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Sizing Optimization Using Genetic Algorithm to Achieve Minimum Offshore Structure

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ABSTRACT

Accelerating marginal field development must consider the economic factor. While the structural strength must remain capable and robust when subjected to environmental loads. To meet the desired objective in design phase, optimization is used. With the rapid growth of computing technology, the optimization method is developed as more advanced and reduced iteration time. However, the structural evaluation of jacket structure is a complex problem. The usual process of structure evaluation is through finite element analysis, and it is still time-consuming. Thus, surrogate models can evaluate the structure, lowering computational time. This study optimizes the jacket structure to get an affordable and robust minimal jacket structure. Sizing optimization will be performed on the jacket's leg and bracing thickness. For single-objective optimization, weight structure is considered the objective function, and multi-objective optimization adds production cost as the second objective function. The surrogate model uses the radial basis function to predict the relation between design variables and ultimate limit strength. The functions generated from the surrogate model will act as behaviour constraints in the optimization process. For consideration, X-type and V-type bracing configurations are compared. Different results were obtained from the single objective and multi-objective optimization process.

***Key words** : genetic algorithm, jacket structure, minimal offshore structure, optimization, radial basis function*

INTRODUCTION

The Indonesian government controls the oil and gas industry as a strategic commodity. One strategy from the government to increase oil and gas production is accelerating marginal field development (Sianturi, 2021). In the case of marginal fields, the economy is highly considered, so development must minimize capital and operational expenditures based on the characteristic of each field (Kartohardjono and Prasetyo, 2020). In addition, the design phase must be analyzed from the minimum field requirements while maintaining quality and safety. Therefore, the offshore platform must be the optimal design for a specific field.

Reducing capital costs could be done by optimizing the design of structures that support oil and gas operations. A commonly used offshore platform is the jacket type. Although the application is limited to shallow sea, jackets are still in demand due to their efficiency and reliability. Offshore structures that are using jacket design as much as 95% (Fu, 2018). Jacket structures are commonly used as wellhead platforms for minimal offshore structures. This structure is usually unmanned because it has no processing unit and accommodation. Thus, this wellhead platform becomes the object of minimizing the infrastructure cost. Jacket structures in Indonesian sea areas are primarily designed based on the standards and codes in a general form. This led to some designs being too conservative, and the development consumed large amounts of material. Thus, many jacket structure designs began to optimized based on the economic and the requirement for marginal fields.

The advantage of structural optimization is that it allows to quickly explore a wide design range. As a result, it may be pretty valuable to the design engineer. However, practical use of the optimization

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requires the applied analytical model to be accurate enough. Finding an appropriate analytic model is typically a challenge since optimization needs multiple function evaluations and, ideally, smooth and differentiable objective and constraint functions.

Thus, the most important in the optimization process for offshore structures is the selection of the optimization algorithm and evaluation of the structural strength. Structure algorithm *genetic algorithms* (GA) shows better results than local optimization algorithms such as Cyclical Parthenogenesis Algorithm (CPA), Particle Swarm Optimization Algorithm (PSO), Colliding Bodies Optimization Algorithm (CBO), Enhanced Colliding Bodies Optimization (ECBO), dan Sequential Quadratic Programming (SQP) (Zhang *et al.* , 2018). Therefore, GA optimization models are widely applied to offshore structure research (Nasseri, Shabakhty and Hadi Afshar, 2014; Bharti, Kumaraswamidhas and Das, 2020; Liu, Lin and Huang, 2020; Burak and Mengshoel, 2021; Liu *et al.* 2021; Motlagh, Shabakhty and Kaveh, 2021).

The GA technique is a search heuristic that is frequently used to develop beneficial solutions to the optimization process. It creates solutions to optimization problems using processes inspired by natural evolution, including inheritance, selection, and mutation (Melanie, 1999). Furthermore, some problems must consider more than one objective function. Therefore, GA can solve multi-objective optimization (Zhang et al., 2018).

Research on design optimization for marginal field offshore structures was conducted by Li *et al.* (2008) with a case study in Bohai Bay. The study proposed a method of optimizing the design of offshore platforms with a combined method of element analysis up to the *pseudo-excitation method* (PEM). The finite element (MEH) method is used to simulate structures globally and tubular joints locally. In comparison, PEM calculates *the power spectral density* (PSD) of the concentrated stress in the tubular. This analysis still takes a long computational time.

Other optimization analyses had been done considering the weight as the objective function (Motlagh et al., 2021). In this study, the objective function was to minimize weight with design variables of thickness and outer diameter of each brace. Computational time is still a challenge in this study because iterations are performed repeatedly from MATLAB for optimization processes to a finite element method-based software to evaluate strength and fatigue.

Optimization is time-consuming as each design variable's iteration must be evaluated not to intersect the constraint function. The structural integrity evaluation is usually done using finite element analysis-based software. It is the most consuming time in the design phase of offshore structures (Häfele et al., 2018; Motlagh et al., 2021). Thus, the surrogate model is proposed to reduce optimization time. It is usually used to simplify complex simulations and processes. It assumes the process as a black box. (Dias et al., 2019). When subjected to environmental loads, such as waves, current and wind, offshore jacket structures will show complex behaviour. The variables that affect the strength parameter is complicated enough. So, to predict the effect of design variables variation on the strength parameters, a surrogate model can be used (Zhang et al., 2018).

Practical optimization usually minimizes weight (Li et al., 2008; Motlagh et al., 2021), but this simplification leads to unrealistic design optimization. Topology must be considered as selection or optimization. Optimization approach considering other factors regarding the jacket structure for a wind turbine is also proposed, such as production, transportation, and installation cost (Häfele et al., 2018). This study proposes at least other factors considered, such as production cost, besides only the weight as the objective function. Welding is another factor that contributes to the production cost after material. The surrogate model is also used to evaluate the structure, and this study uses Gaussian process regression (GPR) for constructing the surrogate model.

The design phase is a critical step in developing a marginal field. The optimization process must be efficient and effective to gain an economically minimal offshore structure yet robust. Thus, this study will optimize offshore jacket structure to achieve minimal offshore structure design. As the jacket material contributes the expense the most, the objective function of this optimization process is the weight of the structure. Therefore, production cost will be considered the second objective function assumed as welding material.

Modelled jacket structures with bracing configuration types X and V are compared. First, static analysis of jacket structure subjected to environmental loads is simulated using finite element-based software. Then, the surrogate model is used to overcome the challenge regarding computational time. Finally, the static analysis results become the sampling data to construct the surrogate model using MATLAB software. After that, the optimization process was done on MATLAB software using a genetic algorithm.

METHODS

Structural Modelling and Analysis

The jacket platform is designed for Natuna waters with a depth of 115 ft. It is a wellhead platform with three legs and a batter of 1:10. The length of the jacket leg element is 22.050 inches for both configurations. At the same time, the bracing element is 4,634 in for the X type brwacing configuration and 17,896 in for the V type. Detailed structures are shown in Figure 1. The structural integrity is analyzed based on the recommendation of API Recommended Practice 2A-WSD (API RP 2A WSD) and the American Institute of Steel Construction (AISC) code. The material for jacket leg is S355 steel plates which has a density of 490 lbs/in.

Figure 1. Jacket Structure Modelling with X-type bracing (left) and V-type bracing (right)

Finite element-based software is used to conduct the static global analysis of the structure. The structure is modelled as a space frame structure which are fixed at the bottom of the legs members. The topside consists of I-section beam elements, and the jacket structure consists of tubular members. The scope of optimization is only for the tubular members of the jacket. The output results from the static analysis are used for constructing surrogate model and will be constraints in the optimization process. Environmental loads that are considered in this study are waves and current in operation and extreme conditions. Detailed environmental data is shown in Table 1. Waves load is calculated based on fifth-order Stokes.

Table 1 Environmental Load Data

Parameters	Operation Condition	Extereme Condition
Significant Wave Height	21 ft	43,5 ft
Wave Period	7.1 s	10 s
Current Velocity (at surface)	4 ft/s	1,3 ft
Current Velocity (at seabed)	1.2 ft/s	1 ft/s

Radial Basis Function

Constructing the surrogate model using the radial basis function need sampling data and the function need to be checked using adaptive sampling. Figure 2 shows the process of constructing a surrogate model. The relationship of the UC ratio with the design variables is predicted as a function. This will save computational time in the evaluation process of optimization. Bear in mind that the mathematical relationship between input and output is also crucial for achieving efficiency in calculations while obtaining high accuracy. Commonly used surrogate models include the surface response model (RS), the Kriging model, the radial basis function (RBF), and the support vector machine (SVM) (Zhang et al., 2018). In this study, RBF is adopted to build a surrogate model.

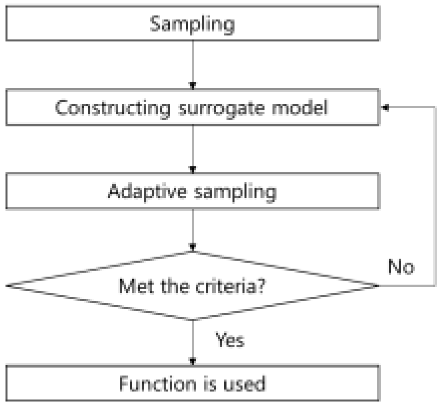

Figure 2. Process of Constructing a Surrogate Model

Regression using radial basis function (RBF) was performed to see the relationship of the UC ratio with the design variables. RBF model is straightforward for finding the optimal shape parameters and is good in using the function. The main reason for using RBF is its ability to train quickly (Thai, 2022). However, the disadvantage of RBF is that this method is not good enough for extrapolation (Nisbet et al., 2018). So the training data must cover the minimum and maximum UC ratio. RBF consists of input, hidden, and output layers. The input and output from static analysis become the sampling data. The input and output data process is assumed as a black box called the hidden layer. RBF will interpolate the output data based on the weights of the network. The weights can be calculated using least square criteria (Lee et al., 1999). RBF architecture is shown in Figure 3.

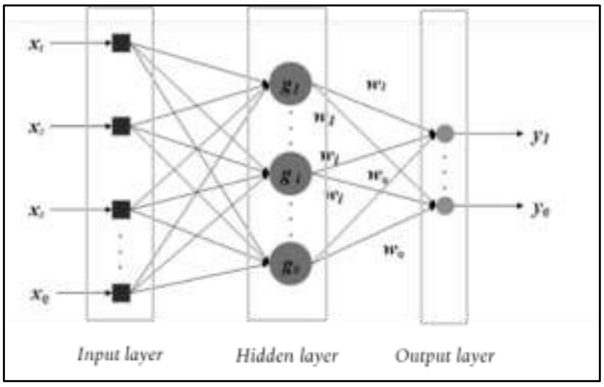

Figure 3. RBF Architecture

Optimization Modelling

The objective function of the optimization is to minimize the jacket structural weight (W). Weight is influenced by member volume and density. Equation (1) express the objective function. L_i and A_i are the member length and the section area of the member. Figure 5 shows the graphic of the objective functions.

$$\min F(x_1, x_2) = [W(x_1, x_2), C(x_1, x_2)] \quad (1)$$

$$W(x_1, x_2) = Wt + Wj = Wt + \sum_{i=1}^{n} \gamma_i L_i A_i \quad (2)$$

More complicated the structure, the higher the production cost. So, the production cost based on tubular and welding material is added as an objective function. The construction cost of jacket structure considers the welding which is different for each bracing type. The welding used is fillet welding. The welding area is divided into two parts: a brace with a brace and a brace with a jacket leg. k_1 and k_3, stating the cost for steel and welding materials. Whereas k_2 and k_4 declared wages of work for production and welding. t is the welding thickness and assumed the weld geometry as shown in Figure 4.

$$C = c_1 + c_2 \quad (3)$$

$$c_1 = (k_1 k_2 W_j) \quad (4)$$

$$c_{2x} = k_3 k_4 (257{,}4) t^2 \quad (5)$$

$$c_{2v} = k_3 k_4 (205{,}8) t^2 \quad (6)$$

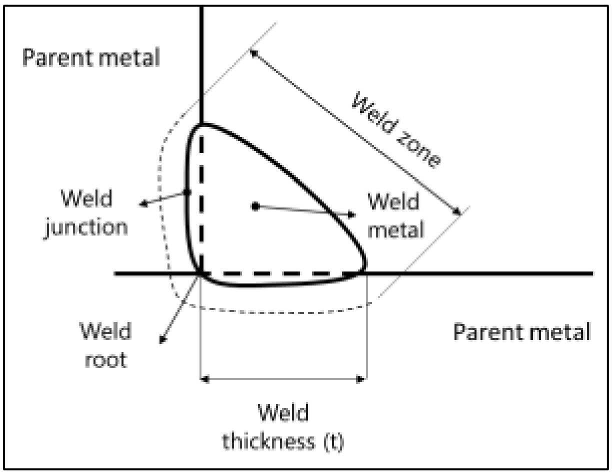

Figure 4. Weld Illustration of Tubular Joint (AWS D1.1, 2010)

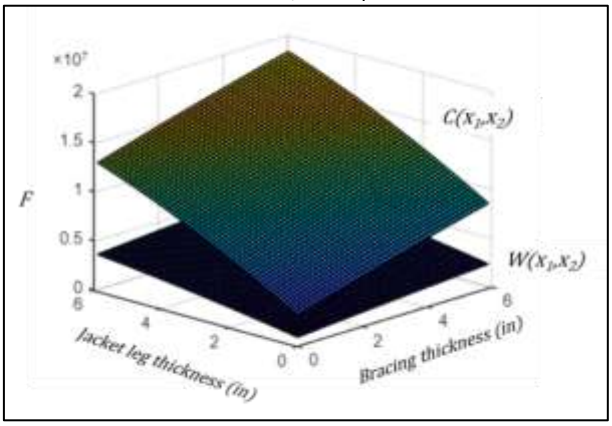

Figure 5. Objective function graphic

The thickness of jacket tubular members become the design variables. Those are the thickness of jacket leg and brace that expressed as x_1 dan x_2. At each elevation, these variables are assumed constant. The initial dimension of design variables is shown in Table 2.

Table 2. Initial Design of Jacket Structure

	ID (in)	OD (in)	t (in)
Jacket Leg	65.50	69	1.75
Brace	28	30	1

As the optimization must consider the structural integrity, it is necessary to evaluate the structure by adding the constraints in the optimization process. Stress or stress rasio on the members are some parameter that can be used to check the structural integrity (Noviyanti et al., 2021; Syalsabila et al., 2022). The reference for the structural analysis is based on API RP 2A WSD and AISC. Unity Check

(UC) ratio on every member is checked so the combined axial-buckling stress and only buckling stress do not exceed the allowable limit. The function for both conditions is stated in equations (7) and (8). *Side constraints* in the form of upper limits and lower limits consider the behaviour of member buckling recommended in the range of 2<D/t<60 (Chakrabarti, 2005). D states the outer diameter, and t is the thickness of the member. In addition, the size of thickness in the market is also considered. Thus, the design variable is continuous between 1.15 inches and 5.9 inches.

$$UC = \frac{f_a}{0.6F_y} + \frac{\sqrt{f_{bx}^2+f_{by}^2}}{F_b} \leq 1.0 \quad (7)$$

$$UC = \frac{f_a}{F_a} + \frac{C_m\sqrt{f_{bx}^2+f_{by}^2}}{\left(1-\frac{f_a}{F_e'}\right)F_b} \leq 1.0 \quad (8)$$

Where:

f_a : axial stress
f_b : bending stress
F_y : yield stress
f_{bx} : bending stress x-axis
F_{by} : bending stress y-axis
F_b : allowable bending stress
C_m : coefficient applied to bending
F_e : buckling stress

RESULTS AND DISCUSSION

Structural Evaluation

Validation is done first by comparing the weight of the initial structure in Matlab and SACS. MATLAB result is 1894.31 kips, and SACS result is 1891.75 kips. The difference of two results is 0.14 percent. To ensure that the model is comparable, the weight of initial design between the X-type and V type bracing is no more than five percent difference. For this study, the difference that was obtained is 3.8%.

Constraint functions for the optimization process are built using RBF. Eleven variations of bracing thickness as input are analyzed using finite element-based software. The output results combine axial-buckling and buckling stress UC ratio of each bracing thickness. Variations are in the range of commonly used thickness of bracing. RBF predicts the data interpolation based on these inputs and output, as shown in Figure 6. It shows good agreement because the UC ratio increases if the bracing thickness increases. There are four functions to be generated. These functions become behaviour functions that restrict the feasible region of the optimization process.

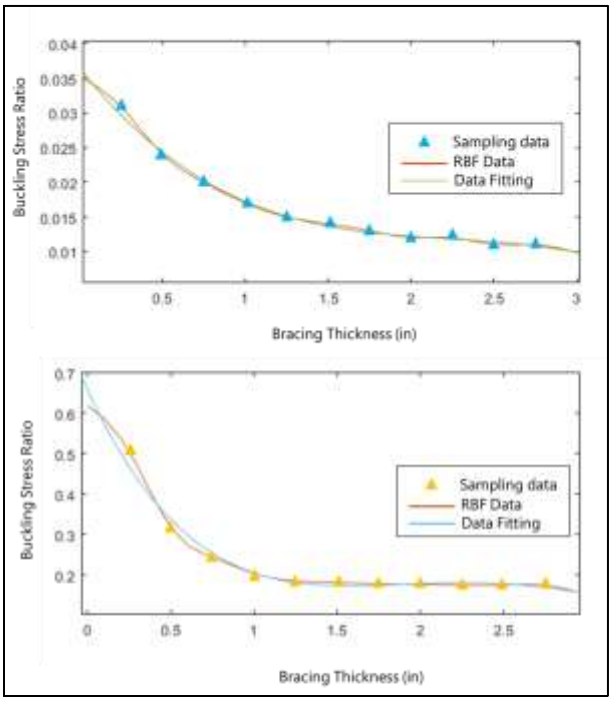

Figure 6. The variations of UC Ratio with Bracing Thickness Based on RBF Model

$$g_1(x_1) = 0.00038\,x_1^4 - 0.0034x_1^3 + 0.0098x_1^2 - 0.015x_1 + 0.973 \leq 0 \quad (1)$$

$$g_2(x_1) = -0.005x_1^3 + 0.038x_1^2 - 0.061x_1 + 0.77 \leq 0 \quad (2)$$

$$g_3(x_2) = 0.015x_2^4 - 0.16x_2^3 + 0.59x_2^2 - 0.9x_2 - 0.34 \leq 0 \quad (3)$$

$$g_4(x_2) = -0.0019x_2^3 + 0.013x_2^2 - 0.03x_2 + 0.963 \leq 0 \quad (4)$$

Optimization Result

Considering two objective functions, the method used for the optimization of the weight and construction cost of jacket structures is *the* Multi-objective Optimization Genetic Algorithm. For comparison, the optimization with the weight structure's objective function only is analysed using a genetic algorithm. This method is also used for single or multi-objective functions and can consider many parameters in the optimal design of the platform simultaneously, especially considering the objectives of more than one (Motlagh et al., 2021). Therefore, this method can optimize complex problems and solve more solution space with fewer algorithm runs (Garcia-Teruel & Forehand, 2021).

The optimum variable designs for weight-only objective function are the jacket leg thickness and bracing thickness becoming 1.15 inches. This result is obtained for both bracing configurations. The iteration stops at the 39th iteration for the X-type. While for the V-type, the iteration stops at 10th. The weight loss achieved from the optimization process sequentially is four and five percent for each X-type configuration and V-type configuration. The detail is shown in Figure 7.

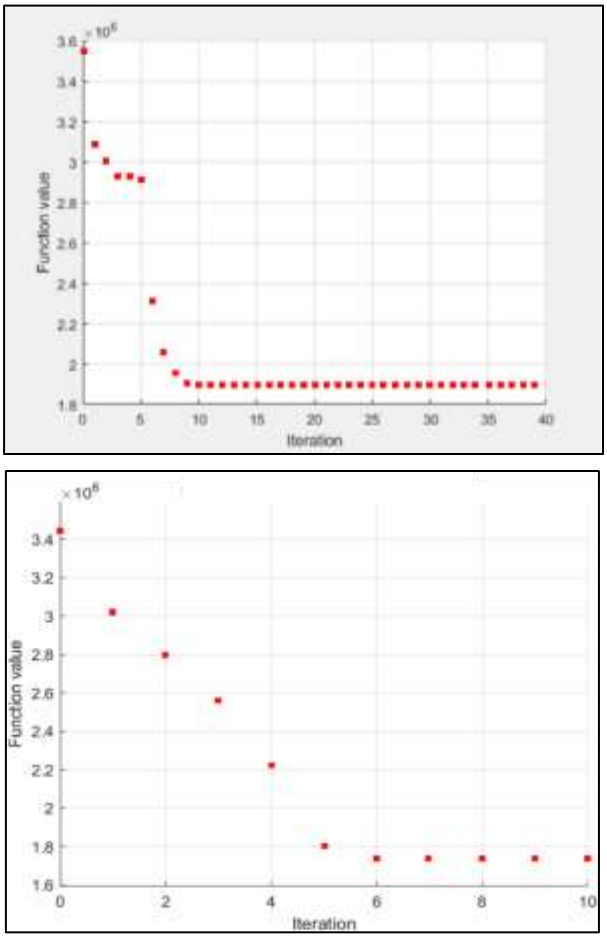

Figure 7. Iteration of the Optimization Process for Single Objective (SO) Optimization

Figure 8 shows that different results are obtained between single objective and multi-objective optimization. The result shows that the optimization ratio is lower for the MO optimization. For X-type configuration, jacket leg thickness obtained for optimum design is 1.30 inches and 1.15 inches for bracing thickness. Furthermore, the optimization ratio is decreased more for the X-type configuration than for the V-type configuration. This is due to a higher welding area based on a more complicated design of X-type than V-type. Detailed results are compared in Table 3.

The results of the two configuration variations did not show a significant effect on optimization. This is due to the initial design being already near the optimum point. Besides, based on research by (Nasseri et al., 2014), Based on the results, diagonal and vertical members do not contribute too much to the optimization process, but horizontal members are influential. In contrast, this study generalized each bracing member's thickness without differentiating between diagonal or horizontal. Therefore, it is needed to divide the design variables into groups in the future.

Table 3. Comparison Between Single-Objective (SO) Optimization Multi-Objective (MO) Optimization

	Initial design	Optimum design					
	Design weight (ton)	SO optimization			MO optimization		
		Design weight (ton)	Weight reduction (ton)	Optimization ratio	Design weight (ton)	Weight reduction (ton)	Optimization ratio
X-Type	1967	1892	75	3.8%	1928	39	1.9%
V-Type	1836	1740	96	5.2%	1743	93	5.0%

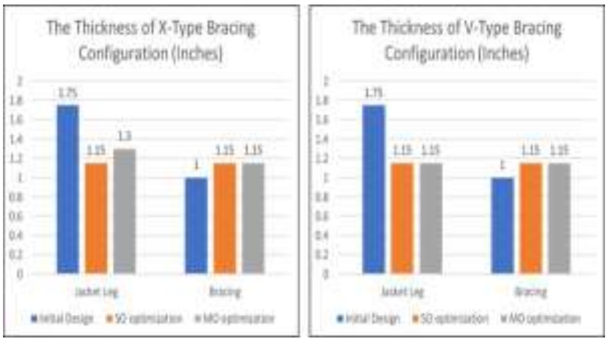

Figure 8. The Thickness of Tubular Members in The Initial And Optimum Designs Of The Jacket Platform

CONCLUSIONS

In this research, a jacket platform designed for the Indonesia Sea was optimized by two optimization scenarios using a genetic algorithm. The design variables were the thickness of the jacket leg and bracing members. The first optimization, SO-Optimization, considered the structural weight as the objective function, while the second, MO-Optimization added production cost as the second objective function. Both scenarios use stress and buckling design requirements as constraints. An evaluation of structural integrity in each iteration is time-consuming. Using a surrogate model led to computational time reduction. Conducting SO-Optimization led to a weight reduction up to 3.8% for X-type and 5.2% for V-type. However, for MO-Optimization, the optimization ratio decreased to 1.9% and 5.0% for X and V-type, respectively. The results show that production cost must be considered the significant objective function in optimising complex bracing configurations.

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