Surrogate Model-Based Optimization of Offshore Jacket Structure to Develop Minimum Structure

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Abstract. A strategy to increase the production of oil and gas is through acceleration the development of marginal fields. Economic factors largely determine the marginal field. Currently, regarding structural design, there are still many results of offshore structures that are overdesigned at a certain level. Thus, structural optimization is important in the design phase. It leads to production cost minimization. Therefore, this study analyses the optimization of a jacket structure to get an economical and reliable minimum jacket structure. Dimension optimization will be carried out on the main structure of the jacket and the objective function in the form of minimizing material costs. Surrogate model is used to evaluate the structure. It is constructed by radial basis function. The optimization process uses the the non linear programming. This research is expected to recommend a minimum jacket structure optimization model approach that can be used especially for Indonesian waters.

Keywords: Design optimization, Nonlinear optimization, Offshore jacket structure, Radial basis function, Surrogate model.

1 Introduction

The demand for offshore platforms is increasing as humans still rely on both conventional and renewable energy. Offshore platforms that are commonly used are the jacket. Although its application is limited to shallow sea depths, jackets are still in demand due to their efficiency and reliability. This can be seen from the number of offshore platforms using a jacket as much as 95% [1]. Jacket structures in the Indonesian sea area is generally designed based on the standards of the Gulf of Mexico or European waters. This has led to some designs being too conservative and the construction spend large amounts of material. While, the development of oil and gas fields, especially the marginal field, must consider the economic aspect [2]. Thus, structural design optimization must be performed to obtain minimum structure.

The optimization model needs to be defined carefully for different cases because different formulation will give varied optimization outcomes. The structural designer must define the problem with constrained or unconstrained, single or multi variables and objectives. For shape optimization, the designer usually use selection method using discrete alternatives [3, 4]. In actual life, a

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jacket will typically have varying sizes for each member depending on the elevation. It leads to complex optimization problems as it will have more than one variable design. Motlagh et al. carried out a study in which they considered this. The optimization was performed by grouping some members with the same dimension, thus becoming multivariable problems [5]. Several factors that result in unrealistic design optimization are design variables that do not consider topology, cost assumptions that only consider weight, load simplification that is too simple, do not consider design code, and repeated simulations [6].

Two crucial processes for design optimization for offshore structures are the selection of optimization algorithms and the process of evaluating the strength of the structure. The main problem in evaluating the strength of the structure is the limited computational capability. The practical approach use simplified calculation to check the structural strength based on criteria. With the rapid growth of computing technology, structural evaluation by finite element analysis is preferred to analyse complex behavior. However, it is usually time-consuming and expensive. The different software to conduct the structural analysis and optimization is another challenge. Therefore, many researchers try to build a surrogate model as a computational evaluation of the structure for each design configuration [6–8].

This study will optimise the jacket structure dimension by using the surrogate model. The design variables are minimised so that minimal construction costs are obtained. Dimension as the design variables consist of the thickness and outer diameter of the bracing and the thickness of the jacket legs. Analysis will consider the design code properly by adding some recommended behaviour constraints. Loads are simulated based on finite element analysis to achieve more accurate structural behaviour. The results will be used to create the surrogate model. The surrogate will shorten iteration time of the optimization.

2 Optimization Problem

In this investigation, the goal that needs to be accomplished is to reduce the amount of money spent on materials. However, the jacket must be safe and reliable based on recommended structural check. Optimization problems consist of three main components, namely the objective function, design variables, and constraints. Those are described in the following sections.

2.1 Objective Function

The objective that must be attained in this study is minimizing material cost expressed by structural weight. The objective function, which is represented by the function of weight, is described in equations 1 and 2. Jacket weight consists of topside weight and jacket members weight. Topside weight and material density (γ_i) are constant for each variables. The cross sectional area which is denoted by A_i changes depending on tubular member's outer diameter (OD) and wall thickness (t).

$$\min F(x) = W(x) = W_{topside} + W_{jacket} = W_{topside} + \sum_{i=1}^{n} \gamma_i L_i A_i \quad (1)$$

$$A_i = \pi(OD^2 - (OD^2 - 2t)^2)/4 \quad (2)$$

2.2 Design Variables

The design variables that will be optimized are the thickness and outer diameter of the bracing and the thickness of the jacket leg. The Table 1 is a list of design variables with initial sizes before the optimization process. The bottom part of the jacket is not considered to be the design variables as it is a crucial part sensitive to the structural load. Therefore, it is not the scope of this study.

Table 1. List of design variables and initial dimensions.

Design Variables	**Member Group**	**Initial Dimension (in)**
x_1	Outer Diameter of Middle Diagonal Bracing	28.00
x_2	Wall Thickness of Middle Diagonal Bracing	1.75
x_3	Outer Diameter of Middle Horizontal Bracing	24.00
x_4	Wall Thickness of Middle Horizontal Bracing	1.00
x_5	Outer Diameter of Upper Diagonal Bracing	28.00
x_6	Wall Thickness of Upper Diagonal Bracing	1.75
x_7	Outer Diameter of Upper Horizontal Bracing	24.00
x_8	Outer Diameter of Upper Horizontal Bracing	1.00
x_9	Wall Thickness of Jackel Leg	2.50

2.3 Constraints

The constraints of the optimization problem comprised of side and behaviour constraints. The lower and upper bound is decided based on the common commercial size in industry and the local buckling ratio (OD/t) must be between 2 and 300 [9]. API RP 2A WSD were used to evaluate tubular members' unity check (UC) that correspond to the stress, buckling, and joint deflection behavior. The UC result must lower than 1.0.

In addition, the tubular joint must be adequate to transfer the loads. Thus, the nondimensional parameter consists of β, τ, dan γ is varied between recommended range by API RP 2A WSD [9] and Ahmadi et al. [10]. β and τ are the ratios between jacket leg and brace diameter and wall thickness, respectively. In comparison, γ is the jacket leg ratio between its diameter and thickness. Equations 3-5 show the validity range. The slenderness ratio of tubular members was also checked.

$$0.3 \leq \beta \leq 0.5 \quad (3)$$

$$0.4 \le \tau \le 1.0 \tag{4}$$

$$10 \le \gamma \le 24 \tag{5}$$

3 Surrogate Model for Evaluating The Platform

3.1 Structural and Environmental model

The three-legged jacket model does not consist topside in the simulation because the optimization focused on the jacket members only. Topside is considered as a joint load with a weight of 1,050 kips applied to the top node of the jacket. Environmental loads considered are current and wave loads. Configuration of upper braces jacket is K-brace while the middle braces is an X-brace. Based on different geometry dimensions for some elevations, the model will be divided into three parts, the top, middle, and bottom as shown in Fig. 1. The tubular members' material is S355 steel in accordance with ASTM A572. Details of the characteristics of the steel used are shown in Table 2.

The analyzed jacket structure is located in Madura Sea, Indonesia and has a depth of 262 ft. Environmental loads considered are waves and currents. The location of environmental data collection based on coordinate 112° 51'00" east and 6° 30'00" south. Wave and current data from 16 directions were used for in-place analysis. The environmental conditions considered are 10-year and 100-year, representing the operational and extreme conditions. Due to the currents, the wave loads on the structure were based on a modified Morison equation by adding the velocity of the wave particles.

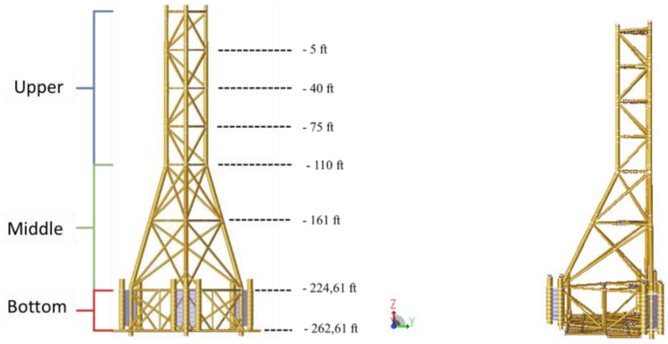

Fig. 1. Classified group of tubular members (left) and jacket structure left view (right).

Table 2. Material properties of tubular members.

Tensile Strength, Ultimate	65,300	psi
Tensile Strength, Yield	50,000	psi
Modulus of Elasticity	29,000	ksi
Poissons Ratio	0.260	
Shear Modulus	11,500	ksi

Density	490	lb/ft^3

3.2 Radial Basis Function

The RBF method solves curve-fitting and regression problems by activating the base function. A base function is a function that depends on the distance between its arguments. The basis function can be expressed in equation 6. Furthermore, this function will be used as a tool in generating new data in accordance with the characteristics of data sampling. New data was generated by interpolation function according to equation 7. The construction of the basis function can be seen in **Fig. 2**, which consists of three layers: input, hidden, and output.

$$g_j(x) = g(\|x - x_j\|), j = 1, \ldots, n \quad (6)$$

$$y_i = \sum_{j=1}^{Q} w_j \, g_j(x_i) \quad (7)$$

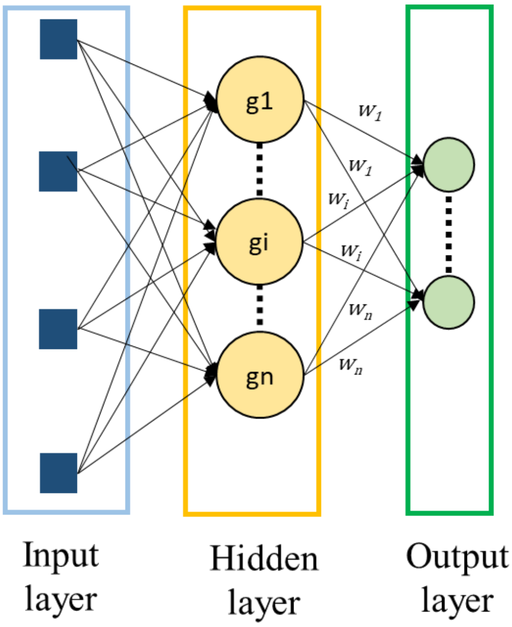

Fig. 2. Anatomy of radial basis function.

Four common types of basis functions are linear, cubic, gaussian, and multi-quadric. The four equations are sequentially shown in equations 8-11.

$$g_j(x) = g(\|x - x_j\|) \quad (8)$$

$$g_j(x) = g\left(\left\|x - x_j\right\|^3\right) \tag{9}$$

$$g_j(x) = exp\left(-\frac{\left\|x-x_j\right\|^2}{2{\delta_c}^2}\right) \tag{10}$$

$$g_j(x) = \sqrt{1 + \frac{\left\|x-x_j\right\|^2}{{\delta_c}^2}} \tag{11}$$

The error criterion for RBF recommended is the Leave-one-out cross validation (LOOCV) method. This method evaluates each predicted data, by sampling data. If the number of prediction data generated is *n* and there are a number of *m* sampling data, then the evaluation is carried out for each *n* of each *m*. This method is suitable for evaluating prediction results in machine learning. Then the root mean square error (RMSE) is calculated to be compared between different activation functions [11].

3.3 Surrogate model for structural evaluation

Replacing the finite element analysis is the purpose of the surrogate model. In this study, surrogate models correlate the design variables as input and maximum UC as output. The results become constraint functions in assessing the structural behavior for the optimization process.

Evaluation in this in-place analysis is a static approach by checking the structure's maximum unity check and maximum joint deflection. Unity check (UC) on the tubular member is the ratio between the stress or buckling that occurs with the allowable stress. The structure is said to be safe if it has a maximum UC of less than 1. According to the findings of the structural analysis, the five UCs with the highest value can be identified, as shown in Table 3. The maximum UC that occurs is far below the limit, which is only 0.26. These dimensions are conservative, so they must be optimized for optimal tubular dimensions.

The outcomes of the structural evaluation determined the constraints for the optimization. According to in-place analysis, the structure experiences the highest UC when exposed to loads from the west-northwest (WNW) direction. So for constructing the surrogate model, the simulations only vary from that direction. Variations for the formation of the model surrogate were performed to predict UC.

Table 3. The most critical members and their maximum unity check ratio.

Member Group	Critical member code	Maximum UC
JL	0023-0026	0.26
JL	0055-0023	0.23
HBT	0050-0104	0.22
DBT	0120-0023	0.19

JL	0001-0012	0.16

Table 4. Error prediction of multiquadric activation function for each design variable.

Design Variables	LOOCV Error
x_1	0.64%
x_2	0.54%
x_3	0.13%
x_4	0.53%
x_5	0.15%
x_6	0.71%
x_7	1.43%
x_8	1.51%
x_9	0.93%

When developing the RBF model, it is essential to select one of the four radial basis functions to reduce the amount of error introduced into the prediction process. Table 4 displays the error predictions that were derived from the LOOCV validation for each of the estimated design variables.

Based on in-place analysis, surrogate model activation functions are multiquadric for all design variables in this study. The results of the surrogate model applied to the design variable x_1 are displayed in **Fig. 3**. Data fitting is done based on the radial basis function model to obtain polynomial equations for each design variable. The compatibility of the equation is seen from the R-squared (R^2), which indicates a better result if it is close to one. The error between prediction and regression is seen from the residual. Equations 12 until 20 will be included in the optimization process as constraint functions as the result of surrogate models. Those nine functions must be under 1,0 because of the maximum unity check ratio.

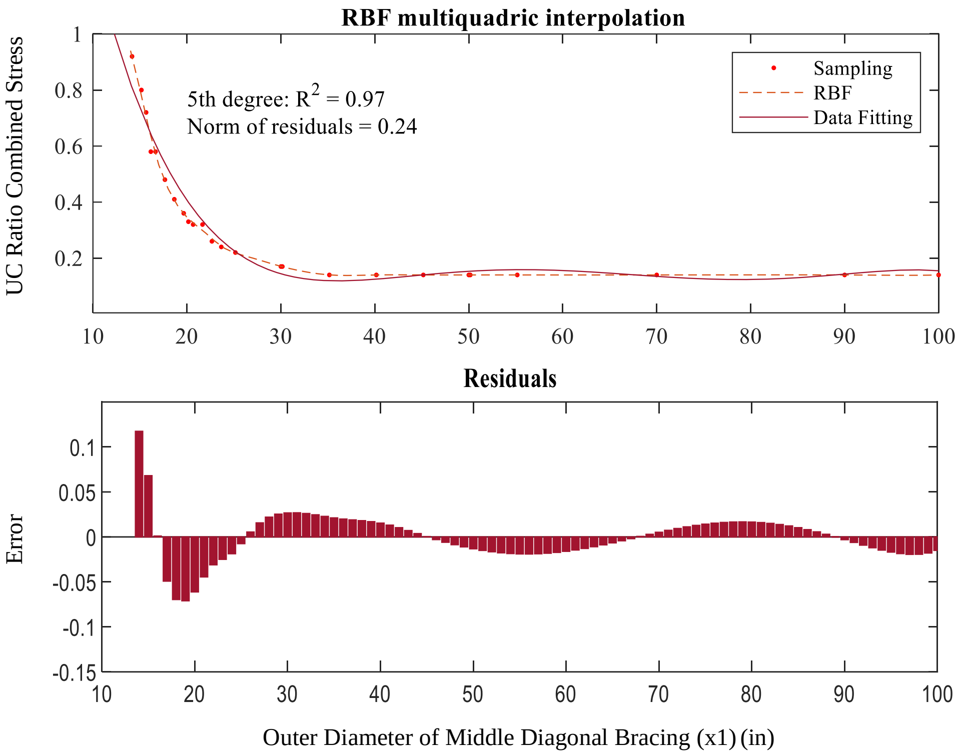

Fig. 3. RBF model for design variable x_1.

$$g_1(x_1) = 3.7e - 9x^5 + 1,2e - 6x^4 - 0,00016x^3 + 0,0099 * x^2 - 0,29x + 3,3 \tag{12}$$

$$g_2(x_2) = - 0,032x^5 + 0,39x^4 - 1,8x^3 + 3,8x^2 - 4x + 1,8 \tag{13}$$

$$g_3(x_3) = -4,3e - 9x^5 + 1,4e - 6x^4 - 0,00017x^3 + 0,0098x^2 - 0,26x + 2,8 \tag{14}$$

$$g_4(x_4) = - 0,00044x^7 + 0,012x^6 - 0,13x^5 + 0,74x^4 - 2,4x^3 + 4,2x^2 - 3,7x + 1,5 \tag{15}$$

$$g_5(x_5) = - 2,9e - 7x^5 + 4,2e - 5x^4 - 0,0025x^3 + 0,071x^2 - 0,98x + 5,5 \tag{16}$$

$$g_6(x_6) = - 0,13x^5 + 1,1x^4 - 3,7x^3 + 5,5x^2 - 3,7x + 1,1 \tag{17}$$

$$g_7(x_7) = - 1,8e - 7x^5 + 3,1e - 5x^5 - 0,002x^3 + 0,062x^2 - 0,94x + 5,7 \tag{18}$$

$$g_8(x_8) = -0{,}48x^5 + 3{,}5x^4 - 9{,}8x^3 + 13x^2 - 7{,}3x + 1{,}7 \quad (19)$$

$$g_9(x_9) = -0{,}021x^5 + 0{,}27x^4 - 1{,}4x^3 + 3{,}4x^2 - 4{,}1x + 2{,}2 \quad (20)$$

4 Optimization Result

The method for optimization in this study is a non-linear programming solution using the fmincon function in MATLAB. This function supports the optimization process for more than one design variable. The optimization stopped at the 53rd iteration, as shown in Fig. 4. The difference between function values must be close to zero to stop the optimization iteration. Optimum design variables are in Table 5.

The optimization obtained the optimal weight at 2,702 kips from the 4,344 kips. Thus, the optimization ratio is 38%. Based on Fig. 5 and Fig. 6, the jacket structure's middle part contributes the most to weight reduction. Furthermore, the wall thickness minimises the weight more than the outer diameter.

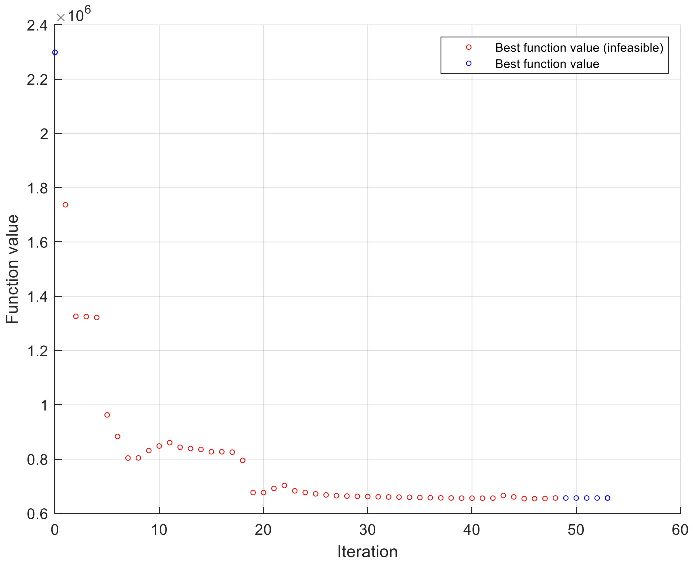

Fig. 4. Optimization iteration process.

Table 5. Optimum design of minimum jacket structure.

Design Variables	Member Group	Initial Design (in)	Optimum Design (in)
x_1	DBT	28.00	23.69
x_2	DBT	1.75	0.39
x_3	HBT	24.00	17.29
x_4	HBT	1.00	0.29

Design Variables	Member Group	Initial Design (in)	Optimum Design (in)
x_5	DBA	28.00	16.97
x_6	DBA	1.75	0.28
x_7	HBA	24.00	12.34
x_8	HBA	1.00	0.21
x_9	JL	2.50	0.95

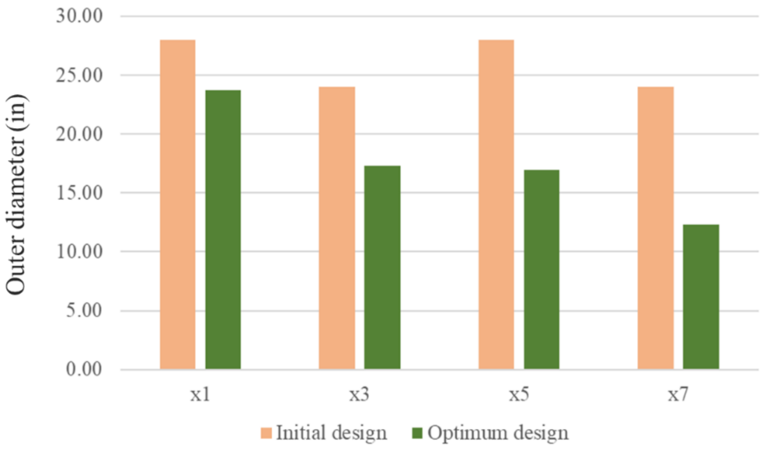

Fig. 5. The outer diameter of classified design variables.

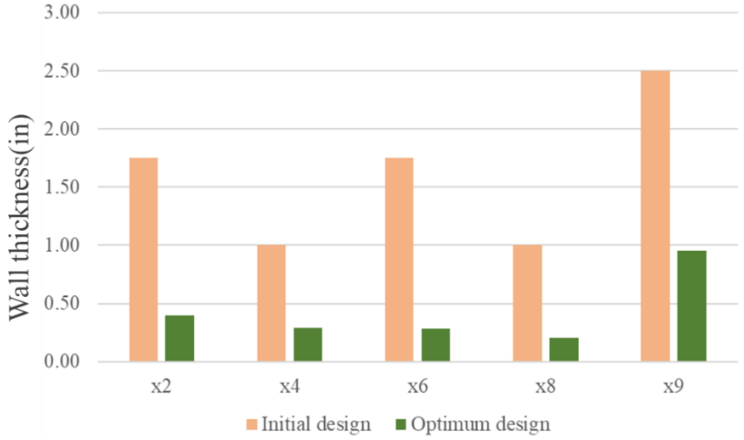

Fig. 6. The wall thickness of classified design variables.

5 Conclusion

This research optimized the jacket to obtain a minimum jacket structure. The tubular members' outer diameter and wall thickness are selected as design variables. A surrogate model using radial basis function with multiquadric activation function has been built and used to assess the structure strength. The optimization ratio is 38%, and the most significant part in reducing the weight is the wall thickness.

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