main transverse frames considered. S is considered as 3 times the normal frame spacing like as considered in the RoRo hull . In order to model as linear load in the STEEL model, sea pressure is multiplied with the spacing of main transverse frames. Since normal frame spacing is 0.745 m as per taken from the BV MARS model provided,
S = 3* .745 m
= 2.235 m.

In order to compare the load distribution between load case a+ and load case c+ which should represent the critical load cases, three locations on the STEEL model were considered.

With reference to Figure 23,

- Point 1: At beam 3, 6.9 m off centreline,( hence y = 6.9,z =0)
- Point 2: At beam 6, 13.57 m off centreline,( hence y = 13.57,z =3.5)
- Point 3: At beam 3, 6.9 m off centreline,( hence y = 13.8,z =15.4)

Table 16 Comparison of Loads due to Sea Pressure

| | Total Loads due to Sea pressure $\mathbf{F_{SP}}$ ( kN /m) | |
|---|---|---|
| | Load Case a+ | Load Case c+ |
| Point 1 | 249.14 | 229.28 |
| Point 2 | 183 | 230 |
| Point 3 | 40.94 | 40.94 |

Since point 3 is above waterline, the loads are calculated considering the minimum limit requirement as shown in Table 14 &15

### b) Wheeled Loads

[29] The loads were calculated in accordance with BV Class rules NR 467, PtB,Ch5,Sec6 assuming that forces transmitted through the tyres are comparable to the pressure uniformly distributed on the tyre print and these forces may be considered as concentrated in the tyre print centre. Based on this, the loads due to wheeled cargo acting on each of the beams were calculated as explained.

The still water and inertial forces transmitted to the hull structures are determined on the basis of the forces obtained, in kN using the axle load data available ( shown in Figure 10).

**The total load due to wheeled cargo at the beams** $\mathbf{F_{wh}= \gamma_{S2}F_S+ \gamma_{W2}F_{w,z}}$ **(22)**

Where;

$F_S$ : is the Still water loads due to the wheeled cargo

$F_{w,z}$ : is the Inertial loads due to the wheeled cargo in the z direction

$\gamma_{S2}$ = 1( Partial safety factor for the Still water loads as per BV Rules Pt B, Ch 7, Sec 3)

$\gamma_{W2}$ = 1.10 ( Partial safety factor for the wave pressure as per BV Rules Pt B, Ch 7, Sec 3)

$\mathbf{F_S} = \mathbf{Mg}$ where M is the mass in tonnes & $g = 9.81\ m/s^2$ **(23)**

$M = \frac{Q_A}{n_W}$ , $Q_A$ is the axle load in tonnes &

$n_W$ is the number of wheels in the axle considered

For Load Case a &b, $\mathbf{F_{w,z}} = \alpha\ M\ a_{z1}$ **(24)**

For Load Case c &d $\mathbf{F_{w,z}} = \alpha\ M\ C_{FA}\ a_{z2}$ **(25)**

Where; $\alpha$ =0.5 in general

$C_{FA}$ is the combination factor as per BV rules applicable. $C_{FA}$ = 0.7 for Load Case c &

$C_{FA}$ = 1 for Load Case d.

$a_{z1}$ , $a_{z2}$ are the reference values of vertical acceleration as per BV Rules NR 467, Pt B, Ch 5, Sec 3.

$$a_{z1} = \sqrt{a_H{}^2 + \alpha_p{}^2 K_X L^2} \qquad \textbf{(26)}$$

$$a_{z2} = \sqrt{0.25\ a_H{}^2 + \alpha_R{}^2 y^2} \qquad \textbf{(27)}$$

$a_H$(heave amplitude) $=a_B * g$ , where : **(28)**

$a_B$= n(0.76F+ 1.875 $\frac{h_W}{L}$; $h_W$ is the wave parameter calculated as per BV RulesPt B,Ch 5,Sec3 Similarly values for $\alpha_p$ (Pitch acceleration in rad/s$^2$), $\alpha_R$(Roll acceleration in rad/s$^2$) are calculated as per BV Rules BV Rules NR 467, Pt B, Ch 5, Sec 3.

Accordingly total loads due to wheeled cargo was calculated using equation (22) for all the beams where the wheeled cargo is carried.

[9] For calculating the axle loads, it was assumed that a single lane width is 2.9m.
As per table 10, wheeled cargo are placed at Deck1, Deck3 & Deck4.

Hence by considering single lane width as 2.9m, 4 lanes of wheeled cargo were considered to be loaded at Deck 3 & Deck 4 similar to as shown in figure 27 .Two lanes were considered at Deck1 as well.

Also in order to consider conservative loading conditions, it was assumed that all the four lanes in Deck3 are of MAFI Trailers while in Deck1 & Deck4 Double Axle Road Trailers were considered while considering the axle loads and number of wheels.

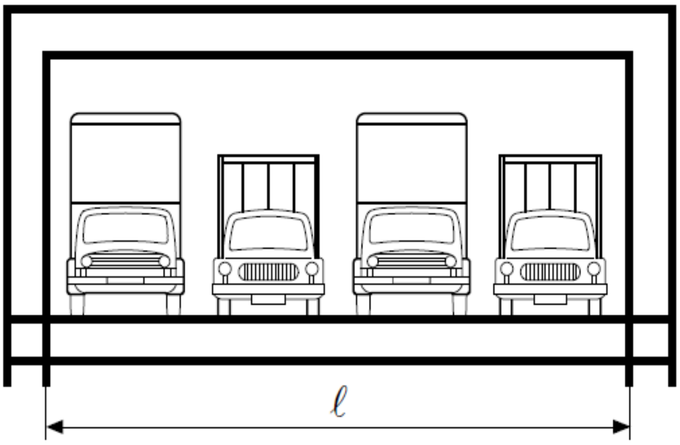


Figure 27 Wheeled cargo distribution with 4 lanes (Source: BV Class Rules NR 467 [29] )

Hence instead of different types of trailers as shown in above figure, it was assumed that all are of MAFI Trailers at Deck3 while triple axle Road Trailers were considered on Deck 1& Deck4.

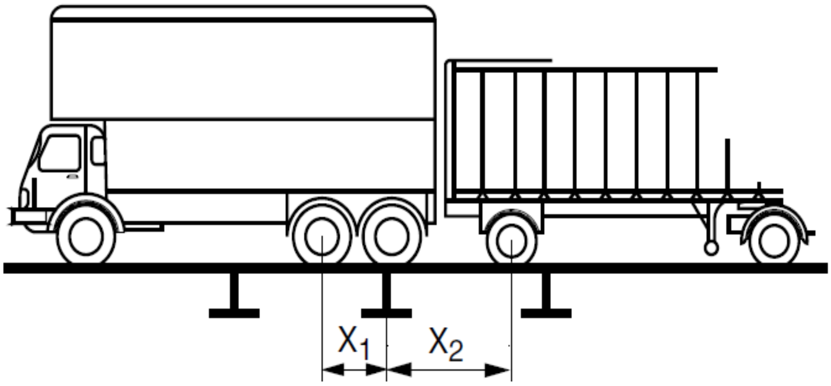


Figure 28 Wheeled cargo distribution on attached plating (Source: BV Class Rules NR 467 [29] )

Also for considering critical loading conditions on the main transverse frame, it was assumed that three axles will be placed at the attached plating similar to as shown in figure 28.

Hence while calculating the load at Deck 3, three axles of MAFI Trailers were considered similar to as shown in Figure 27 above and those loads were considered as acting on the beams coming on deck3. Same procedure was adopted for the remaining decks as well which can be considered as conservative design.

Finally considering all these, wheeled cargo loads were calculated on all the beams as per (22).

Table 17 Loads due to Wheeled Cargoes on RoPax Hull

| | Deck 3 ( With MAFI Trailers) | | | Deck 4 & Deck1 (With Double Axle Road Trailers) | | |
|---|---|---|---|---|---|---|
| | $F_S$ (in kN) | $F_{w,z}$ (in kN) | $F_{wh}$ (in kN) | $F_S$ (in kN) | $F_{w,z}$ (in kN) | $F_{wh}$ (in kN) |
| Load Case a | 78.48 | 0 | 235.84 | 73.58 | 0 | 220.73 |
| Load Case b | 78.48 | 8.91 | 264.83 | 73.58 | 8.35 | 248.78 |
| Load Case c | 78.48 | 2.64 | 244.16 | 73.58 | 2.48 | 228.90 |
| Load Case d | 78.48 | 3.78 | 247.90 | 73.58 | 3.54 | 232.41 |

Table 17 shows the loads to be modelled at the Deck1, Deck3 & Deck 4 beams as described earlier. $F_S$ & $F_{w,z}$ are calculated directly according to equations (23),(24) & (25) accordingly without adding the partial safety factors.

The total wheeled load $F_{wh}$ is calculated considering the partial safety factors as per (22) and also the number of axles considered at the beams (3 No.) is also multiplied to this value in order to get the final wheeled load indicated in the table 17.

### c) Accommodation Loads at Deck 6

As per the preliminary GA provided for the RoPax hull by one of the design partner within WP7 of HOLISHIP project, it was noted that large passenger space is located at Deck 6. Hence corresponding loads were considered as per BV Class Rules applicable.

Still water pressure

Still water pressure acting on the deck is taken from Pt B, Ch 5, Sec 6.[7] considering maximum deck pressure possible.

Hence Still water pressure, $P_S$ = 5 kN/m2

Inertial Pressure :

There are no inertial pressure applicable for Load Case a.

Inertial Pressure for Load Case b , $P_w = \frac{P_S\, a_{z1}}{g}$ **(29)**

Also inertial pressure can be disregarded for load cases on inclined conditions as well according to the BV Class rules applicable. Hence only still water pressure is considered as applicable for load case c&d.

Table 18 Accommodation Loads on RoPax Hull

| Load Case | Deck 6<br>Accommodation Loads | | |
|---|---|---|---|
| | $P_S$ (in kN/m$^2$) | $P_w$ (in kN/m$^2$) | $F_{accom}$ (in kN/m) |
| Load Case a | 5 | 0 | 11.175 |
| Load Case b | 5 | 1.13 | 13.97 |
| Load Case c | 5 | 0 | 11.175 |
| Load Case d | 5 | 0 | 11.175 |

Table 18 shows the loads due to accommodation Strill water & inertial pressure at Deck6.

$F_{accom}$ in kN/m = $(\gamma_{s2} P_S + \gamma_{w2} P_w)*S$ **(30)**

Where $\gamma_{s2}$, $\gamma_{w2}$ are the artial safety factors and S is the spacing of the main transverse frame as mentioned earlier. (30) calculates the linear accommodation loads in kN/m accordingly which is applied to beams on Deck 6.

### d) Final Load Distribution

Comparing the different load cases and loads obtained, it was noted that Load Case a+ represent one of the critical load cases and hence Load Case a+ was only included in the STEEL model for the RoPax at this stage and to establish the optimization loop using CAESES at later stages.

All the values for loads obtained in z direction were applied to corresponding beams and the distribution obtained from the STEEL tool is represented below for reference for load Case a+.

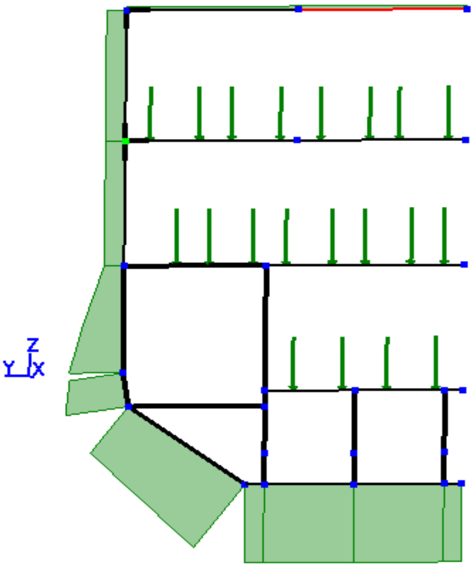


Figure 29 Load distribution in RoPax hull for Load Case a+

A table showing the values of loads applied to each beam for load case a+ is added in Appendix A3

Also below figure shows the overall stress distribution obtained from the STEEL model with final loading conditions applied for the initial configuration considered for the beam scantlings. The overall stress is found to reach slightly above the limit for yield check in this case.

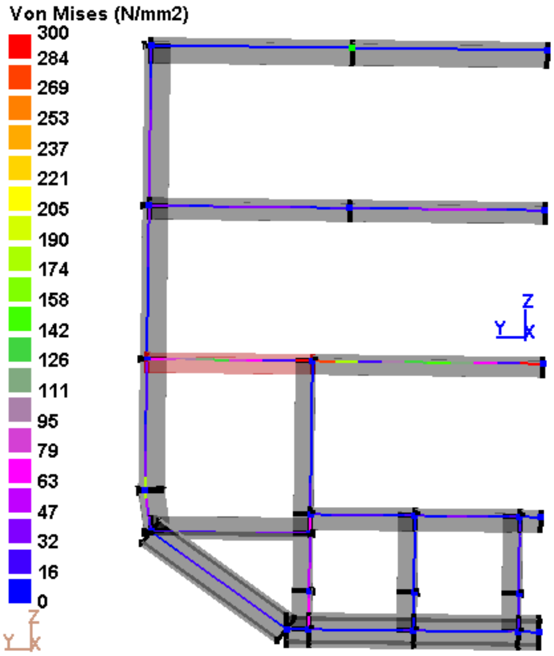


Figure 30 Load distribution in RoPax hull for Load Case a+

## 5.2 Setting Up The Optimization Work Flow

Based on the structural and load modeling done with STEEL, an optimization loop was established using CAESES tool by coupling STEEL tool in batch mode for WP7 application similar to as done earlier for RoRo hull using modeFRONTIER.

### 5.2.1 About CAESES® Tool

[30] CAESES® (Name stands for CAE System Empowering Simulation) is a software developed by FRIENDSHIP SYSTEMS AG. The tool is suited for fully-automated workflows, such as parameter studies and shape optimizations with CFD (Computational Fluid Dynamics). CAESES allows to create and control parametric geometrical models and also to couple external software for running several design iterations for finding optimum shape and performing design analysis. CAESES was used as the optimization platform for WP7 application using the RoPax STEEL model during the Author's internship at FRIENDSHIP SYSTEMS.

### 5.2.2 Setting up the STEEL- CAESES optimization loop

Using the feature called Software Connector available within CAESES, STEEL tool was coupled into CAESES for doing the structural analysis and running design iterations.

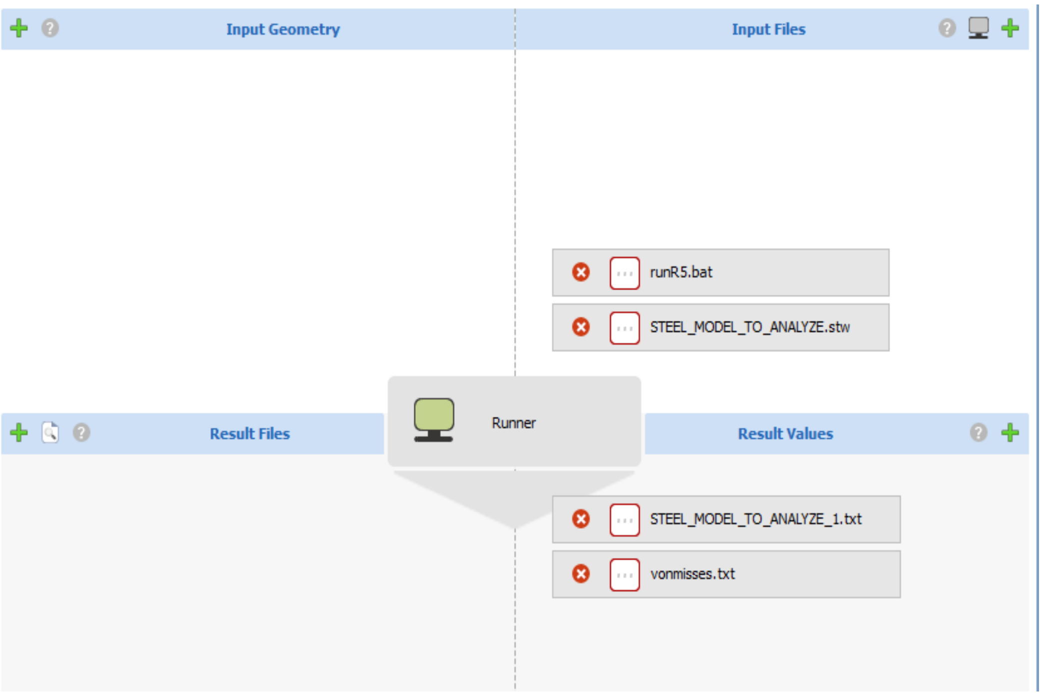


Figure 31 Software Connector Setup from STEEL-CAESES Loop

The STEEL input file in ASCII format, batch file , STEEL outfile and the output file from 'SteelBeamStressExtractor' executable application for finding the maximum Von mises stress in the entire model are connected to the optimization work flow using the software connector similar to the STEEL- modeFRONTIER optimization loop established earlier as part of WP4 application.

The input design variables were selected as the scantlings of different deck beam sections. With reference to Figure 23, optimization loop was established with 8 design variables which are the beam scantlings of Deck 3 and Deck 4 beam sections. With 4 design variables only considered, no sufficient feasible solutions were obtained.

The list of design input variables selected for the optimization run are shown in below table. The range of values for design variables considered in the loop were taken in accordance with the initial data shown in figure 20 for beam scantlings.

Table 19 Design Variables from STEEL-CAESES loop for the RoPax Hull

| Design Variable | Description | Min. Value | Max. Value |
|---|---|---|---|
| Hw_Deck4 | Web Height of Deck4 Beam section | 0.600 m | 1.000 m |
| Tw_Deck4 | Web Thickness of Deck4 Beam Section | 8 mm | 12 mm |
| Bf_Deck4 | Flange Width of Deck4 Beam Section | 0.200 m | 0.400 m |
| Tf_Deck4 | Flange Thickness of Deck4 Beam Section | 15 mm | 25 mm |
| Hw_Deck3 | Web Height of Deck3 Beam section | 0.600 m | 1.000 m |
| Tw_Deck3 | Web Thickness of Deck3 Beam Section | 8 mm | 12 mm |

| | | | |
|---|---|---|---|
| Bf_Deck3 | Flange Width of Deck3 Beam Section | 0.200 m | 0.400 m |
| Tf_Deck3 | Flange Thickness of Deck3 Beam Section | 15 mm | 25 mm |

The input variables ,attached plate scantlings and the parameteres for calculating the total weight of main transverse frame and Von mises stress were all defined within CAESES accordingly.

Similar to STEEL-modeFRONTIER loop, the objective function is defined as to minimize the weight of entire STEEL model. In CAESES, all the design engines minimize the objective function by default.

Constraints for the loop were also defined using the inequality constraints available within CAESES. Both constraints for yield check and geometrical constraints were considered similar to STEEL-modeFRONTIER loop of the RoRo hull. Since the thickness of web considered in the loop is more than $t_{MIN}$ as required by (15), same is not considered as a constraint within the optimization.

There are several options for the design engines in order to run design iterations using CAESES. However initially a Design explorer like SOBOL algorithm was chosen which creates an initial design pool for the optimization design engine.

### 5.2.3 Optimisation procedure Adopted

i) Creating an initial design pool with SOBOL algorithm

The main objective of running SOBOL initially is to perform a uniform sampling of design space. SOBOL is a kind of algorithm also known as quasi-random or low discrepancy sequence as it is a deterministic algorithm that imitates the behaviour of a random sequence. eventhough the clustering effects seen to occur with random sequences are lesser. Also the convergence charecteristics of SOBOL type algorithms are known to be superior to random sequences.

Using the SOBOL, design variables and objective function were defioned within CAESES and some iterations around 50 were run initially in order to see the trends over the design space.

At a further stage, using a desig engine, design iterations were run again with constraints also defined.

### ii) Running Design iterations using DAKOTA Global Optimisation Deign Engine

[22] DAKOTA is an optimisation package developed by Sandia National Laborataries which is available within CAESES. Advanced optimisation strategies can be used with the help of DAKOTA package. DAKOTA Global optimisation helps to find the global optimum among the design space for the objective function. Generally genetic algorithm based global optimisation methods require large number of iterations and could be compuitationally costly.

However it was noted that optimisation using STEEL tool required less than 5 seconds to complete an iteration when run using SOBOL algorithm. Hence Design engine was selected as DAKOTA Global optimisation. This design engine is based on MOGA ( Multi Objective Genetic Algorithm) which can be used for finding the pareto frontier in multi objective optimisation problems. Since in our case, there is only one objective function, it reduces to single objective optimisation problem.

There are different optimisation engines available within the DAKOTA package in CAESES such as Sensitivity analysis, local optimization, Global optimization on response surface etc.

Sensitivity analysis is used to create an initial design pool for performing a detailed optimisation using other design engine at later stages.With local optimization, the aim is to find local find a design point that is lowest relative to a “nearby” region of the parameter design space.

Using DAKOTA global optimisation, around 300 iterations were run and the trend in the objective function , constraints and design variables were studied.

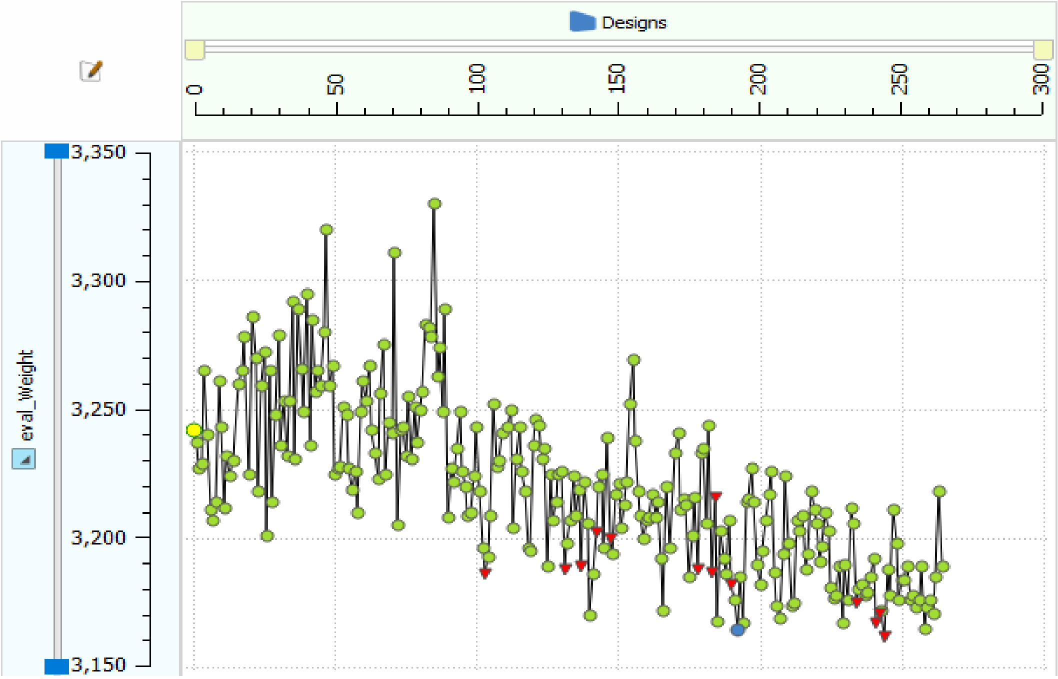


Figure 32 History Chart of Weight from STEEL-CAESES Loop

Figure above indicates the variation of weight as the design iterations are progressed. Clearly the optimization loop tries to find an optimum design in which total weight is lesser than obtained in the initial stages.

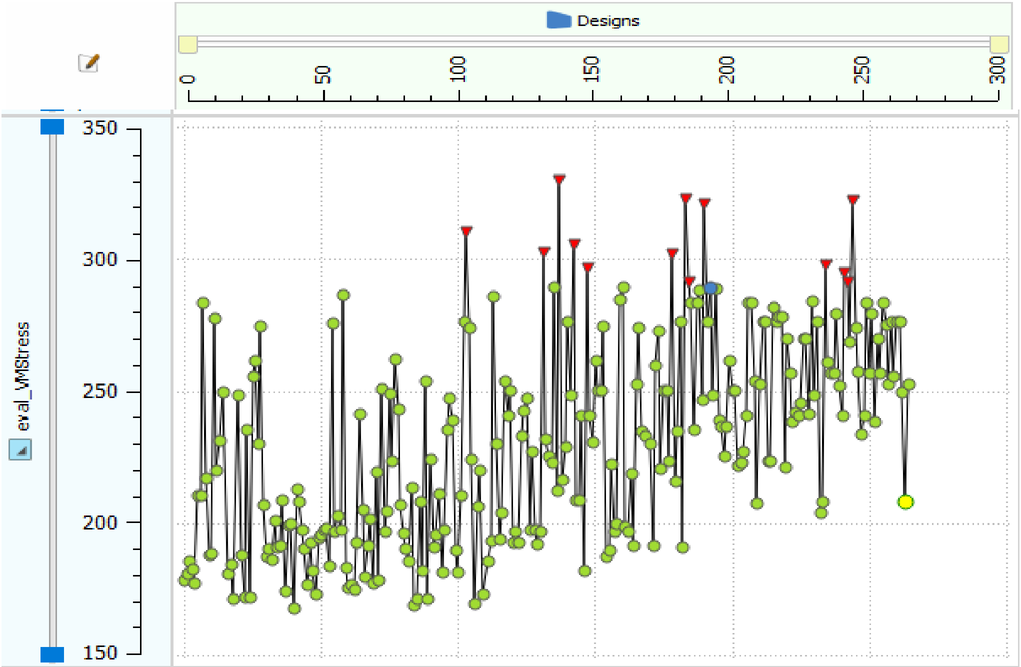


Figure 33 History Chart of Von Mises Stress (MPa) from STEEL-CAESES Loop

Also Figure 33 denotes variation of Von mises stress in the structure with different design iterations. As expected von mises stress vcalues were close to the limit (290 Mpa) for the designs which give reduced structural weight.

There were a few designs which were not feasible and failed the requirements set by the constraints, though very less in number which are hilighted by the red points in the figures.The distribution of the design variables considered in the design space is added in Appendix A1.

## 5.3 Building Response Surface

Using the results obtained from the STEEL-CAESES loop for the RoPax hull, surrogate models were established using polynomial regression based RSM option available within CAESES-DAKOTA platform.

Sample Output obtained using DAKOTA export option available in CAESES for polynomial quadratic surrogate model with 4 design variable is added in Appendix A9.

Taking around 250 feasible designs as reference from previous optimization run, response surface was built accordingly. The final obtained polynomial relation between input design variables (beam scantlings of Deck 3 & 4) and the response variable W (structural weight of main transverse frame section) is added below;

$$W = 2975.203 - 9.235*x_1+4.983*x_1^2 + 12.787*x_1*x_2 - 4.058*x_1*x_3 + 0.795*x_1*x_4 + 10.741*x_1*x_5 -0.171*x_1*x_6 + 0.152*x_1*x_7 + 0.444*x_1*x_8 + 16.356*x_2 + 3.567*x_2^2 - 4.499*x_2*x_3 - 8.974*x_2*x_4 + 0.008*x_2*x_5+10.518*x_2*x_6 -0.337*x_2*x_7 - 0.736*x_2*x_8 - 3.130*x_3-0.182*x_3^2 -2.808*x_3*x_4-0.0430*x_3*x_5 + 0.0899*x_3*x_6 +10.945*x_3*x_7 + 0.371*x_3*x_8 + 7.464*x_4 -2.257*x_4^2+0.122*x_4*x_5 -0.0761*x_4*x_6 + 0.016*x_4*x_7 + 10.519*x_4*x_8 + 0.199*x_5 - 0.001*x_5^2 + 0.0004*x_5*x_6 - 0.0121*x_5*x_7-0.013*x_5*x_8 + 0.037*x_6-0.0046*x_6^2+0.005*x_6*x_7+0.015*x_6*x_8 -0.168*x_7-0.0085*x_7^2 + 0.0310*x_7*x_8 - 0.2897*x_8-0.0071*x_8^2 \quad \textbf{(31)}$$

$x_1$ ,$x_2$ , $x_3$ , $x_4$ , $x_5$ , $x_6$ , $x_7$ ,$x_8$ are the input design variables which are the flange width, web height , flange thickness and web thickness of both deck 3 & deck 4 respectively in accordance with the values shown in below table.

Table 20 Comparison of results obtained from STEEL tool & RSM using CAESES for 8 design variables

| $B_f$_Deck 3 | $B_f$_Deck 4 | $H_w$_Deck 3 | $H_w$_Deck 4 | $T_f$ _ Deck 3 | $T_f$ _Deck 4 | $T_w$_Deck 3 | $T_w$_ Deck 4 | W from STEEL | W from RSM | % Diff |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.2026 | 0.2672 | 0.7439 | 0.7154 | 23.100 | 16.734 | 11.940 | 9.541 | 3242 | 3241.982 | 0.0005 |
| 0.2034 | 0.2553 | 0.8045 | 0.6227 | 22.577 | 20.375 | 9.847 | 10.692 | 3237 | 3237.012 | -0.0004 |
| 0.2035 | 0.3027 | 0.8192 | 0.6687 | 21.479 | 15.543 | 10.536 | 8.530 | 3227 | 3226.623 | 0.0117 |
| 0.2039 | 0.2963 | 0.8129 | 0.6654 | 16.824 | 16.151 | 11.818 | 8.694 | 3229 | 3228.763 | 0.0073 |
| 0.2042 | 0.3205 | 0.8026 | 0.6667 | 22.933 | 19.268 | 10.161 | 11.985 | 3265 | 3264.727 | 0.0084 |
| 0.2099 | 0.3156 | 0.8335 | 0.6546 | 15.394 | 20.105 | 8.902 | 11.697 | 3240 | 3239.965 | 0.0011 |
| 0.2120 | 0.3330 | 0.8153 | 0.6305 | 15.623 | 16.209 | 9.144 | 9.110 | 3211 | 3210.685 | 0.0098 |
| 0.2142 | 0.2617 | 0.5662 | 0.5710 | 23.827 | 20.012 | 8.249 | 11.494 | 3207 | 3206.892 | 0.0034 |
| 0.2161 | 0.2640 | 0.7459 | 0.5829 | 15.405 | 23.444 | 10.596 | 8.258 | 3214 | 3214.092 | -0.0029 |
| 0.2170 | 0.3326 | 0.6949 | 0.6304 | 24.540 | 24.413 | 11.338 | 8.456 | 3261 | 3260.926 | 0.0023 |
| 0.2178 | 0.3097 | 0.7739 | 0.8087 | 20.705 | 17.283 | 10.228 | 8.885 | 3243 | 3243.169 | -0.0052 |
| 0.2219 | 0.3613 | 0.5839 | 0.5646 | 15.323 | 16.450 | 11.240 | 10.889 | 3212 | 3212.204 | -0.0063 |
| 0.2225 | 0.3491 | 0.7289 | 0.6299 | 21.771 | 19.155 | 8.365 | 9.915 | 3232 | 3231.644 | 0.0110 |
| 0.2323 | 0.2481 | 0.5752 | 0.6061 | 23.488 | 23.407 | 11.073 | 9.081 | 3224 | 3223.543 | 0.0142 |
| 0.2452 | 0.3006 | 0.5767 | 0.6445 | 19.792 | 20.812 | 10.499 | 10.192 | 3230 | 3230.054 | -0.0017 |
| 0.2463 | 0.3170 | 0.7862 | 0.7526 | 16.779 | 22.143 | 11.354 | 8.661 | 3260 | 3260.384 | -0.0118 |
| 0.2465 | 0.3485 | 0.7894 | 0.6393 | 15.294 | 24.510 | 11.625 | 8.685 | 3265 | 3265.150 | -0.0046 |

As shown in the above table, both results were found to give similar results with relative error as low as it can be neglected, thus ensuring the reliability of the surrogate model.

# 6. COUPLING BV STEEL WITH RO-PAX PARAMETRIC HULL LOOP

The Work Package 7 (WP7) within HOLISHIP project concentrates on integration of methods and tools, software platforms which are required for different phases of life cycle based design of ships such as hydrodynamics, structural anlysis, cost analysis, stability calculations etc and CAESES is used as one of the integration platform for this purpose.

A parametric hull of RoPax vessel which is one of the WP7 application cases was already developed at FRIENDSHIP SYSTEMS using the CAESES software . The parametric hull was developed as a loop with its own pre defined design variables like length between perpendicular, beam, height, draft, Block coefficient etc which can be varied within specified limits in order to see the changes in hull and to do further anlysis for finding the optimum hull and vessel dimensions.

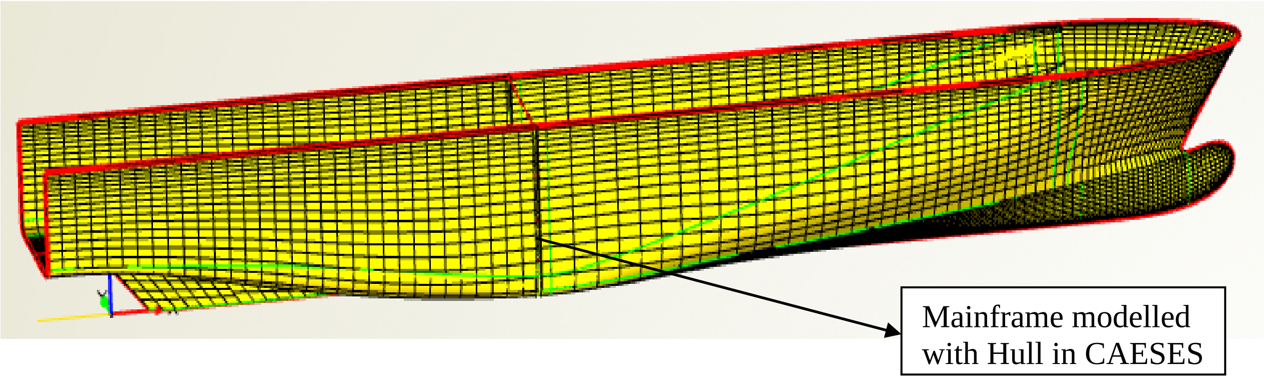

Mainframe modelled with Hull in CAESES

Figure 34 Initial configuration of RoPax hull showing Profile view

Since this thesis is part of the structural analysis module as part of HOLISHIP project, it was interesting to couple the STEEL–CAESES optimisation loop which was established in the earlier section with the parametric hull loop so that with each design iteration of the hull (which would modify the midship configuration of the hull as well), the new transverse section is imported to the STEEL tool and to perform the structural analysis accordingly.

Hence by integrating these two optimisation loops, feasibility of successfull designs satisfying the constraints defined inside STEEL – CAESES loop can be checked for the new hull designs generated by the parametric hull loop.

## 6.1 Integration of Optimization Loops

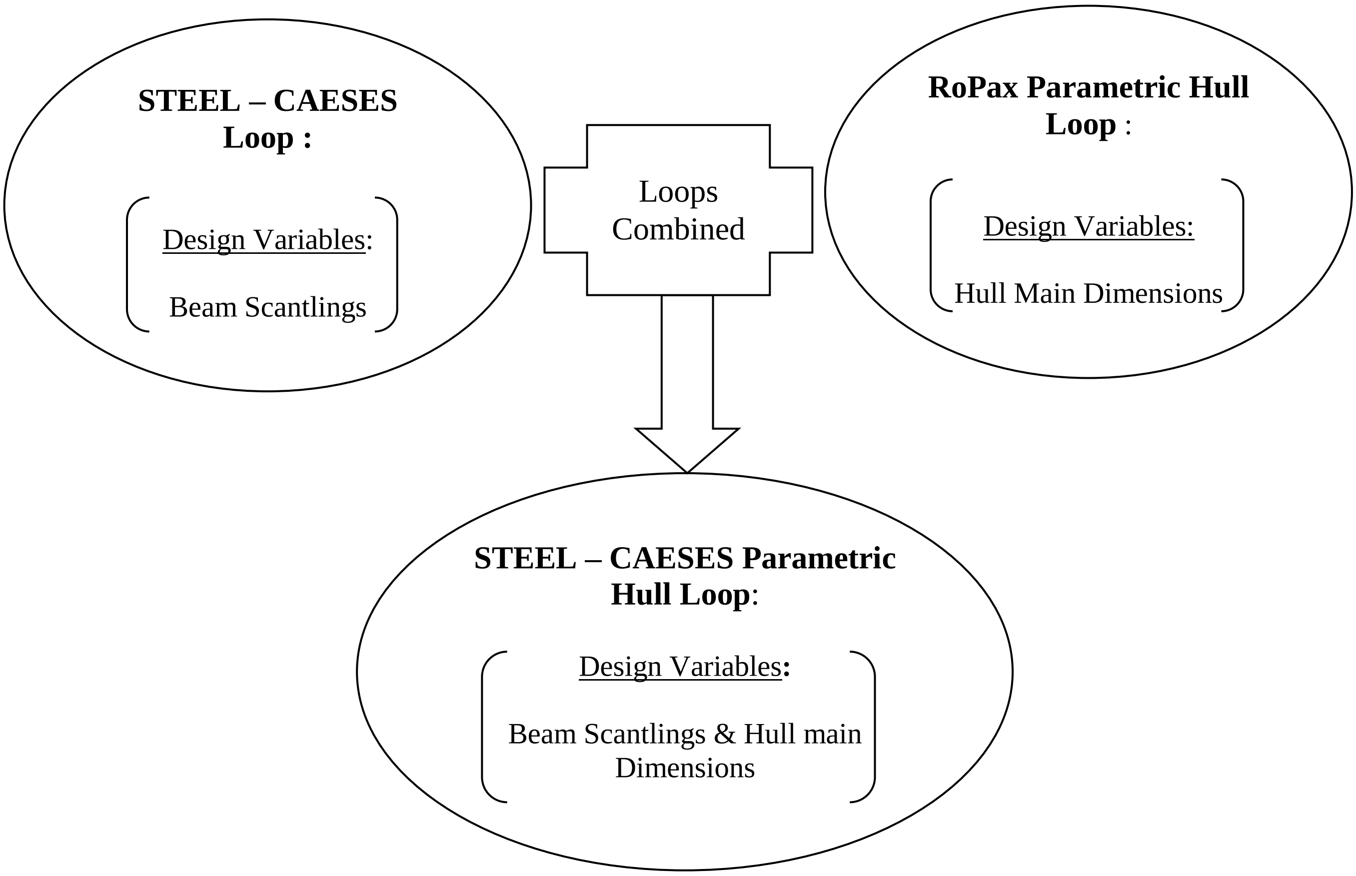


Figure 35 Integration of Optimization Loops

As shown in previous figure, the two loops are combined accordingly. The different steps done in order to combine the two different loops are added below

### 6.1.1 Parameterization of Nodes defined within the STEEL Batch mode Input file

When the main dimensions within the RoPax Parametric hull loop are changed, the midship configuration also changes. Hence it is required to import the new midship configuration into STEEL tool so that then nodes and beams are re-aligned within STEEL tool and complete structural analysis of the modified main transverse frame configuration accordingly.

For this purpose, the node coordinates defined within the STEEL batch mode input file of RoPax hull need to be parameterized. So y & z local axis coordinates of all nodes were normalized with respect to the maximum width and height of the transverse section.

Table 21 Normalized Node Coordinates

| | Max Width | Max height |
|---|---|---|
| | 13.8 m | 21.25 m |
| Nodes | y | Z |
| N1 | 0 | 0 |
| N2 | 0.052898551 | 0 |
| N3 | 0.317391304 | 0 |
| N4 | 0.581884058 | 0 |
| N5 | 0.637681159 | 0 |
| N6 | 0.983333333 | 0.164705882 |
| N7 | 1 | 0.235294118 |
| N8 | 1 | 0.461176471 |
| N9 | 1 | 0.724705882 |
| N10 | 1 | 1 |
| N11 | 0 | 1 |
| N12 | 0 | 0.724705882 |
| N13 | 0 | 0.461176471 |
| N14 | 0 | 0.197647059 |
| N16 | 0.052898551 | 0.065882353 |
| N17 | 0.317391304 | 0.065882353 |
| N18 | 0.581884058 | 0.065882353 |
| N19 | 0.052898551 | 0.197647059 |
| N20 | 0.317391304 | 0.197647059 |
| N21 | 0.581884058 | 0.197647059 |
| N23 | 0.581884058 | 0.461176471 |
| N24 | 0.581884058 | 0.164705882 |
| N25 | 0.581884058 | 0.724705882 |
| N26 | 0.581884058 | 1 |

Above table shows the normalized Node coordinates. With reference to Figure 23 , Node N1 is located at the origin of the STEEL model and N10 is located at extreme width and extreme height of the model. Hence considering these as reference nodes, all other nodes in between were parameterized.

Then these nodes were reproduced in the Parametric hull of RoPax and the transvers frame was modeled using CAESES.The parametric hull of RoPax vessel modeled with CAESES had a mainframe defined already within the parallel middle body as indicated in figure 34.N1 was the starting point of mainframe and N10 was the end point.
With reference to figures 23 & 34 , below picture shows the main transverse frame and nodes modeled being integrated to the RoPax parametric hull.

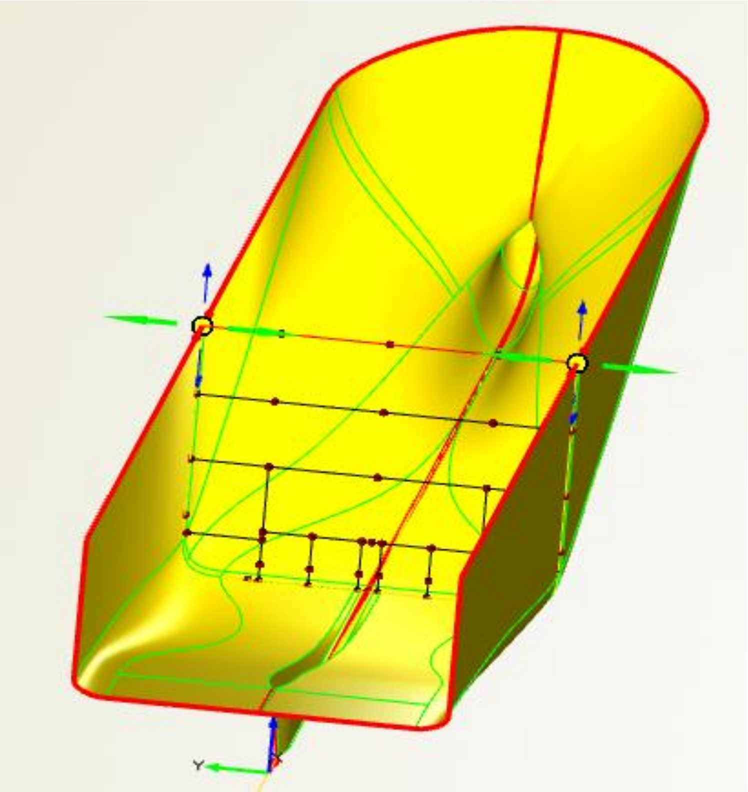
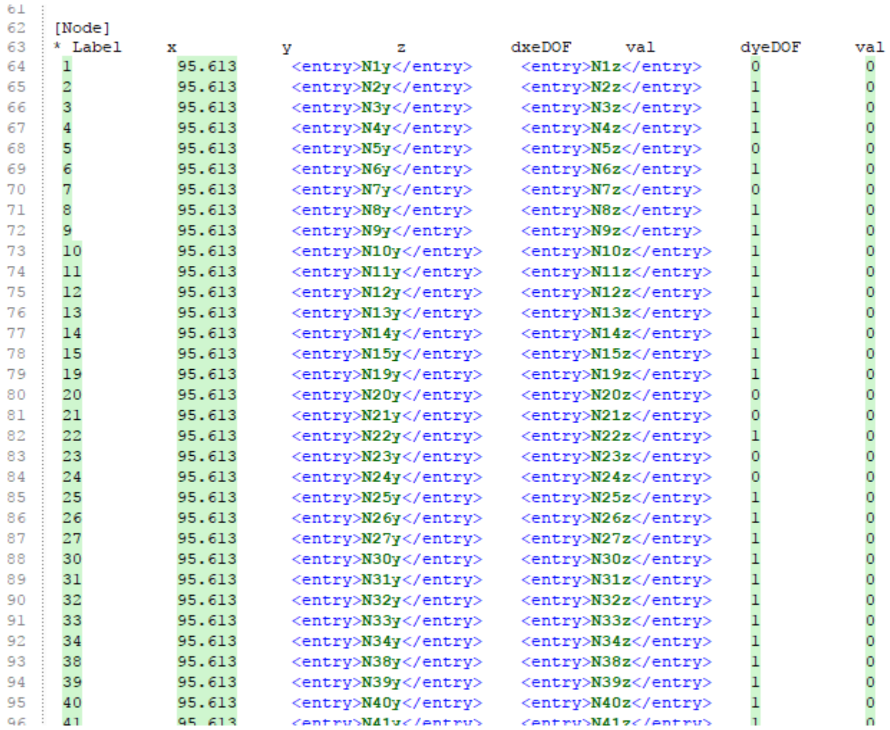


Figure 36 Transverse Frame& nodes modeled in CAESES

Then the nodes defined within the STEEL batch mode input file were parameterized using the corresponding above nodes created in CAESES.



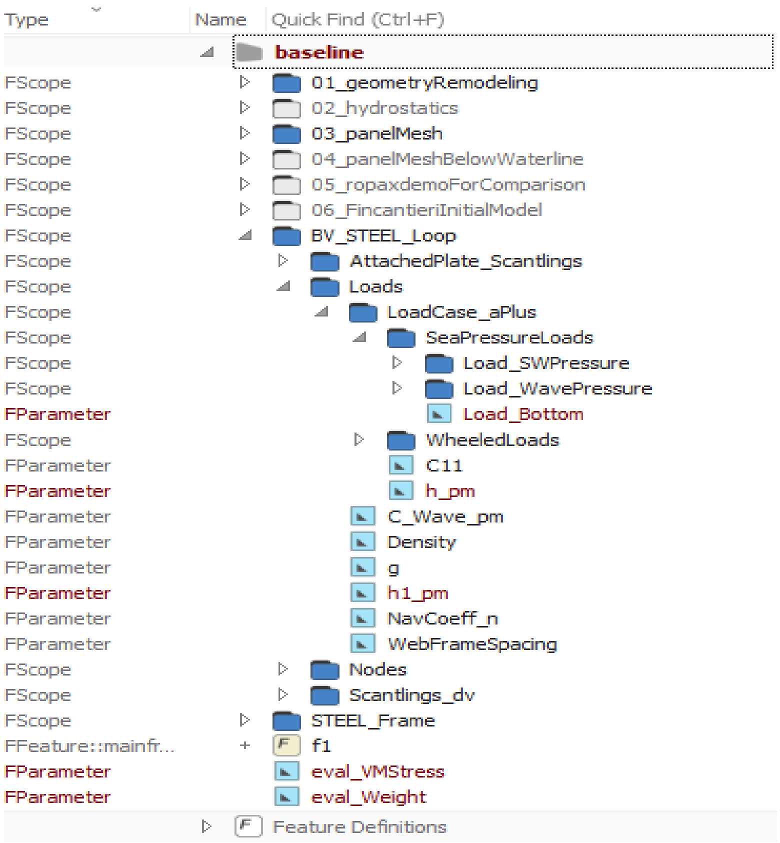
```

[Node]
* Label     x           y           z           dxeDOF      val         dyeDOF      val
  1          95.613      <entry>N1y</entry>      <entry>N1z</entry>      0           0
  2          95.613      <entry>N2y</entry>      <entry>N2z</entry>      1           0
  3          95.613      <entry>N3y</entry>      <entry>N3z</entry>      1           0
  4          95.613      <entry>N4y</entry>      <entry>N4z</entry>      1           0
  5          95.613      <entry>N5y</entry>      <entry>N5z</entry>      0           0
  6          95.613      <entry>N6y</entry>      <entry>N6z</entry>      1           0
  7          95.613      <entry>N7y</entry>      <entry>N7z</entry>      0           0
  8          95.613      <entry>N8y</entry>      <entry>N8z</entry>      1           0
  9          95.613      <entry>N9y</entry>      <entry>N9z</entry>      1           0
  10         95.613      <entry>N10y</entry>     <entry>N10z</entry>     1           0
  11         95.613      <entry>N11y</entry>     <entry>N11z</entry>     1           0
  12         95.613      <entry>N12y</entry>     <entry>N12z</entry>     1           0
  13         95.613      <entry>N13y</entry>     <entry>N13z</entry>     1           0
  14         95.613      <entry>N14y</entry>     <entry>N14z</entry>     1           0
  15         95.613      <entry>N15y</entry>     <entry>N15z</entry>     1           0
  19         95.613      <entry>N19y</entry>     <entry>N19z</entry>     1           0
  20         95.613      <entry>N20y</entry>     <entry>N20z</entry>     0           0
  21         95.613      <entry>N21y</entry>     <entry>N21z</entry>     0           0
  22         95.613      <entry>N22y</entry>     <entry>N22z</entry>     1           0
  23         95.613      <entry>N23y</entry>     <entry>N23z</entry>     0           0
  24         95.613      <entry>N24y</entry>     <entry>N24z</entry>     0           0
  25         95.613      <entry>N25y</entry>     <entry>N25z</entry>     1           0
  26         95.613      <entry>N26y</entry>     <entry>N26z</entry>     1           0
  27         95.613      <entry>N27y</entry>     <entry>N27z</entry>     1           0
  30         95.613      <entry>N30y</entry>     <entry>N30z</entry>     1           0
  31         95.613      <entry>N31y</entry>     <entry>N31z</entry>     1           0
  32         95.613      <entry>N32y</entry>     <entry>N32z</entry>     1           0
  33         95.613      <entry>N33y</entry>     <entry>N33z</entry>     1           0
  34         95.613      <entry>N34y</entry>     <entry>N34z</entry>     1           0
  38         95.613      <entry>N38y</entry>     <entry>N38z</entry>     1           0
  39         95.613      <entry>N39y</entry>     <entry>N39z</entry>     1           0
  40         95.613      <entry>N40y</entry>     <entry>N40z</entry>     1           0
  41         95.613      <entry>N41y</entry>     <entry>N41z</entry>     1           0
```

Figure 37  Assigning parameters for Nodes in STEEL input file

### 6.1.2 Parameterization of Loads Within CAESES

As explained in earlier section, local loads as per BV Class rules are only considered. Among the local loads, Sea pressure loads and wheeled loads were defined within CAESES. The parameters to define these loads as per BV rules were also defined as shown below.



```
Type                 Name    Quick Find (Ctrl+F)
                     ◢ baseline
FScope               ▷ 01_geometryRemodeling
FScope               ▷ 02_hydrostatics
FScope               ▷ 03_panelMesh
FScope               ▷ 04_panelMeshBelowWaterline
FScope               ▷ 05_ropaxdemoForComparison
FScope               ▷ 06_FincantieriInitialModel
FScope               ◢ BV_STEEL_Loop
FScope                   ▷ AttachedPlate_Scantlings
FScope                   ◢ Loads
FScope                       ◢ LoadCase_aPlus
FScope                           ◢ SeaPressureLoads
FScope                               ▷ Load_SWPressure
FScope                               ▷ Load_WavePressure
FParameter                             Load_Bottom
FScope                           ▷ WheeledLoads
FParameter                         C11
FParameter                         h_pm
FParameter                     C_Wave_pm
FParameter                     Density
FParameter                     g
FParameter                     h1_pm
FParameter                     NavCoeff_n
FParameter                     WebFrameSpacing
FScope                   ▷ Nodes
FScope                   ▷ Scantlings_dv
FScope               ▷ STEEL_Frame
FFeature::mainfr...  +   f1
FParameter               eval_VMStress
FParameter               eval_Weight
                     ▷ Feature Definitions
```

Figure 38 Defining Design Variables & Loads in CAESES

As shown above in Figure 40, the design variables, attached plate scantlings, node coordinates and loads are all defined in the CAESES workflow thus enabling automated structural optimization.

Among the local loads, only sea pressure loads were parameterized at this stage and also load case a+ is only considered as explained earlier in 5.1.3. Hence with design iteration of hull, the modified loads according to the changed hull dimensions are applied to the structure thus allowing automated structural analysis of the corresponding section through STEEL.

## 6.2 Performing Integrated optimization with RoPax hull

With the two loops now integrated, total 15 design variables were considered while running the optimization as shown in table 22. The range of design variables considered for the hull dimensions were originally pre defined in the parametric hull loop.

Table 22 Design Variables from STEEL-CAESES Parametric Hull loop

| | DOE | Design Engine |
|---|---|---|
| Chosen Type | DAKOTA Sensitivity Analysis | DAKOTA Global Optimisation |
| Total No. of Iterations | ~500 | |

| Design Variable | Description | Min. Value | Max. Value |
|---|---|---|---|
| Hw_Deck4 | Web Height of Deck4 Beam section | 0.550 m | 0,850 m |
| Tw_Deck4 | Web Thickness of Deck4 Beam Section | 8 mm | 12 mm |
| Bf_Deck4 | Flange Width of Deck4 Beam Section | 0.200 m | 0.400 m |
| Tf_Deck4 | Flange Thickness of Deck4 Beam Section | 15 mm | 25 mm |
| Hw_Deck3 | Web Height of Deck3 Beam section | 0.550 m | 0,850 m |
| Tw_Deck3 | Web Thickness of Deck3 Beam Section | 8 mm | 12 mm |
| Bf_Deck3 | Flange Width of Deck3 Beam Section | 0.200 m | 0.400 m |
| Tf_Deck3 | Flange Thickness of Deck3 Beam Section | 15 mm | 25 mm |
| $L_{PP}$ | Length b/w Perpendiculars | 155 | 180 |
| $L_{cb}$ | Long. centre of buoyancy (in % of $L_{PP}$) | 0.44 | 0.47 |
| B | Breadth | 27,6 | 30,6 |
| Draft | Design draft | 6,5 | 7,1 |
| Height Factor | Scale factor for height | 0.95 | 1.02 |
| $C_B$ | Block Coefficient | 0.56 | 0.58 |
| $C_M$ | Midship section coefficient | 0.965 | 0.985 |

The evaluated parameters for each design iteration include weight of main transverse frame which is kept as the objective, hull main dimensions together with the von mises stress of entire section and then the displacement of the vessel which is calculated by CAESES.

Initially DAKOTA Sensitivity analysis was run in order to create initial design result pool for the DAKOTA global optimization design engine. Since there are total 15 design variables, number of initial run is selected as 150 while defining the design engine.

Generally number of initial run need to be 5 times the design variables atleast.

The variation of structural weight with each hull iteration is shown in figure 39. Structural weight of transverse frame was again kept as the objective function to minimize within the optimization loop which resulted in reduction in weight as the iterations progressed.

Also the trends in Breadth and length between perpendiculars against weight of transverse frame are also shown in figures 42 & 43. The figures indicate a linear increase in weight with increase of both parameters.

The trends of CB, draft, CM against the structural weight are added in Appendix A5.

Figure 39 Variation of weight with design iterations from STEEL-CAESES parametric hull loop

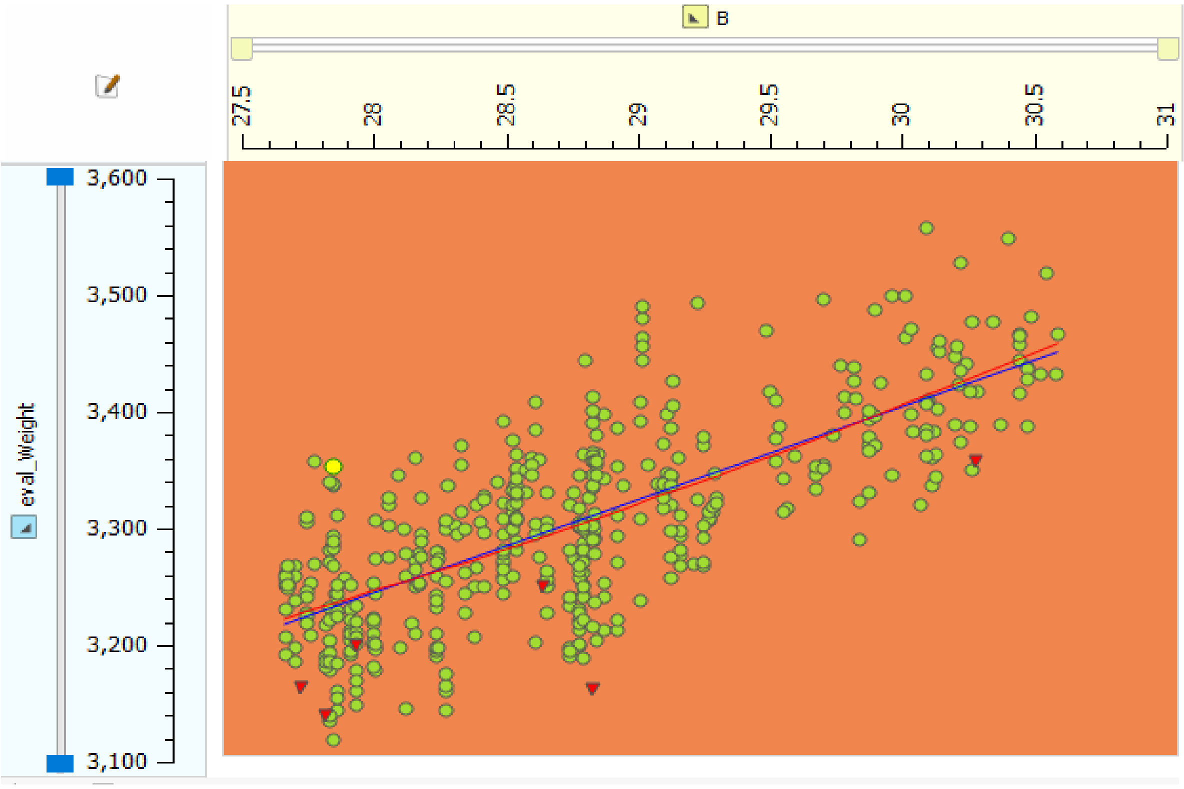


Figure 40 Breadth, B (in m) against Weight of main transverse frame(Ton/100)

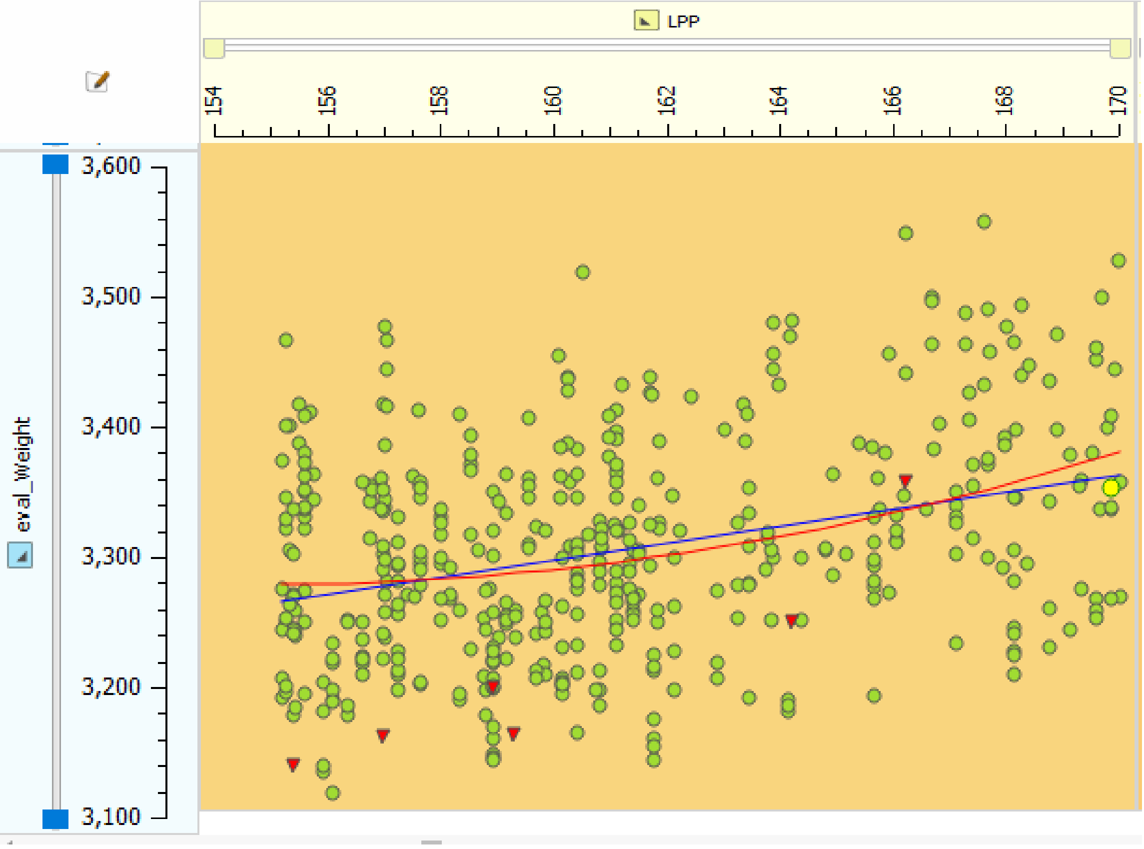


Figure 41 LPP (in m) against Weight of main transverse frame (Ton/100)

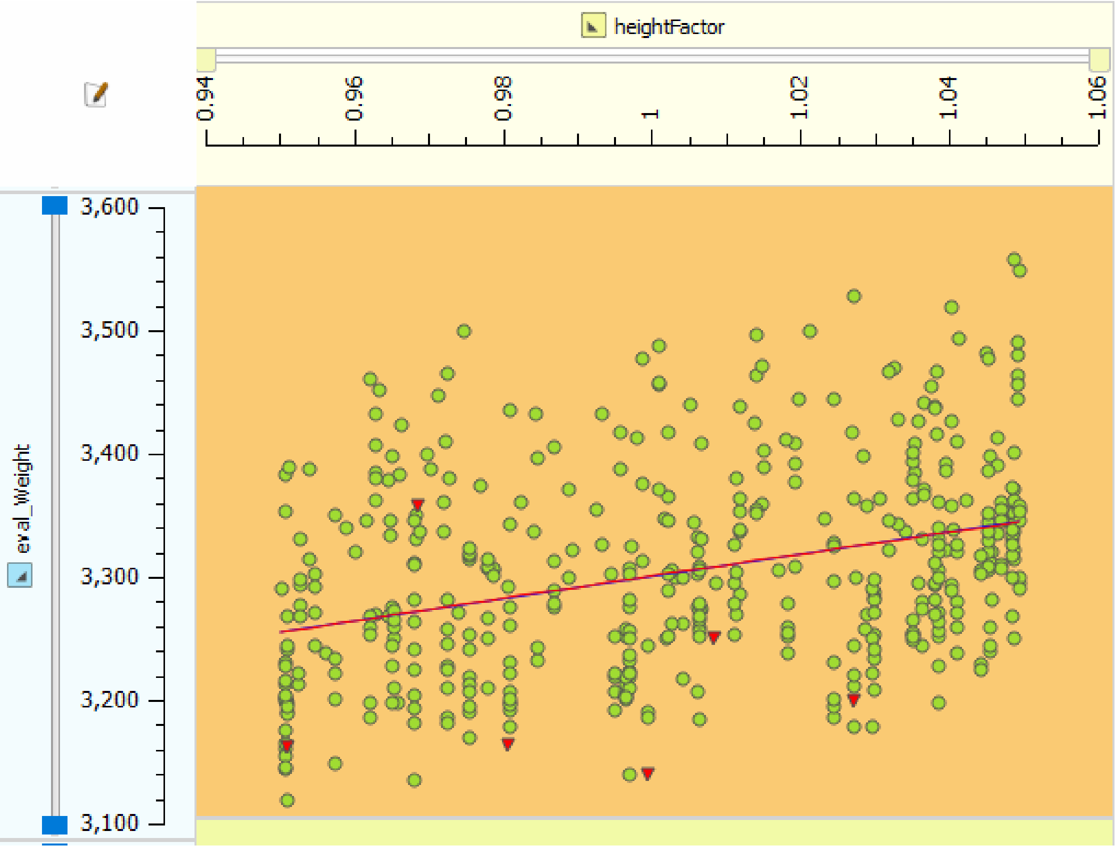


Figure 42 Height Factor against Weight of main transverse frame (Ton/100)

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# 7. CONCLUSION & RECOMMENDATIONS FOR FUTURE WORK

## 7.1 Conclusion

The main objective was to establish an integrated structural optimization loop for the analysis of main transverse frame which was achieved through this thesis. Optimization loop involving BV STEEL tool and other optimization platforms were integrated keeping the structural weight of main transverse frame as the objective function to minimize. Design Constraints as per BV Class rules were considered and it was found that structural weight can be significantly reduced for the entire vessel if optimum scantlings were chosen. Hence this could be a major advantage during the concept design phase in order to consider optimum initial design scantlings to save lightship weight of entire vessel which could results in cost benefits in life cycle based design of ships.

Among the design constraints considered as per the classification society rules, geometrical constraints were found to be complying in most cases of design iterations while the critical constraint to be taken care was the Von mises stress criteria required for the yield check. Local loads due to wheeled cargo and sea pressure were considered to act in the structure, based on which structural behavior of the model and stresses developed were studied.
As the design progresses and with more availability of information, it will be possible to see the distribution of von mises stress considering impact of other local stresses and global huill girder stresses as well.

A literature survey was also done concentrating mainly about the integrated structural analysis of type of vessels considered and also about application about response surface methodology in structural optimization problems. Feasibility to establish reliable surrogate models using Response surface methodology and artificial neural networks etc. was also checked. Results found that RSM could be a reliable solution in order to replace existing optimization loops in later stages when more tools, methods or design components will need to be integrated together. Polynomial regression based RSM found to give very good approximate empirical relations of the second order polynomial with reliable fit connecting input design variables and the response variable. Also when the difference in the ranges of values of different design variables are very high , artificial neural networks could be a solution for building the surrogate models.

## 7.2 Recommendations for Future Work

Impact of global loads were not considered in the thesis as it will be determined by the BV MARS loop. When the MARS loop is integrated, it will be possible to analyze combined impact of global hull girder loads and local loads on the stress distribution with various design variables considered. Also the integrated MARS-STEEL could be coupled with the parametric hull lopp as well to enable structural analysis of each design iteration of hull. Also the impact of changes in frame spacing and with changes in attached plate scantlings; it would be interesting to study the impact on structural behavior of transverse frames and the changes in stress distribution.

Also an approximate empirical method was established by the Author for finding the total hull steel weight of RoRo/RoPax vessels to be used as an objective function for the optimization loop when both BV STEEL & MARS loops are integrated to enable complete structural analysis of the midship section. The method was developed considering total weight of main transverse section given by STEEL tool and weight given by MARS model. Then the weight of midship section was extended to full length of the ship considering allowances for the remaining structural components and changes in the midship section area on the forward and aft ends. Hence once MARS loop is integrated into the STEEL loop established by the author, it could be interesting to see the influence of different design variables like beam scantlings, distribution of ordinary stiffeners etc on the total hull lightship weight and also on the structural integrity.

The response surface was established using the results obtained from the current optimization loops. As the design progresses and with more increased number of design variables, the response surface could be extended to suit modified design variables or to accommodate multi objective problems. In particular, Neural network could be a solution for establishing the surrogate models to avoid integrated loops and different tools for establishing a reliable surrogate model especially if ranges of value of design variables has large variations.

## 8. ACKNOWLEDGEMENTS

First of all I would like to thank both FRIENDSHIP SYSTEMS AG and University of Liege for giving me the opportunity to do a coupled internship as part of the HOLISHIP Project based on which this thesis was developed. I would like to thank Prof. Philippe Rigo for providing this platform and for being the mentor during the internship. The guidance and suggestions from Dr.-Ing. Stefan Harries from Friendship Systems, Mr. Abbas Bayatfar from University of Liege and Dr.-Ing. Thomas Lindemann from University of Rostock were immensely helpful in shaping this thesis and would like to thank them for the incredible support they have offered. Also the help from my colleagues at both organizations were immensely helpful, especially Mr. Ivan Montenegro and Mr. Renaud Warnotte from University of Liege and Mr. Heinrich, Mr. Carsten, & Mr. Joerg Palluch from FRIENDSHIP SYSTEMS who had offered me their kind support throughout the internship and in understanding different tools better. Also I would like to thank Mr. Nicolas Meyer from Bureau Veritas, France, Ms. Chiara Notaro from CETENA and all the other design partners of WP4 & WP7 who had extended their support and for providing all the required information required for this thesis.

I would like to thank all my EMSHIP colleagues who has brought new experiences to my life and also all my dearest friends for keeping me inspired. The help from all the EMSHIP professors and administration staff were invaluable which enabled me to survive during the program and would like to thank them for sharing their knowledge and experiences. I am grateful to my parents who have given strength and support throughout various stages of my life.

Altogether EMSHIP was a really nice learning experience both personally and professionally and my sincere thanks to all those who has helped in each different phases.

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# APPENDIX A1. DOE from STEEL-CAESES Loop With 8 Variables

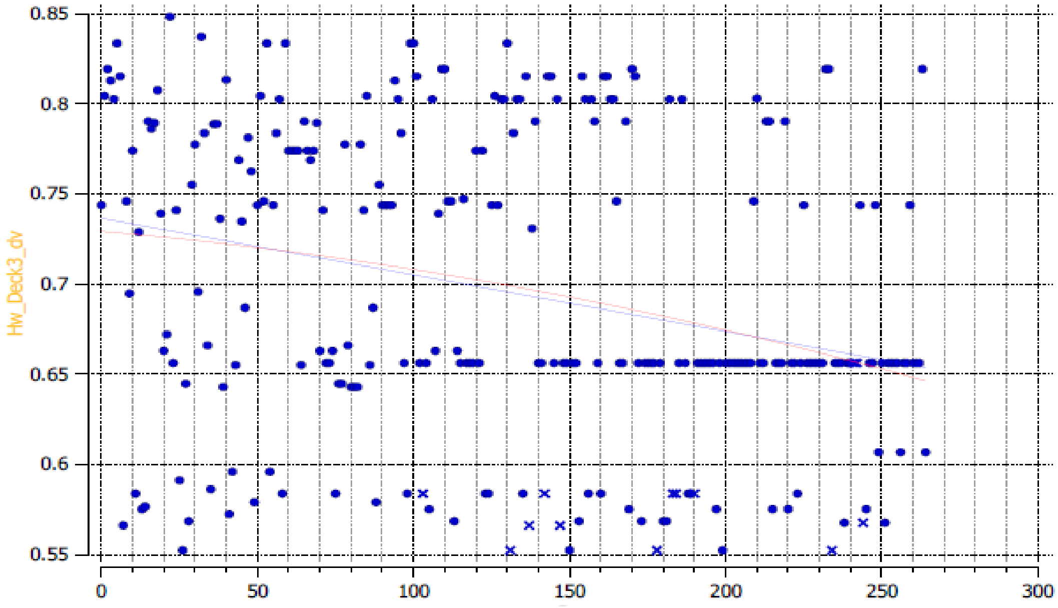


Figure 42 distribution of Hw_Deck3 in design space

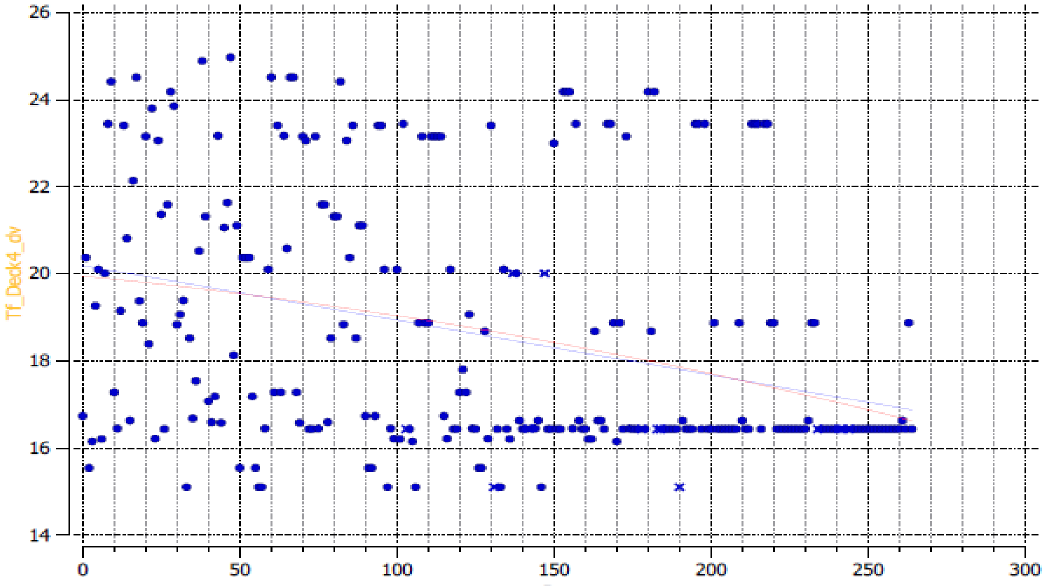


Figure 43distribution of Tf_Deck4 in design space

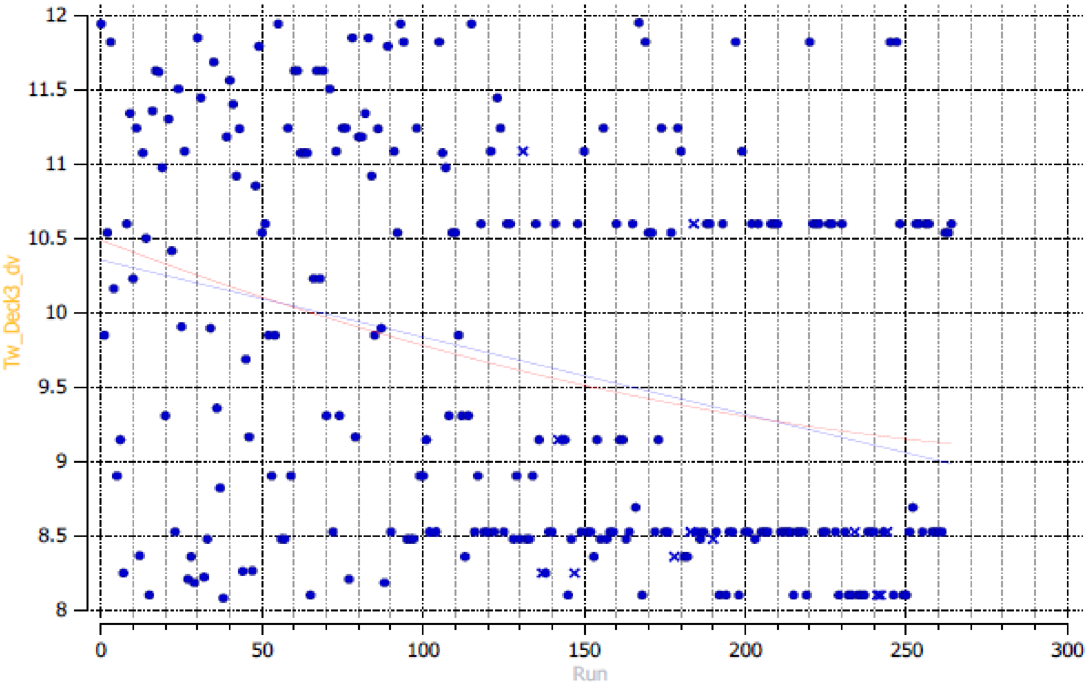


Figure 44 distribution of Tw_Dec3 in design space

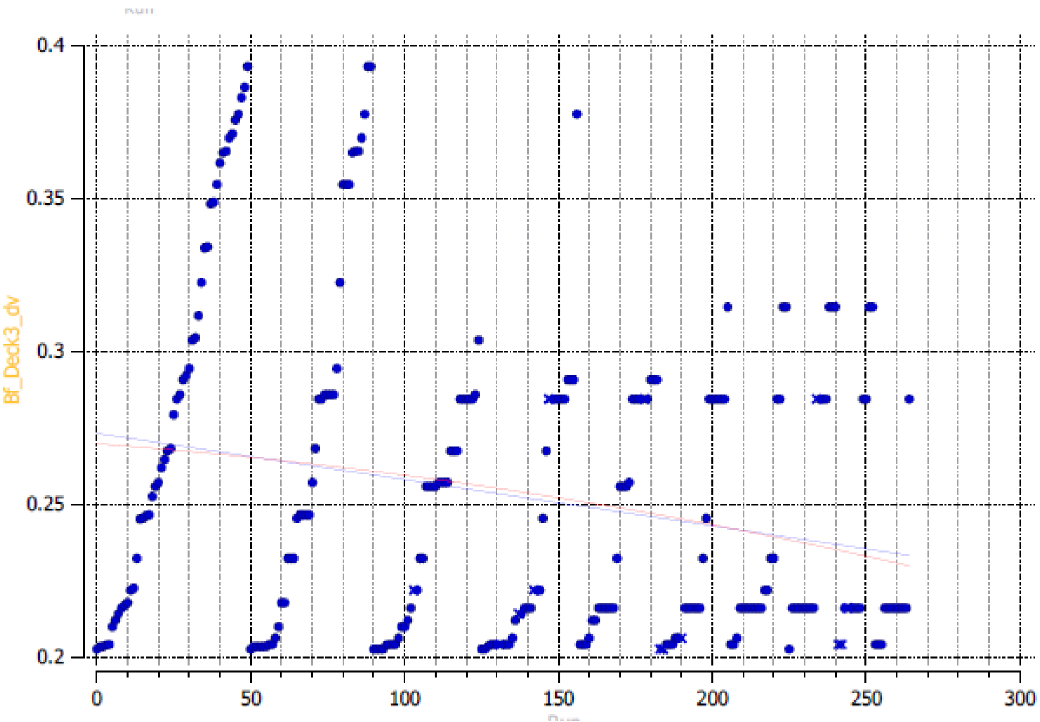


Figure 45distribution of Bf_Dec3 in design space

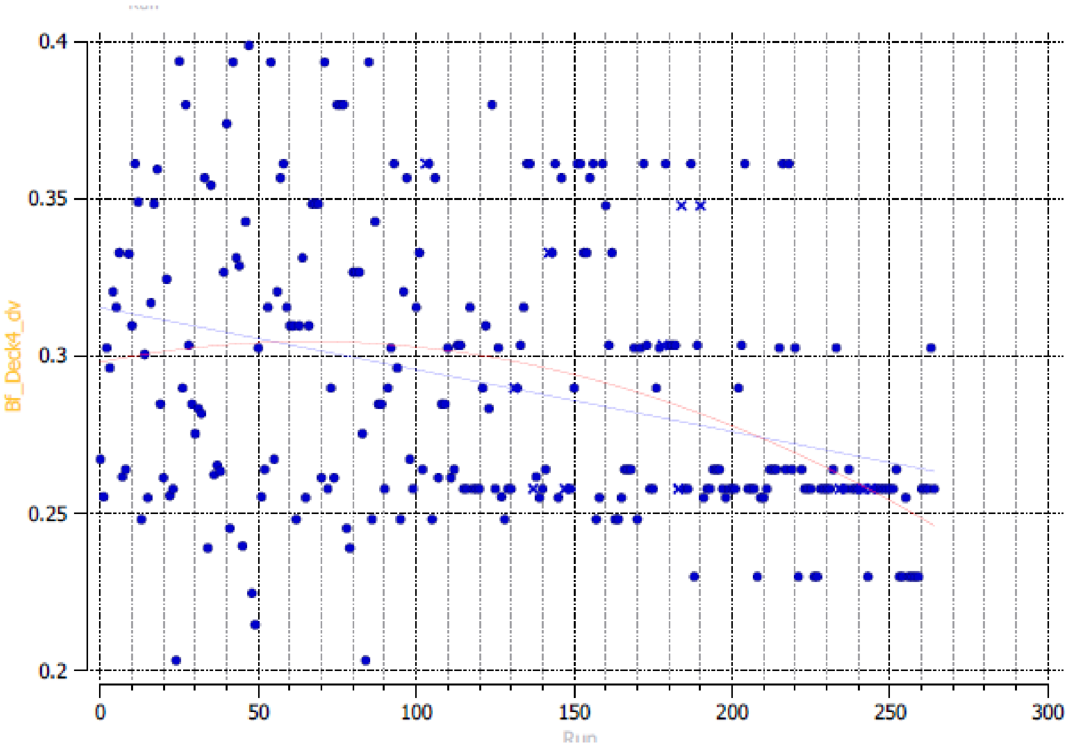


Figure 46 distribution of Bf_Deck4 in design space

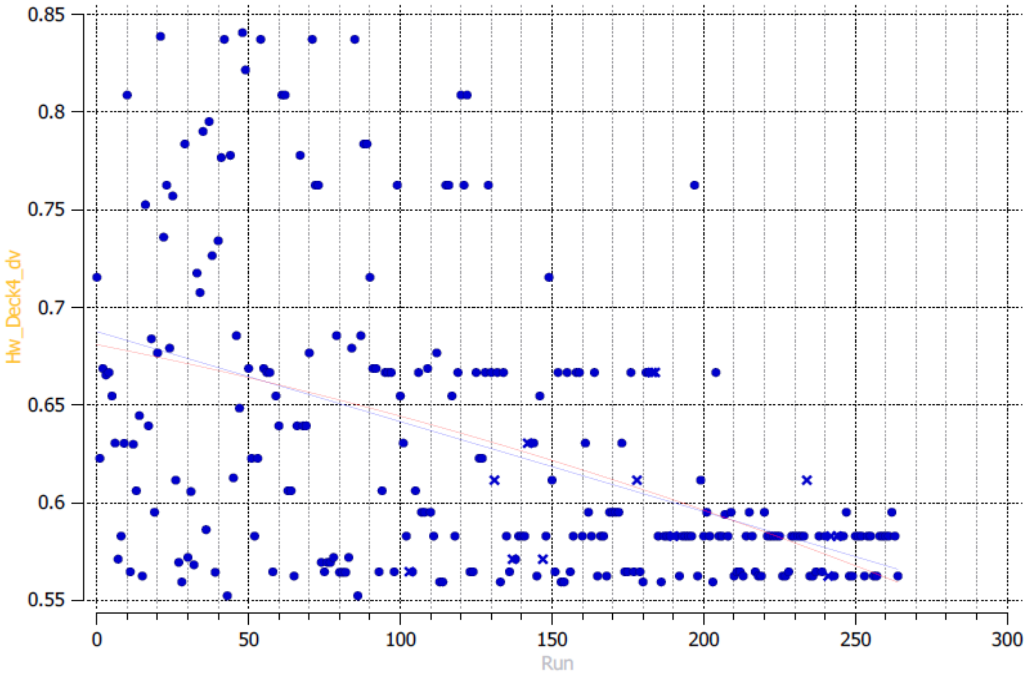


Figure 47distribution of Hw_Deck4 in design space

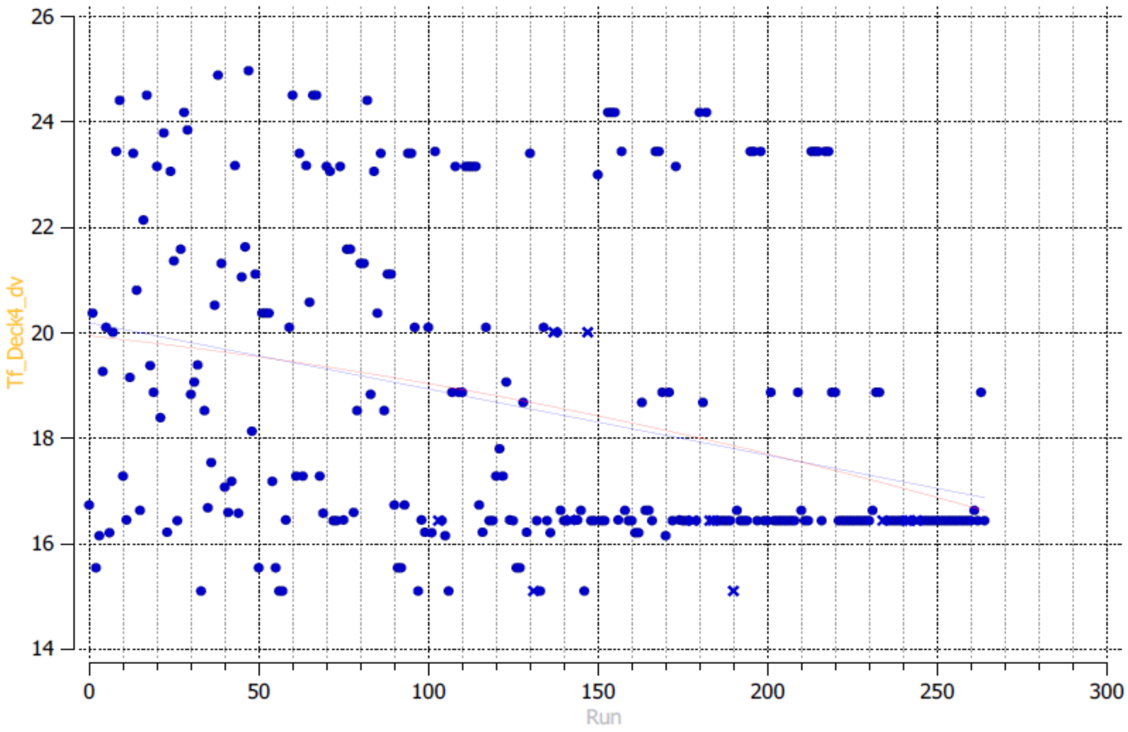


Figure 48 distribution of Tf_Deck3 in design space

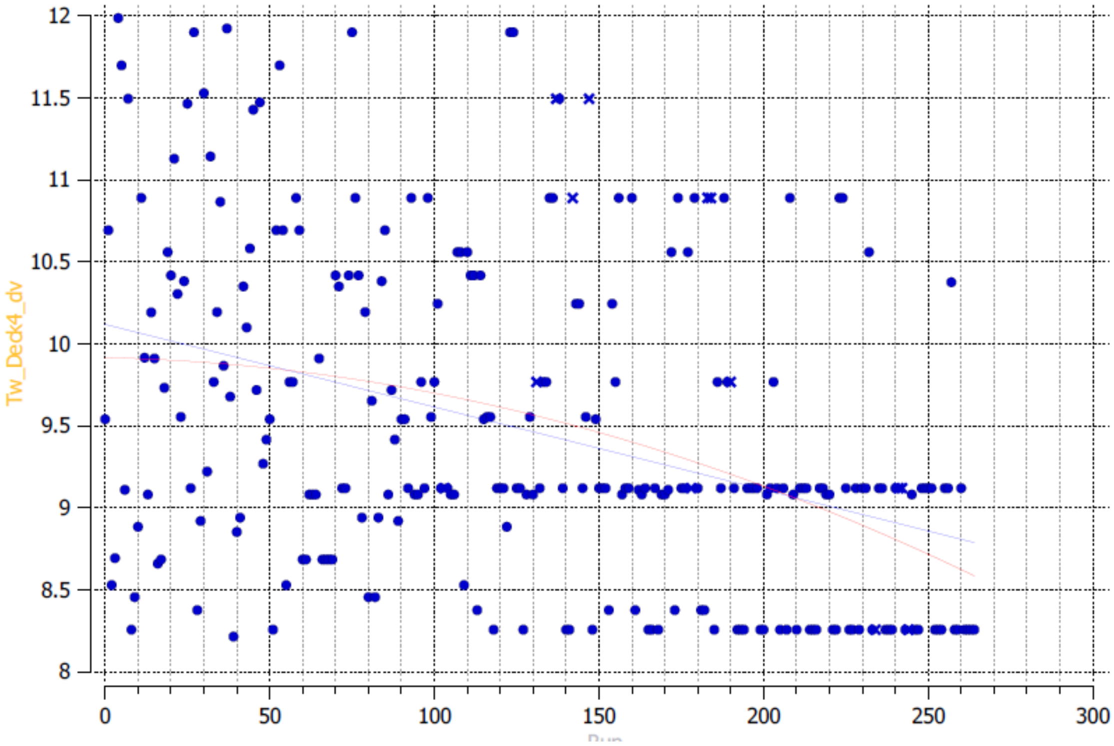
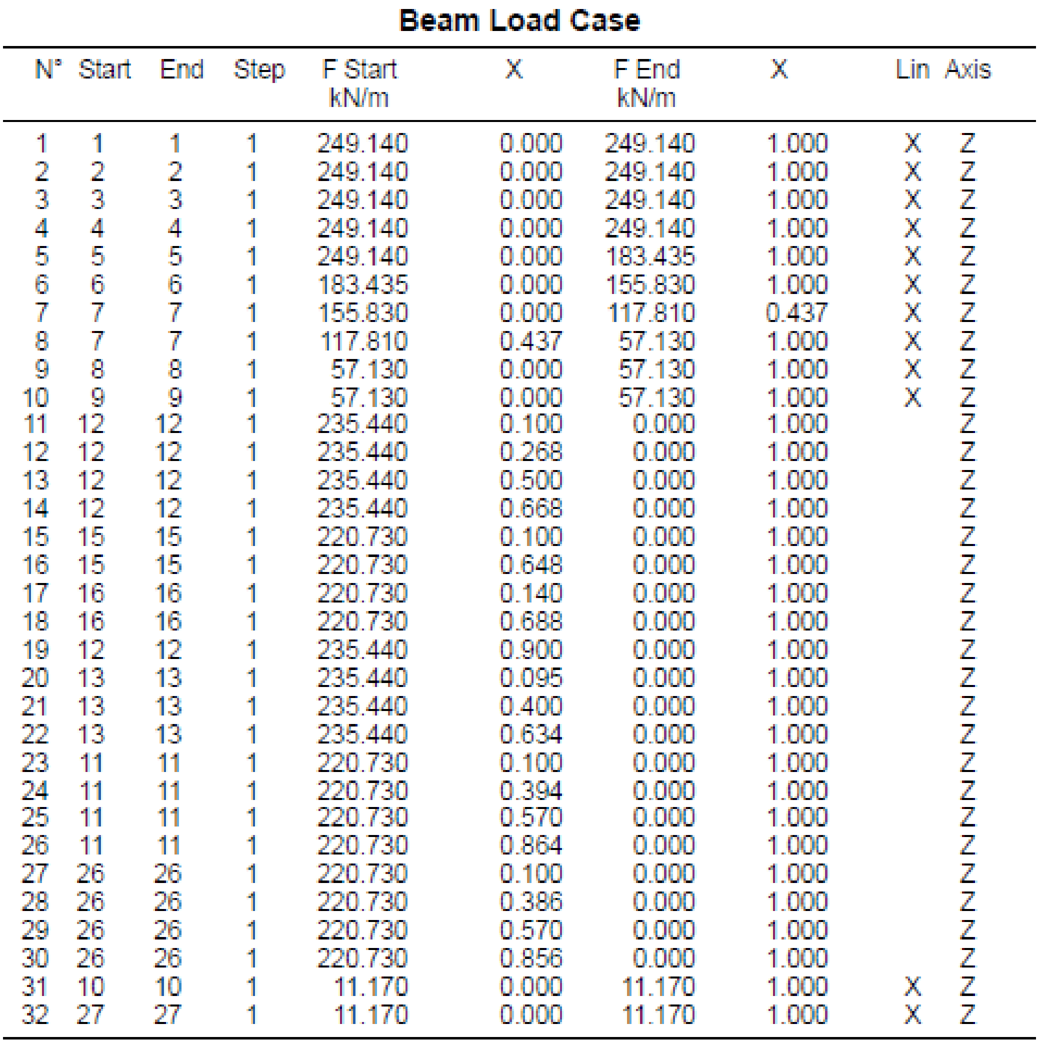


Figure 49 distribution of Tw_Deck4 in design space

# **APPENDIX A2.** Load Case a+ from RoPax STEEL model



**Beam Load Case**

| N° | Start | End | Step | F Start kN/m | X | F End kN/m | X | Lin | Axis |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 249.140 | 0.000 | 249.140 | 1.000 | X | Z |
| 2 | 2 | 2 | 1 | 249.140 | 0.000 | 249.140 | 1.000 | X | Z |
| 3 | 3 | 3 | 1 | 249.140 | 0.000 | 249.140 | 1.000 | X | Z |
| 4 | 4 | 4 | 1 | 249.140 | 0.000 | 249.140 | 1.000 | X | Z |
| 5 | 5 | 5 | 1 | 249.140 | 0.000 | 183.435 | 1.000 | X | Z |
| 6 | 6 | 6 | 1 | 183.435 | 0.000 | 155.830 | 1.000 | X | Z |
| 7 | 7 | 7 | 1 | 155.830 | 0.000 | 117.810 | 0.437 | X | Z |
| 8 | 7 | 7 | 1 | 117.810 | 0.437 | 57.130 | 1.000 | X | Z |
| 9 | 8 | 8 | 1 | 57.130 | 0.000 | 57.130 | 1.000 | X | Z |
| 10 | 9 | 9 | 1 | 57.130 | 0.000 | 57.130 | 1.000 | X | Z |
| 11 | 12 | 12 | 1 | 235.440 | 0.100 | 0.000 | 1.000 |  | Z |
| 12 | 12 | 12 | 1 | 235.440 | 0.268 | 0.000 | 1.000 |  | Z |
| 13 | 12 | 12 | 1 | 235.440 | 0.500 | 0.000 | 1.000 |  | Z |
| 14 | 12 | 12 | 1 | 235.440 | 0.668 | 0.000 | 1.000 |  | Z |
| 15 | 15 | 15 | 1 | 220.730 | 0.100 | 0.000 | 1.000 |  | Z |
| 16 | 15 | 15 | 1 | 220.730 | 0.648 | 0.000 | 1.000 |  | Z |
| 17 | 16 | 16 | 1 | 220.730 | 0.140 | 0.000 | 1.000 |  | Z |
| 18 | 16 | 16 | 1 | 220.730 | 0.688 | 0.000 | 1.000 |  | Z |
| 19 | 12 | 12 | 1 | 235.440 | 0.900 | 0.000 | 1.000 |  | Z |
| 20 | 13 | 13 | 1 | 235.440 | 0.095 | 0.000 | 1.000 |  | Z |
| 21 | 13 | 13 | 1 | 235.440 | 0.400 | 0.000 | 1.000 |  | Z |
| 22 | 13 | 13 | 1 | 235.440 | 0.634 | 0.000 | 1.000 |  | Z |
| 23 | 11 | 11 | 1 | 220.730 | 0.100 | 0.000 | 1.000 |  | Z |
| 24 | 11 | 11 | 1 | 220.730 | 0.394 | 0.000 | 1.000 |  | Z |
| 25 | 11 | 11 | 1 | 220.730 | 0.570 | 0.000 | 1.000 |  | Z |
| 26 | 11 | 11 | 1 | 220.730 | 0.864 | 0.000 | 1.000 |  | Z |
| 27 | 26 | 26 | 1 | 220.730 | 0.100 | 0.000 | 1.000 |  | Z |
| 28 | 26 | 26 | 1 | 220.730 | 0.386 | 0.000 | 1.000 |  | Z |
| 29 | 26 | 26 | 1 | 220.730 | 0.570 | 0.000 | 1.000 |  | Z |
| 30 | 26 | 26 | 1 | 220.730 | 0.856 | 0.000 | 1.000 |  | Z |
| 31 | 10 | 10 | 1 | 11.170 | 0.000 | 11.170 | 1.000 | X | Z |
| 32 | 27 | 27 | 1 | 11.170 | 0.000 | 11.170 | 1.000 | X | Z |

## APPENDIX A3: Results from STEEL–modeFRONTIER RoRo hull Loop With 8 Design Variables

| X1 | X2 | X3 | X4 | X5 | X6 | X7 | X8 | W |
|---|---|---|---|---|---|---|---|---|
| 1.1 | 8.25 | 0.3125 | 17.5 | 1.1 | 10.75 | 0.3125 | 22.5 | 4435 |
| 1.15 | 11.375 | 0.28125 | 18.75 | 1.15 | 10.125 | 0.46875 | 18.75 | 4502 |
| 1.05 | 7.625 | 0.46875 | 21.25 | 1.05 | 11.375 | 0.28125 | 16.25 | 4449 |
| 1.075 | 11.0625 | 0.359375 | 24.375 | 0.825 | 11.0625 | 0.484375 | 19.375 | 4507 |
| 1.2 | 7 | 0.281145 | 15.3175 | 1.2 | 12 | 0.25 | 24.9412 | 4434 |
| 1.2 | 9.8113 | 0.278115 | 20.3012 | 1.2 | 11.30165 | 0.2969575 | 17.511 | 4470 |
| 1.001432 | 10.6889 | 0.33569 | 22.7166 | 0.999768 | 9.5712 | 0.38798 | 15.715 | 4443 |
| 1.05 | 7.4714 | 0.46875 | 17.9732 | 1.05 | 10.5558 | 0.36285 | 15.8404 | 4431 |
| 1.110072 | 9.2196 | 0.4478475 | 21.3011 | 0.94292 | 12 | 0.4020425 | 19.4444 | 4503 |
| 1.11122 | 9.62965 | 0.25 | 23.1278 | 1.12714 | 8.7146 | 0.4743625 | 22.9894 | 4482 |
| 1.2 | 7.4714 | 0.30491 | 15.3175 | 1.2 | 12 | 0.25 | 24.9412 | 4446 |
| 1.035548 | 7.75905 | 0.388815 | 21.1904 | 1.02324 | 10.9165 | 0.378855 | 15.6248 | 4435 |
| 1.001436 | 10.8937 | 0.34049 | 22.7164 | 0.999768 | 9.5776 | 0.38806 | 16.5342 | 4450 |
| 0.986136 | 7.7866 | 0.458515 | 20.0718 | 1.094136 | 11.74325 | 0.391495 | 17.6009 | 4475 |
| 1.082112 | 7 | 0.5 | 15 | 0.990644 | 12 | 0.2939975 | 15 | 4410 |
| 1.179812 | 7.96865 | 0.442865 | 16.0583 | 1.087224 | 11.843 | 0.27191 | 17.6395 | 4445 |
| 1.105952 | 7 | 0.2530225 | 15 | 1.2 | 8.1921 | 0.4353225 | 25 | 4421 |
| 1.172344 | 7.13245 | 0.45429 | 15.3503 | 1.153132 | 10.15705 | 0.25479 | 15 | 4404 |
| 0.959304 | 9.63045 | 0.5 | 20.231 | 1.012844 | 9.4282 | 0.48336 | 19.3165 | 4495 |
| 1.2 | 7.4714 | 0.30491 | 15.3175 | 1.2 | 12 | 0.25 | 24.9348 | 4446 |
| 1.038328 | 7.5545 | 0.4721375 | 20.5352 | 0.9357 | 11.25115 | 0.3762675 | 15 | 4439 |
| 1.06006 | 7.3285 | 0.401045 | 15 | 1.114936 | 10.7385 | 0.311115 | 16.4224 | 4404 |
| 1.056252 | 9.62895 | 0.5 | 15.3014 | 0.939068 | 11.9787 | 0.3058325 | 15.1539 | 4439 |
| 1.2 | 7 | 0.5 | 15 | 1.063416 | 12 | 0.25 | 16.7105 | 4428 |
| 1.120488 | 7 | 0.3093025 | 15 | 1.057588 | 10.372 | 0.38537 | 22.2153 | 4418 |
| 1.2 | 7 | 0.48521 | 15.3797 | 1.2 | 8.6251 | 0.25 | 15 | 4392 |
| 0.959304 | 9.63045 | 0.5 | 20.231 | 1.0579 | 10.372 | 0.38537 | 19.3161 | 4489 |
| 1.100388 | 8.44385 | 0.370265 | 15 | 0.947096 | 10.83295 | 0.3705025 | 17.9736 | 4415 |
| 1.2 | 8.4772 | 0.477805 | 15 | 1.099336 | 10.4364 | 0.28251 | 15.3655 | 4432 |
| 0.95372 | 7.49695 | 0.4169 | 15 | 1.133724 | 10.0741 | 0.313175 | 15.7777 | 4390 |
| 1.15086 | 7 | 0.43332 | 15.0361 | 1.118112 | 9.8604 | 0.294865 | 15.415 | 4395 |
| 1.2 | 7 | 0.5 | 15 | 1.114936 | 10.7385 | 0.311115 | 16.704 | 4431 |
| 1.124204 | 7 | 0.28928 | 15 | 1.045992 | 9.4162 | 0.5 | 23.2604 | 4439 |
| 1.2 | 7 | 0.48521 | 20.2311 | 1.0579 | 10.372 | 0.25 | 15 | 4429 |
| 1.136996 | 7.29555 | 0.426965 | 15.3091 | 1.180636 | 8.5096 | 0.3139725 | 17.2138 | 4396 |
| 1.15086 | 8.4432 | 0.370265 | 15 | 0.947096 | 10.83295 | 0.3705025 | 16.3352 | 4413 |
| 1.2 | 8.4772 | 0.477805 | 15 | 1.133724 | 10.4325 | 0.28251 | 15.3655 | 4436 |
| 0.95424 | 7.49695 | 0.4169 | 15 | 1.114936 | 10.7385 | 0.311115 | 16.704 | 4400 |
| 1.032772 | 7.42515 | 0.462375 | 15.0127 | 1.17456 | 9.7853 | 0.30031 | 15.9113 | 4404 |
| 0.95372 | 7.01055 | 0.43332 | 15.0361 | 1.118112 | 9.8604 | 0.294865 | 15.7782 | 4379 |
| 1.2 | 7 | 0.5 | 15 | 1.114936 | 10.7417 | 0.311115 | 16.704 | 4431 |
| 0.977892 | 7.30955 | 0.3636575 | 15.0284 | 1.118996 | 10.21865 | 0.3238775 | 15 | 4379 |
| 0.95372 | 7.49695 | 0.43332 | 15.0361 | 1.118112 | 9.8604 | 0.313175 | 15.7777 | 4388 |
| 1.100332 | 7.42595 | 0.41818 | 15 | 1.12438 | 10.2634 | 0.32432 | 15.4267 | 4405 |
| 1.150424 | 7.23125 | 0.3739 | 15.4162 | 1.1908 | 8.62855 | 0.31655 | 17.0845 | 4390 |
| 0.9232 | 9.06465 | 0.3026 | 15 | 0.946208 | 10.99295 | 0.3376875 | 17.6804 | 4384 |
| 0.918336 | 7.2139 | 0.421265 | 15.0316 | 1.13914 | 9.81595 | 0.295535 | 15.6011 | 4377 |
| 0.954232 | 7.01055 | 0.43332 | 15.0361 | 1.118112 | 9.8604 | 0.294865 | 15.7782 | 4379 |
| 0.987368 | 7.21775 | 0.437385 | 15.2237 | 1.151236 | 9.34335 | 0.302995 | 16.5214 | 4387 |
| 0.950312 | 7.2535 | 0.327925 | 15.0206 | 1.074532 | 9.9803 | 0.3209125 | 17.2671 | 4369 |
| 0.8 | 8.74685 | 0.4095525 | 15.0161 | 1.084876 | 10.36155 | 0.30074 | 17.7342 | 4389 |
| 1.150408 | 7.2312 | 0.37358 | 15.4162 | 1.190672 | 9.85735 | 0.31655 | 17.0845 | 4408 |
| 0.918336 | 7.2179 | 0.437385 | 15.2237 | 1.151236 | 9.34335 | 0.302995 | 16.5214 | 4381 |
| 0.91596 | 7.04785 | 0.43924 | 15.0599 | 1.117656 | 9.4733 | 0.2675625 | 15.7832 | 4367 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.953688 | 10.28735 | 0.4538 | 15.0361 | 1.118112 | 9.8604 | 0.294865 | 15.7782 | 4422 |
| 0.987368 | 7.21775 | 0.437385 | 15.2237 | 1.151236 | 9.34335 | 0.302995 | 16.5254 | 4387 |
| 1.061672 | 7.2887 | 0.2809925 | 15 | 1.032576 | 9.71585 | 0.3587 | 17.6933 | 4372 |
| 0.979388 | 7.11675 | 0.4342125 | 15.1239 | 1.137636 | 9.3668 | 0.2776025 | 16.5504 | 4378 |
| 0.954232 | 7.01055 | 0.4314 | 15.036 | 1.085344 | 9.86045 | 0.294825 | 22.2294 | 4398 |
| 0.918336 | 7.2179 | 0.432265 | 15.0361 | 1.151232 | 9.34335 | 0.302995 | 16.5214 | 4379 |
| 0.975652 | 7.1665 | 0.4212375 | 15.0175 | 1.114072 | 10.14165 | 0.3083325 | 16.9748 | 4391 |
| 0.930736 | 8.81555 | 0.41887 | 15.1765 | 1.11976 | 9.4292 | 0.3019975 | 16.2858 | 4393 |
| 0.940216 | 7.0633 | 0.4391375 | 15.128 | 1.13028 | 9.4082 | 0.28113 | 16.3244 | 4374 |
| 0.955 | 7.01055 | 0.43332 | 15.0361 | 1.118112 | 9.8604 | 0.294865 | 15.7782 | 4379 |
| 0.922636 | 7.01155 | 0.434835 | 15.0938 | 1.11928 | 9.46065 | 0.2709775 | 16.2855 | 4368 |
| 0.917484 | 7.11555 | 0.287875 | 15.0338 | 1.108084 | 9.4717 | 0.2957125 | 17.1663 | 4349 |
| 0.950648 | 7.11915 | 0.43244 | 15.0784 | 1.125948 | 9.355 | 0.2783825 | 15.4878 | 4370 |
| 0.91596 | 7.21825 | 0.432265 | 15.0361 | 1.151232 | 9.47335 | 0.2675625 | 15.7832 | 4371 |
| 0.97514 | 7.1665 | 0.2574775 | 15.1263 | 1.112028 | 10.14165 | 0.3083325 | 16.9748 | 4361 |
| 0.920476 | 7.20665 | 0.43527 | 15.0744 | 1.134116 | 9.39405 | 0.285395 | 16.382 | 4375 |
| 0.940624 | 7.10245 | 0.4268425 | 15.0854 | 1.087 | 9.30535 | 0.2890125 | 17.4946 | 4372 |
| 0.91596 | 7.04785 | 0.43332 | 15.0585 | 1.117656 | 9.4733 | 0.2675625 | 15.7832 | 4365 |
| 0.954232 | 7.04575 | 0.4314 | 15.036 | 1.085344 | 9.86045 | 0.294825 | 22.2294 | 4399 |

## APPENDIX A4. R Code for Polynomial quadratic RSM with 8 Variables

```
R version 3.4.1 (2017-06-30) -- "Single Candle"
Copyright (C) 2017 The R Foundation for Statistical Computing
Platform: x86_64-w64-mingw32/x64 (64-bit)

R is free software and comes with ABSOLUTELY NO WARRANTY.
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.

>library("rsm", lib.loc="~/R/win-library/3.4")
>library(readr)
>Dataset_8Variables <- read_delim("D:/EMSHIP/Internship/HOLISHIP/Liege-ULg/Work/R
Tool/with 8 variables/Dataset_8Variables.dat",
+     "\t", escape_double = FALSE, trim_ws = TRUE)
>library("rsm", lib.loc="~/R/win-library/3.4")
>Dataset_8Variables_CODED <- coded.data(Dataset_8Variables,x1~(A-1)/0.2,x2~(B-
9.1875)/2.1875,x3~(C-.375)/.125,x4~(D-19.6875)/4.6875,x5~(E-1.0125)/.1875,x6~(F-
10.09605)/1.90395,x7~(G-.375)/.125,x8~(H-20)/5)
>wCODED.rsm<-  rsm(W ~ SO(x1,x2,x3,x4,x5,x6,x7,x8),Dataset_8Variables_CODED)
>summary(wCODED.rsm)
```

# APPENDIX A5: Trends of parameters against weight of transverse frame from STEEL- CAESES Parametric Hull loop

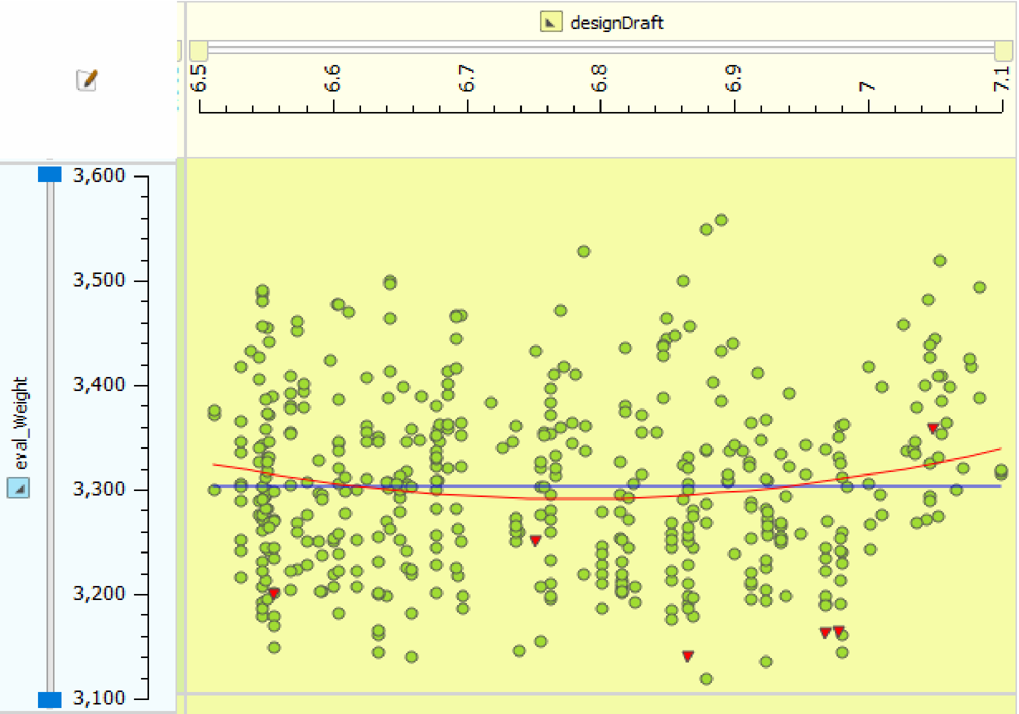


Figure 50 Design draft (in m) against Weight of main transverse frame (Ton/100)

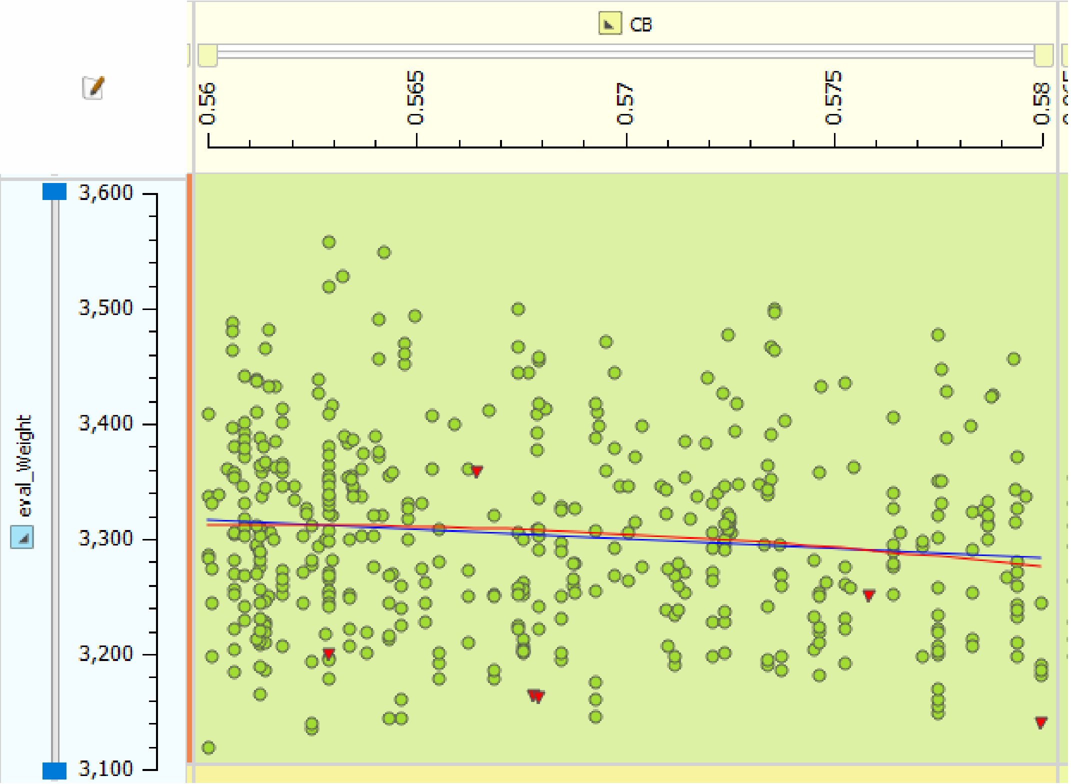


Figure 51 CB against Weight of main transverse frame (Ton/100)

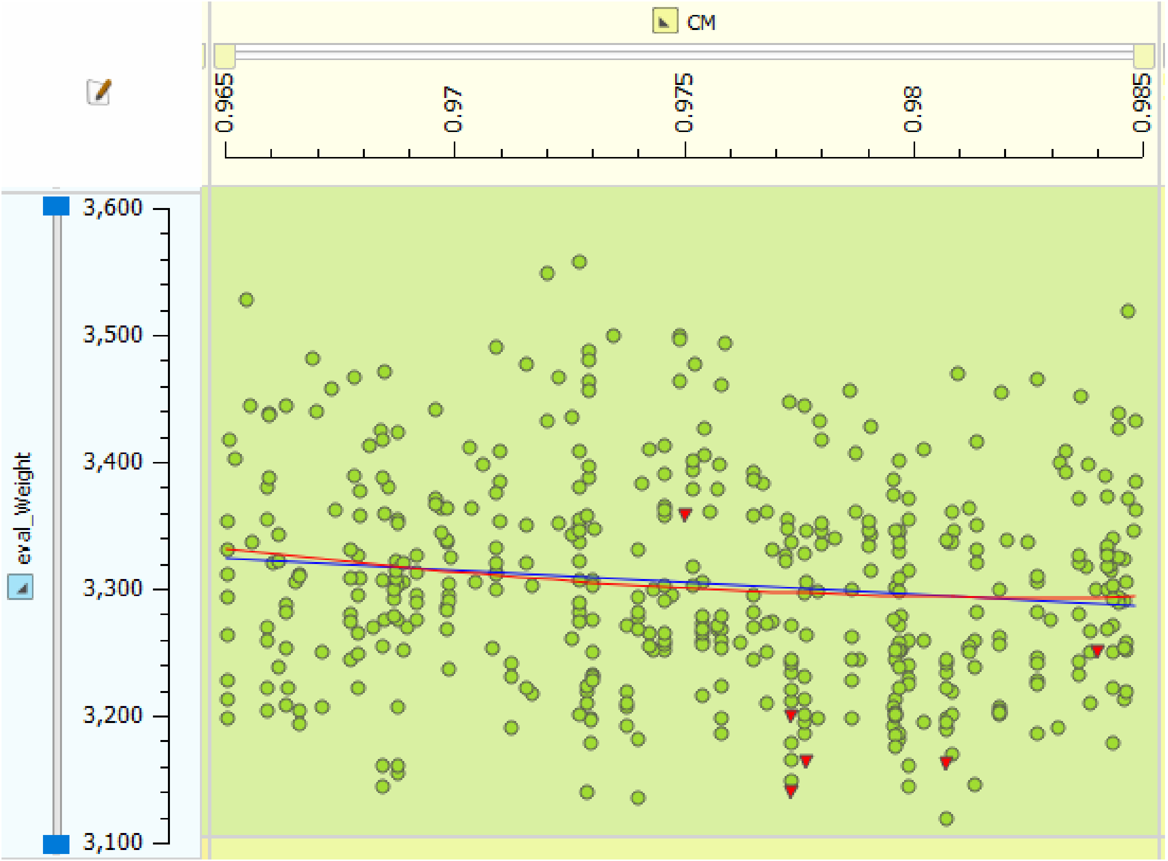


Figure 52 CM against Weight of main transverse frame (Ton/100)

## APPENDIX A6: R Code For Artificial Neural Network

```
R version 3.4.1 (2017-06-30) -- "Single Candle"
Copyright (C) 2017 The R Foundation for Statistical Computing
Platform: x86_64-w64-mingw32/x64 (64-bit)

R is free software and comes with ABSOLUTELY NO WARRANTY.
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.

> library("neuralnet", lib.loc="~/R/win-library/3.4")
> set.seed(400)
> library(readr)
> rsm_database <- read_delim("C:/Users/Lenovo/Desktop/Master Thesis/Data/R
Tool/modeFRONTIER dataset/rsm_database.dat",
+     "\t", escape_double = FALSE, trim_ws = TRUE)

> DataFrame<-rsm_database
> maxs<-apply
> maxValue<-apply(DataFrame,2,max)
> minValue<-apply(DataFrame,2, min)
> DataFrame<-as.data.frame(scale(DataFrame,center = minValue,scale = maxValue -
minValue))
> ind<-sample(1:nrow(DataFrame),250)
> trainDF<- DataFrame[ind,]
> testDF<- DataFrame[-ind,]
> allVars<-colnames(DataFrame)
> predictorVars<-allVars[!allVars%in%"W"]
> predictorVars<-paste(predictorVars,collapse = "+")
> form=as.formula(paste("E~",predictorVars,collapse = "+"))
> form=as.formula(paste("W~",predictorVars,collapse = "+"))
> neuralModel<-neuralnet(formula=form,hidden = c(8,4,2),linear.output = T,data = trainDF)
> View(neuralModel)
> plot(neuralModel)
> predictions<- compute(neuralModel,testDF[,1:8])
> predictions<- compute(neuralModel,testDF[,1:8])
> predictions$net.result
> actualvalues<-testDF$W*(max(rsm_database$W)-
min(rsm_database$W))+min(rsm_database$W)
> actualpredictions<-predictions$net.result*(max(rsm_database$W)-
min(rsm_database$W))+min(rsm_database$W)
> MSE<- sum((actualpredictions- actualvalues)^2)/nrow(testDF)
> MSE
```

## APPENDIX A7: DAKOTA Export From CAESES for Polynomial quadratic model with 4 variables

```
Model for response obj_fn:
-----
Surfpack polynomial model
f(x) = sum_k{c_k * prod_k[x(i) ^ p(k,i)]}; where

inputs = 4
bases = 15

c (1 x bases) =
4.1925069504637058e+003 1.9318548454755760e+001 -2.9868440342483842e+000
1.1644774910670472e+001 -1.2645921561634282e+001 -5.1046831964153591e-002
3.5806171040143369e+000 -1.3268262337334019e-001 2.2806266504931433e-001 -6.7122387863977877e-
003 1.9949632572572771e+001 -1.1130346535697022e+001 1.2284709313310014e+001
2.7821822493996878e-001 -3.0438477522011518e-003

p (bases x inputs) =
  0   0   0   0
  1   0   0   0
  2   0   0   0
  1   1   0   0
  1   0   1   0
  1   0   0   1
  0   1   0   0
  0   2   0   0
  0   1   1   0
  0   1   0   1
  0   0   1   0
  0   0   2   0
  0   0   1   1
  0   0   0   1
  0   0   0   2
```

# APPENDIX A8: Results from STEEL–modeFRONTIER RoRo hull Loop With 4 Design Variables

| X1 | X2 | X3 | X4 | W |
|---|---|---|---|---|
| 0.9 | 10.75 | 0.4375 | 22.5 | 4469 |
| 1.15 | 11.375 | 0.28125 | 18.75 | 4455 |
| 1.075 | 11.0625 | 0.359375 | 24.375 | 4483 |
| 0.975 | 9.8125 | 0.296875 | 21.875 | 4426 |
| 1.125 | 10.4375 | 0.453125 | 15.625 | 4460 |
| 0.825 | 11.6875 | 0.390625 | 18.125 | 4434 |
| 1.0375 | 11.84375 | 0.4921875 | 16.5625 | 4480 |
| 0.9375 | 10.59375 | 0.4296875 | 19.0625 | 4452 |
| 1.1875 | 9.96875 | 0.3359375 | 22.8125 | 4469 |
| 1.187468 | 9.96875 | 0.3359375 | 22.8125 | 4469 |
| 0.9 | 10.75 | 0.4426225 | 22.4984 | 4470 |
| 1.125524 | 8.91145 | 0.25 | 20.7246 | 4416 |
| 0.825 | 11.3803 | 0.36317 | 18.125 | 4425 |
| 0.9174 | 11.3764 | 0.4297375 | 20.1806 | 4464 |
| 1.034196 | 10.44545 | 0.4267725 | 21.4625 | 4474 |
| 1.083084 | 11.53765 | 0.3602025 | 18.4535 | 4464 |
| 0.843912 | 11.6875 | 0.390625 | 18.125 | 4437 |
| 1.032756 | 10.8141 | 0.3556875 | 17.8668 | 4444 |
| 1.07332 | 11.0452 | 0.33681 | 16.8342 | 4444 |
| 0.9375 | 11.84175 | 0.4296875 | 19.0625 | 4466 |
| 0.937532 | 10.59415 | 0.4296825 | 19.0593 | 4452 |
| 1.16446 | 9.32185 | 0.29867 | 22.0312 | 4443 |
| 1.2 | 10.7039 | 0.3600225 | 19.387 | 4473 |
| 1.187468 | 9.32185 | 0.33593 | 22.8125 | 4459 |
| 0.937532 | 10.74775 | 0.4426225 | 19.0616 | 4457 |
| 0.9174 | 11.3252 | 0.430365 | 20.9998 | 4468 |
| 1.125524 | 9.15145 | 0.347545 | 20.346 | 4442 |
| 1.125436 | 10.75995 | 0.2626625 | 18.6844 | 4438 |
| 1.083028 | 11.53765 | 0.3602025 | 18.4535 | 4464 |
| 0.842888 | 11.6875 | 0.390625 | 18.125 | 4437 |
| 1.032864 | 10.0922 | 0.26455 | 19.4204 | 4420 |
| 1.125524 | 10.59465 | 0.2500025 | 20.7246 | 4439 |
| 1.125548 | 8.91145 | 0.25 | 22.0312 | 4420 |
| 1.015308 | 11.49435 | 0.25 | 20.415 | 4435 |
| 0.8 | 12 | 0.37254 | 17.699 | 4428 |
| 1.094892 | 10.25845 | 0.25674 | 19.3222 | 4428 |
| 1.005728 | 11.10985 | 0.2843575 | 18.235 | 4430 |
| 1.04554 | 9.5055 | 0.25 | 18.3784 | 4407 |
| 0.828584 | 11.3803 | 0.36317 | 18.125 | 4425 |
| 1.174892 | 8.73415 | 0.25 | 21.9526 | 4422 |
| 0.966564 | 11.58665 | 0.25 | 17.0776 | 4419 |
| 1.2 | 8.9882 | 0.25 | 21.3034 | 4427 |
| 0.936252 | 11.84715 | 0.3324625 | 17.2007 | 4435 |
| 1.101916 | 8.89625 | 0.25 | 20.5232 | 4412 |
| 0.980896 | 9.6704 | 0.3054675 | 21.0368 | 4424 |
| 1.011768 | 10.8596 | 0.2560925 | 19.1926 | 4424 |
| 1.120924 | 9.54555 | 0.25705 | 21.5152 | 4428 |
| 1.037148 | 9.7289 | 0.26575 | 17.1055 | 4408 |
| 1.2 | 7.96845 | 0.25 | 25 | 4423 |
| 0.962156 | 10.27715 | 0.2653975 | 18.127 | 4409 |
| 1.04554 | 9.5055 | 0.25 | 16.8424 | 4402 |
| 1.134872 | 10.6342 | 0.2548825 | 20.5161 | 4441 |
| 1.09072 | 11.3803 | 0.36301 | 18.125 | 4462 |
| 1.2 | 8.1425 | 0.25 | 21.7427 | 4415 |
| 1.2 | 8.9882 | 0.25 | 21.3098 | 4427 |
| 1.034556 | 9.7289 | 0.33247 | 17.2007 | 4423 |

| | | | | |
|---|---|---|---|---|
| 1.101916 | 8.89625 | 0.26575 | 17.1055 | 4405 |
| 1.149692 | 8.28965 | 0.2982925 | 24.358 | 4435 |
| 1.033052 | 9.7289 | 0.26591 | 17.1047 | 4408 |
| 1.2 | 8.14245 | 0.25 | 21.7427 | 4415 |
| 1.16764 | 10.63425 | 0.2549225 | 16.9672 | 4435 |
| 1.2 | 9.2065 | 0.25 | 20.0705 | 4426 |
| 1.045668 | 9.5055 | 0.25 | 17.0776 | 4403 |
| 1.064732 | 9.04845 | 0.26351 | 20.8838 | 4415 |
| 1.000408 | 10.26895 | 0.25 | 19.6644 | 4415 |
| 1.17522 | 9.04375 | 0.25 | 17.1307 | 4412 |
| 1.093144 | 9.22545 | 0.2883825 | 17.0925 | 4413 |
| 1.035884 | 9.7289 | 0.26575 | 18.1271 | 4412 |
| 0.982516 | 10.86615 | 0.25 | 15 | 4406 |
| 1.108628 | 9.1209 | 0.25632 | 17.6114 | 4408 |
| 1.113232 | 10.28365 | 0.261615 | 18.1107 | 4428 |
| 0.962284 | 10.27715 | 0.3063375 | 21.431 | 4431 |
| 1.004504 | 10.26895 | 0.25 | 19.6644 | 4416 |
| 1.148684 | 8.96985 | 0.285505 | 17.2273 | 4416 |
| 1.052796 | 10.1436 | 0.25 | 15.8863 | 4409 |
| 1.17522 | 9.04375 | 0.28072 | 17.0925 | 4418 |
| 1.03922 | 9.4732 | 0.2683475 | 17.9749 | 4409 |
| 1.053748 | 9.50405 | 0.26984 | 18.1996 | 4412 |
| 0.990176 | 11.32955 | 0.25 | 15 | 4412 |
| 1.2 | 10.8546 | 0.25 | 20.5776 | 4452 |
| 0.995644 | 10.5635 | 0.26295 | 16.0676 | 4410 |
| 1.113268 | 9.02925 | 0.25 | 17.1307 | 4405 |
| 1.17522 | 10.27895 | 0.2500175 | 17.1307 | 4430 |
| 0.962156 | 10.27715 | 0.2653625 | 18.127 | 4409 |
| 0.951768 | 10.34675 | 0.28252 | 20.7069 | 4422 |
| 1.035884 | 10.2689 | 0.26574 | 18.1271 | 4419 |
| 1.026652 | 9.7177 | 0.2538 | 17.2957 | 4405 |
| 0.984024 | 10.86615 | 0.25 | 19.664 | 4420 |
| 1.044588 | 9.5047 | 0.41384 | 16.8297 | 4436 |
| 1.045564 | 9.5055 | 0.25 | 15.8952 | 4399 |
| 1.108628 | 9.1209 | 0.28072 | 17.0925 | 4412 |
| 1.04554 | 9.5055 | 0.25 | 18.0712 | 4406 |
| 1.019184 | 10.4762 | 0.25 | 16.6599 | 4411 |
| 1.195656 | 8.89995 | 0.255305 | 18.5431 | 4418 |
| 1.03284 | 10.15065 | 0.254485 | 16.0381 | 4407 |
| 0.962228 | 10.27715 | 0.2500025 | 17.1307 | 4403 |
| 0.98642 | 10.01635 | 0.25414 | 17.2431 | 4404 |
| 1.011572 | 11.9534 | 0.25 | 15 | 4423 |
| 1.024296 | 10.0378 | 0.264245 | 17.4336 | 4412 |
| 1.045532 | 9.5055 | 0.25256 | 17.2957 | 4404 |
| 1.052796 | 10.886 | 0.25 | 19.664 | 4430 |
| 1.037436 | 9.51945 | 0.3486075 | 17.5016 | 4425 |
| 1.08314 | 9.20355 | 0.25 | 15.837 | 4400 |
| 1.030536 | 9.6042 | 0.30008 | 17.1934 | 4414 |
| 0.98642 | 10.01635 | 0.251015 | 17.2249 | 4403 |
| 1.144968 | 10.9493 | 0.25 | 17.0972 | 4435 |
| 1.113268 | 9.02925 | 0.25 | 17.2431 | 4405 |
| 0.986884 | 10.01635 | 0.25414 | 15.8383 | 4399 |
| 1.011572 | 10.277 | 0.2500025 | 17.1307 | 4409 |
| 1.052796 | 10.3484 | 0.2500025 | 17.1307 | 4415 |
| 1.045692 | 9.4152 | 0.25 | 16.9363 | 4401 |
| 1.06248 | 9.47985 | 0.25 | 15 | 4398 |
| 1.037436 | 9.5055 | 0.25 | 17.5016 | 4403 |