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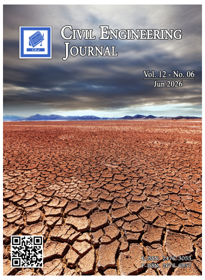

Reliability-Based Topology, Shape, and Size Optimization to Find the Optimal Four-Legged Jacket Offshore Platform

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Abstract

This study aims to establish a comprehensive reliability-oriented optimization framework for a four-legged offshore platform jacket without batter, addressing the persistent issue of material overuse in conventional deterministic design. The proposed methodology sequentially integrates topology, shape, and reliability-based size optimization to achieve a lightweight yet safe structural configuration. Topology optimization is first performed using the Solid Isotropic Material with Penalization (SIMP) method to minimize strain energy under prescribed volume constraints, generating an optimal load-transfer mechanism. The obtained layout is refined through shape optimization to improve joint configuration and stress redistribution. Finally, reliability-based design optimization (RBDO) is implemented using a Kriging surrogate model coupled with Sequential Quadratic Programming (SQP) and Monte Carlo simulation to minimize structural weight under probabilistic constraints, including strength, displacement, and target reliability index ($\beta \geq 3$). The optimized jacket achieves a 53.71% weight reduction while satisfying safety requirements with a maximum unity check of 0.77 and a reliability index of $\beta = 3.11$. The proposed surrogate-assisted RBDO significantly reduces computational effort compared to direct reliability analysis. The primary novelty lies in the unified integration of topology, shape, and probabilistic size optimization for a non-battered platform jacket, which has not been comprehensively reported in previous offshore structural optimization studies.

Keywords: Topology Optimization; Shape Optimization; Size Optimization; RBDO; Jacket Platform.

1. Introduction

Fixed jacket-type offshore structures are among the most widely used support systems in marine engineering, particularly for offshore oil and gas production as well as wind turbine installations [1–3]. Their continued application in water depths ranging from approximately 10 to 200 meters is attributed to their structural simplicity, proven reliability, cost-effectiveness, and high construction strength [4–6]. Structurally, a jacket comprises a reinforced three-dimensional steel framework consisting of tubular legs and bracing members interconnected by welded joints [7, 8]. This configuration provides a stable platform for supporting topside facilities, conductors, and auxiliary substructures required for hydrocarbon extraction and power generation [9, 10]. Offshore jacket structures are continuously subjected to complex combinations of static and dynamic loads, including wave, wind, and current actions [11]. These environmental forces induce cyclic stresses and vibrations, making the structures susceptible to fatigue, corrosion, denting, and other forms of material degradation in harsh marine environments [12, 13]. The tubular members and welded joints, as the primary load-transferring components, play a critical role in maintaining global structural integrity

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[14, 15]. Consequently, enhancing structural efficiency and durability while ensuring cost-effectiveness has become a central concern in offshore structural engineering.

Despite their proven performance, conventional jacket structures are often designed using conservative and traditional modeling approaches, which typically result in excessive structural weight and material usage [16]. Such overdesign increases fabrication and installation costs and may also amplify dynamic responses due to greater mass and volume [17]. Thus, the central research challenge lies in achieving an optimal balance between structural safety, stiffness, and material efficiency under both static and dynamic loading conditions. A general solution involves employing advanced structural optimization techniques capable of minimizing structural weight while satisfying strength and serviceability limit state requirements [18, 19]. Although the topology optimization process in this study focuses solely on static loading conditions and does not account for dynamic effects or fatigue behaviour. Topology optimization (TO) has emerged as a powerful computational approach for determining the optimal material layout within a prescribed design domain under specific loading and boundary conditions [20, 21]. Methods such as Solid Isotropic Material with Penalization (SIMP), evolutionary structural optimization (ESO), and level-set approaches have been widely adopted in structural engineering [22–24]. Among these, the SIMP method is particularly favored due to its computational efficiency and its ability to identify optimal force transmission paths during the conceptual design phase [25, 26]. Several studies have demonstrated the effectiveness of TO in improving the structural performance of offshore and wind turbine jacket structures [27, 28].

In addition to deterministic optimization approaches, reliability-based design optimization (RBDO) has been introduced to incorporate uncertainties in material properties, environmental loads, and operational conditions [29, 30]. RBDO integrates probabilistic constraints into the optimization process to ensure that the reliability index or probability of failure meets predefined target levels [31–33]. Compared to conventional safety factor approaches, RBDO offers a more rational balance between safety and economy by avoiding unnecessary material use while maintaining structural reliability [34–36]. Reliability assessment is particularly critical for offshore structures subjected to random environmental loading [37, 38]. Numerous studies have focused on optimizing offshore wind turbine jacket structures especially those incorporating battered configurations using integrated topology, shape, and size optimization techniques [18, 34]. These approaches have demonstrated significant reductions in structural weight while satisfying stiffness and strength requirements [39–41]. However, the majority of existing research emphasizes wind turbine support structures, with limited attention to platform jackets used in oil and gas applications.

Moreover, although TO and RBDO have independently shown promise, their combined application to four-legged offshore platform jackets without batter remains limited [42]. Only a few studies have explored integrated optimization frameworks involving topology, shape, and size, and these are predominantly focused on battered wind turbine jackets [34]. Therefore, a clear research gap exists in the optimization of non-battered four-legged platform jacket structures, particularly within frameworks that prioritize stiffness enhancement and weight reduction under serviceability constraints.

This study aims to develop an optimized lightweight structural model for a four-legged offshore platform jacket without batter, satisfying both serviceability and strength limit state criteria. The proposed framework integrates topology optimization using the SIMP method to minimize strain energy under volume constraints, followed by shape and size optimization to reduce the total structural weight under allowable stress conditions. The novelty of this research lies in the comprehensive application of topology, shape, and size optimization to a non-battered four-legged platform jacket configuration an area not comprehensively addressed in prior studies. The study is limited to numerical structural modeling and optimization using the finite element method, with the objective of identifying an efficient structural layout that improves rigidity while minimizing material usage and overall weight.

2. Method

This study develops a reliability-based topology, shape, and size optimization method by applying the earliest topological optimization to the structure to find the optimal layout based on the objective functions and constraints applied to the design model. Topology optimization applies the objective function of minimizing strain energy by determining the expected design volume ratio to generate multiple models and finding the optimal model for the jacket structure. Shape and size optimization is continued after the optimal topology model is found by applying the RBDO concept to minimize the structure's weight. However, it has the strength of the structure that still meets the serviceability limit state. The application of the RBDO method used the surrogate model method to predict the optimal design of the jacket structure with lighter dimensions and weight. This method offers a shorter time due to the optimization carried out simultaneously between modeling and the calculation of the strength of the jacket structure. Applying combined topology, shape, and size optimization based on reliability with a computational approach is expected to provide an effective solution in designing platform jacket structures, especially four-legged jacket structures that do not have a batter. The steps taken to complete this research are described in Figure 1.

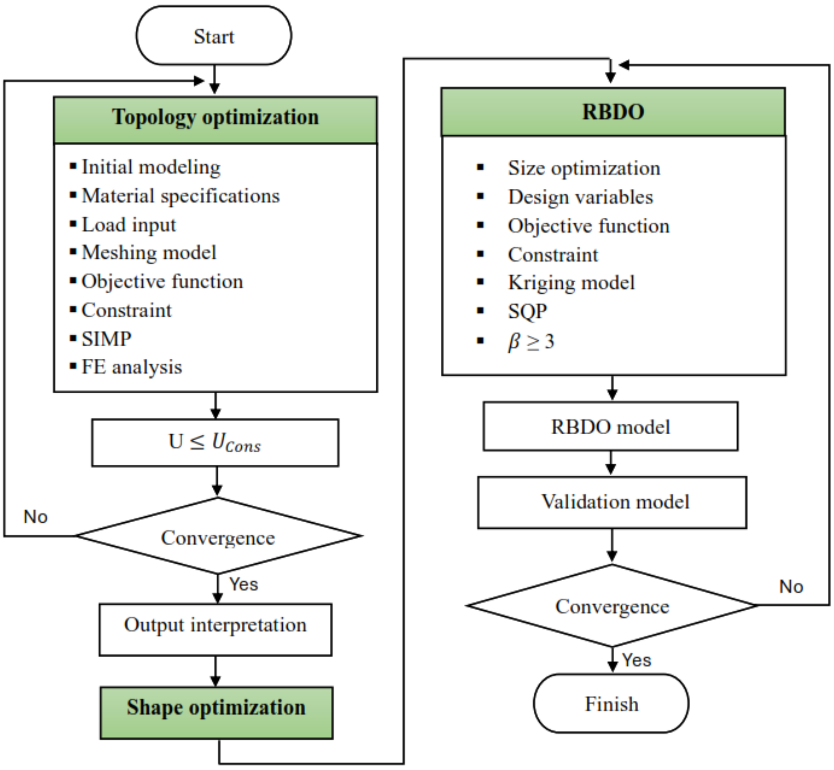

Figure 1. Flowchart of the research process

2.1. Reference Structure Model

The reference structure model used in this study is a four-legged platform jacket that does not have batters with a total of three levels, and the brace pattern consists of an X brace, a horizontal brace, and a single diagonal brace. The model of the reference jacket can be seen in Figure 2.

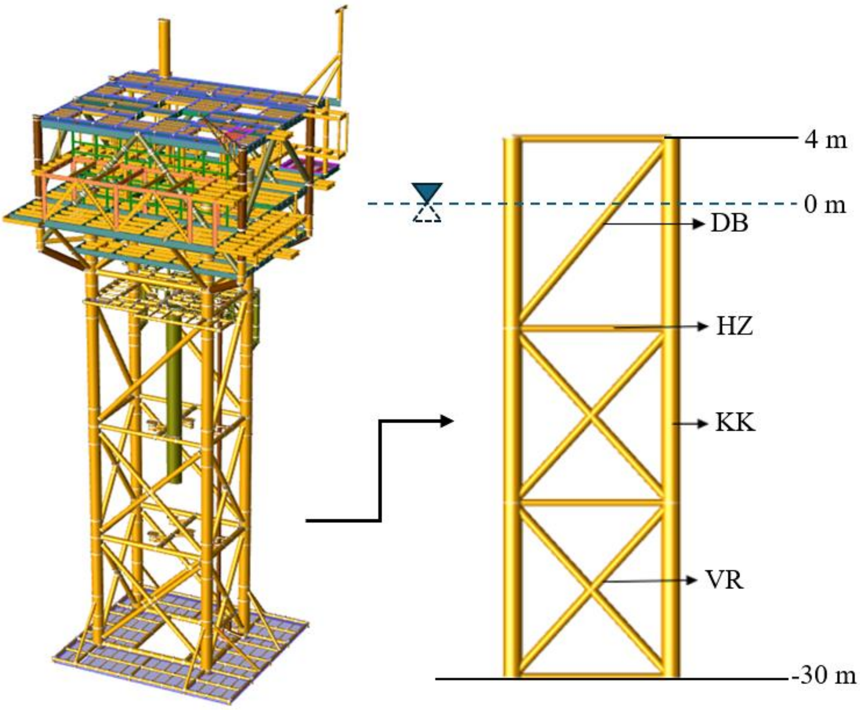

Figure 2. Reference jacket platform

The structural dimensions of the reference jacket are used in topology optimization, such as the height and width of the structure and the material specifications in the structural modelling. The data of the dimension and material properties of the reference jacket structure used in this study are described in Tables 1 and 2.

Table 1. Jacket reference structure dimensions

Part	Members Name	Outer Diameters (cm)	Wall Thickness (cm)
Jacket legs	KKI	109.700	4.000
Diagonal brace 1	DB	55.900	1.270
Diagonal brace 2	VR	50.800	1.270
Horizontal brace	HZ	45.700	1.270

Table 2. Material properties

Property	Symbol	Value
Young's modulus	E	2×10^5 N/mm^2
Shear modulus	τ	8×10^4 N/mm^2
Yield strength	F_y	345 N/mm^2
Density	ρ	7850 kg/m^3
Poisson ratio	μ	0.3

2.2. Numerical Modelling

Numerical modeling was performed in two sequential stages: solid-material-based topology optimization and in-place structural analysis of the tubular jacket using structural analysis computer system (SACS). During the topology optimization stage, the design domain was represented as a three-dimensional isotropic solid encompassing the full geometric envelope of the jacket structure. The domain was discretized using three-dimensional solid finite elements, with controlled mesh refinement to ensure numerical stability and solution convergence. Material properties were defined according to the reference jacket structure adopted in this study. Both the solid model and the subsequent tubular frame model employed fully fixed boundary conditions at the base of the jacket legs to conservatively represent pile–soil interaction effects. The applied loading conditions included self-weight, vertical top side loads, and lateral environmental loads induced by wave, current, and wind actions. Load combinations were defined in accordance with relevant offshore structural design standards to realistically simulate operational and extreme environmental scenarios.

The optimized material distribution obtained from topology optimization was subsequently interpreted to derive a practical tubular frame configuration along the primary load paths. This transformation involved geometric rationalization into a system of chord and bracing members suitable for structural fabrication and offshore construction. The resulting tubular model was analyzed using SACS under in-place conditions. A linear static analysis was conducted to determine member stress distributions, unity check (UC) values, and global structural displacements. These numerical results were subsequently used as input parameters for the reliability-based size-optimization process.

2.3. Topology Optimization

Topology optimization constitutes the initial stage of this research, in which the structural domain is modeled as a three-dimensional solid continuum using Abaqus software. An isotropic linear elastic material model is adopted to represent structural steel. The Solid Isotropic Material with Penalization (SIMP) method is implemented to determine the optimal material distribution within the predefined design domain. In the SIMP approach, the material density variable is defined over the range 0 to 1, where 0 represents a void and 1 represents solid material. Penalization is applied to intermediate-density values to suppress artificial gray regions and promote a clear distinction between the solid and void phases [1]. The Equation of SIMP is as follows [2]:

$$k_e=(\rho_e)^p k_0 \tag{1}$$

where, k_e is an element stiffness, ρ_e represents the density of the elements, and p is the penalty value. In general, the topology optimization equation in this study is explained in Equation 2:

$$\begin{aligned} &\text{Find } \rho = (\rho_{1,}, \rho_2, \cdots, \rho_n)^T \\ &f = \text{Minimize SE} = \textstyle\sum_{e=1}^{n} (\rho_e)^p \; u_e^T \; k_0 \; u_e \end{aligned} \tag{2}$$

$$\text{Subject to} \begin{cases} U \leq U_{Cons} \\ \frac{V_x}{V_0} = R_V \\ 0 < \rho_{min} \leq \rho_e \leq 1 \end{cases} \tag{3}$$

$$U_{cons} = {}^{1}\!/_{200}\ h \quad [3]$$

where, ρ is a design variable, ρ_e is the relative density level of an element, f is an objective function, SE refers to strain energy, K & K_0 is the global stiffness matrix, elemental stiffness matrix U is a displacement vector, V_x&V_0 respectively, the specified design volume, and the initial volume of the model, R_v is the volume ratio, $\rho_{\min}$ is the lowest relative density, n is the number of design elements, Ucons is the maximum displacement, h is the height of the jacket structure, i.e., 34 m.

In this study, topology optimization is conducted using a full-solid representation to accurately capture the jacket structure's inherent load-transfer mechanism. The design domain is discretized into three-dimensional solid elements, enabling material redistribution throughout the entire structural volume. Fixed boundary conditions are imposed at the four lower leg ends to simulate pile–soil restraint at the seabed, thereby representing realistic in-place support conditions. To preserve global stability and prevent the elimination of essential load-carrying members, material densification is maintained in the leg regions. These regions serve as the primary load paths transmitting gravity and environmental loads from the upper structure to the foundation. Enforcing higher material retention near the leg support ensures sufficient stiffness and prevents numerical instabilities during the optimization process.

By adopting this solid-based topology framework, the optimization procedure identifies the most efficient material layout that reflects the natural stress flow from the deck level to the fixed supports. The resulting topology configuration provides a mechanically consistent structural concept, which is subsequently interpreted and reconstructed into a practical tubular jacket system for shape and size optimization.

2.4. Shape Optimization

This stage constitutes a continuation of the topology optimization process, in which the preliminary structural layout obtained from the solid-based topology model is refined to achieve a more practical and structurally efficient tubular configuration. The shape and joint arrangement resulting from topology optimization are adjusted to ensure constructability, structural continuity, and compliance with offshore design requirements, while maintaining the objective of volume minimization.

Shape optimization is performed using SACS by reconstructing the jacket as a three-dimensional tubular frame. The geometric and material properties of the reference jacket structure, including member diameters, wall thicknesses, and steel grade specifications, are used as the initial input parameters for the optimization process. These reference dimensions serve as the baseline configuration from which nodal coordinates and member inclinations are systematically modified to achieve an improved structural layout.

After modeling, the structure is directly subjected to in-place analysis to evaluate stress distribution and structural performance under the prescribed loading conditions. Structural adequacy is assessed using the unity check (UC) value, which ensures that all members satisfy the allowable stress and stability criteria. The governing formulation for the shape optimization process is expressed as follows:

$$\begin{aligned}&\text{Find sh}=(\text{sh}_1, \text{sh}_2, \cdots, \text{sh}_n)\\&\text{Function} = \text{Minimize Volume}\\&\text{Subject to} = \sigma_{max} \leq \sigma_{\text{allowable}}\end{aligned} \tag{4}$$

where, Sh is a shape optimization design variable, σ_{Max} is the maximum working stress, and $\sigma_{allowable}$ is allowable stress of the material.

2.5. Size Optimization

Size optimization of thickness and diameter is carried out to obtain optimal dimensions from the topology optimization model and shape optimization; size optimization is carried out on the design variables of the member brace and chord of the jacket structure; it is still possible to optimize the results of the strength analysis carried out using finite element software SACS. Design variables are described in Table 3.

Table 3. Variable-size optimization design

Variable	Member Group	Description
OD_c	KKI	Outer diameter of the legs of the jacket structure
OD_{b1}	DB	Outer diameter of the upper diagonal brace
OD_{b2}	VR	Outer diameter of the X brace
OD_{b3}	HZ	Outer diameter of the horizontal brace
t_c	KKI	Thickness of the legs of the jacket structure
t_{b1}	DB	Thickness of the upper diagonal brace structure
t_{b2}	VR	Thickness of the X brace
t_{b3}	HZ	Thickness of the horizontal brace

Size optimization is a method that can be used to optimize a structure, such as the dimensions of the structure in the form of diameter and thickness. The application of the objective function usually minimizes weight with various parameters set so that the size optimization results get the optimal jacket structure but still meet the requirements of the service limit state. Size optimization was carried out using MATLAB software in this study. Size optimization was carried out using the surrogate model method, the Kriging model method, and the sequential quadratic programming (SQP) method.

Size optimization is the final process of structural optimization, which is expected to provide the most optimal size to provide the lightest jacket model and meet the serviceability limit state requirements of the jacket structure with a reliability index of $\beta \geq 3$. The reliability-based design optimization (RBDO) method is applied to this study so that size optimization runs simultaneously with reliability analysis, with one module using Matlab software. The size optimization results can be generated simultaneously with the reliability index value of the optimized jacket structure. The RBDO equations in this study are as follows:

$$\begin{gathered}\text{Find D, T} = (\,\mathrm{D_1, D_2, \dots\ D_n\,, T_1, T_2, \dots\ T_n})\\ \text{Minimize Weight} = \mathrm{W(OD_{b1}, OD_{b2}, OD_{b3}, OD_c, T_{b1}, T_{b2}, T_{b3}, T_c)}\\ \sum_{i=1}^{n} \gamma_i L_i A_I \text{ where } A_i = \pi\left(OD_i{}^2 - (OD_i - 2t_i)^2\right)/4\\ \text{Subject to} \begin{cases} \sigma \leq \sigma_I, \mathrm{UC} \ \leq 1, \beta \geq 3 \\ \mathrm{U} \leq \mathrm{U_{Cons}} \\ D_{Min} \leq D_i \leq D_{Max} \\ T_{Min} \leq T_i \leq T_{Max} \end{cases}\end{gathered} \tag{5}$$

where D is the optimization design variable: a member diameter, brace, and a chord, T is the optimization design variable in member brace thickness and chord, U is the maximum displacement, σ is the working stress, σ_i is the allowable stress, β is a reliability index, W is the weight of the structure, γ_i is the material density, L_i is the length of the tubular section, A_i is the cross-section area of the tubular member, OD_b is the Outer diameter brace, OD_c is the outer diameter chord, T_b is the thickness of the brace, T_c is the chord thickness.

In addition, in the process of optimizing the size of the platform jacket structure, several obstacles must be considered, namely the pile diameter of the jacket structure and the non-dimensional variables of tubular members according to API RP-2A, which consist of β_t, τ_t, and γ_t. This parameter is a validity range to assess the ability of tubular connections to transfer loads. β_t is the comparison of the outer diameter of the bracing with the outer diameter of the chord, τ_t is the comparison between bracing thickness and chord thickness, and γ_t is the comparison of the jacket leg between its diameter and thickness. As for the details explained in the Equation.

$$0.3 \leq \left(\beta_t = \frac{OD_{bi}}{OD_{ci}}\right) \leq 0.5 \tag{6}$$

$$0.4 \leq \left(\tau_t = \frac{t_{bi}}{t_{ci}}\right) \leq 1.0 \tag{7}$$

$$10 \leq \left(\gamma_t = \frac{OD}{2t}\right) \leq 50 \tag{8}$$

These limits are changed to lower and upper limits in the optimization calculation. Another criterion to consider is the bending criterion and the slenderness ratio. This criterion is based on the API RP 2A WSD standard. The constraint bending criteria are shown in the following Equation.

$$2.0 \leq \frac{OD_i}{t_i} \leq 60 \tag{9}$$

where the bending criterion is the comparison of the outer diameter (OD_i) with thickness member (t_i), while the slenderness ratio is the comparison between the effective length of a member section (kL) and radius of gyration (r), with a radius of gyration estimated to be 0.35 outer diameter (OD). The limits of bending failure due to compressive loads on lean cylinders are as follows:

$$\frac{kL}{0{,}35OD_i} \leq 80 \tag{10}$$

2.6. Loads on the Jacket Structure

During the operating life of the jacket structure, the platform is subjected to environmental loads such as waves, wind, and current loads, as well as the load from the upper structure, called the deck. The operational location of the platform jacket structure is in the eastern part of the Java Sea. The environmental load data are described in Table 4.

Table 4. Environmental conditions

Parameter	Condition	Parameters and values
Wind	Operating	Wind velocity is 14.6 m/s
	Storm	Wind velocity is 20.7 m/s
Wave	Operating	Wave height is 2.9 m, period is 8.1 s
	Storm	Wave height is 4.3 m, period is 11.3 s
Current	Operating	Current flow rate is 0.44 m/s
	Storm	Current flow rate is 0.50 m/s

Table 4 The environmental load data working on the jacket platform is obtained from the location where the jacket structure is manufactured [4]. In addition to environmental loads, a topside load accumulated from the weight of the entire deck and the equipment during operational conditions, with a total weight of 10025.63 kN, works vertically on the jacket structure. Wave loads on jacket structures act laterally by using the Morison Equation.

$$f = \rho C_M \frac{\pi O D^2}{4} \dot{u} + \frac{1}{2} \rho_w C_D D_o |u + U|(u + U) \tag{11}$$

where, C_M is the inertial force coefficient, ρ_w is the density of seawater, C_D is the drag coefficient, D_o is the pipe's diameter, and |U| u is the horizontal acceleration and velocity of perpendicular water particles. The numerical analysis of the current force in this study uses Equation 12.

$$F = {}^{1}\!/_{2}\, \rho\, C_D\, U_c^2 \tag{12}$$

where, F is the force of the current, ρ is the density of seawater that has a value of 1025 kg/m^3, C_D is the coefficient of drag, and U_c is the flow rate of the current. The wind force is calculated using Equation 13.

$$F = {}^{\rho}\!/_{2}\ V^2\, C_s\, A \tag{13}$$

where, F is the wind force, V is the wind velocity, C_s is the shape coefficient of the jacket structure building side, an area of the side of the building, and ρ is the density of air. The force working on the jacket structure is modelled as shown in Figure 3.

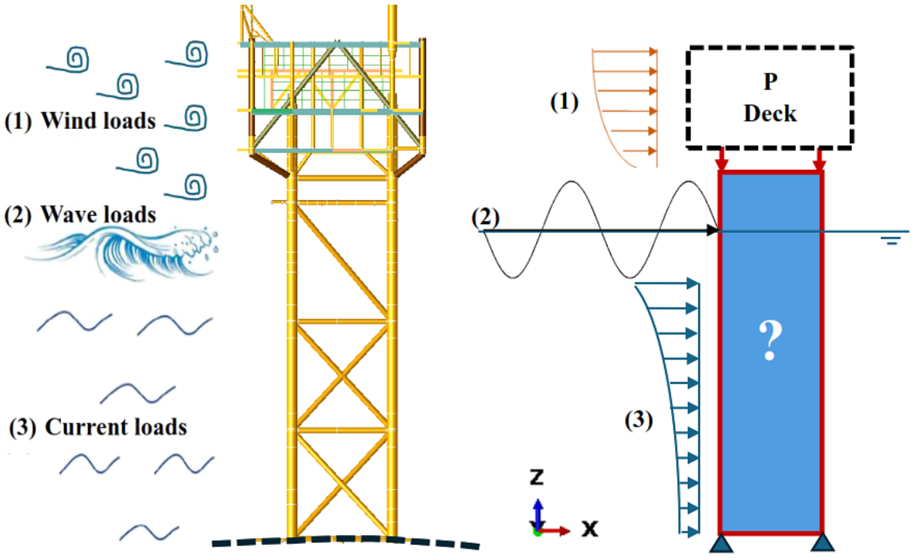

Figure 3. Load conditions in jacket topology optimization modelling

Figure 3 is the loading condition in the topological optimization jacket structure, where the lateral working load is the wind load, wave load, and current load, while the working vertical load is the deck load accumulated from the total weight of the deck. The lateral and vertical loads on the structure are simultaneously applied during the optimization process. In the in-place analysis, the combination load is made into 2 loading conditions, namely normal and storm, with 8 directions of lateral loading as seen in Figure 4.

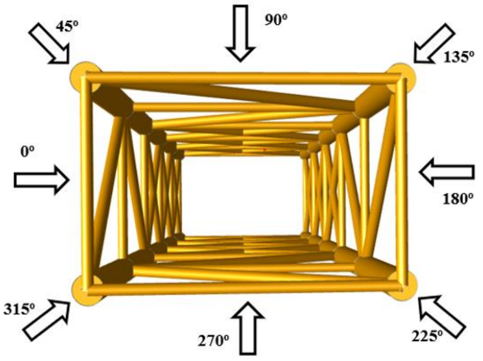

Figure 4. Lateral loading direction of the jacket platform

Figure 4 shows the lateral loading direction for the in-place analysis of the jacket platform with 8 loading directions. This method is the standard applied to jacket structures with 4, 6, or 8 of legs. While vertical loads work in the direction of the -Z axis, in place analysis on the jacket platform was carried out using the design code of API RP 2A-WSD, which is commonly used in the analysis and modeling of the platform jacket.

3. Results and Discussion

3.1. Topology Optimization Result

This study developed topology optimization by applying the objective function of minimizing strain energy by determining the design volume ratio to find the optimal topology model on the jacket structure. In the topology optimization process, volume ratios are applied variously to find a lightweight jacket structure with strength that meets the serviceability limit state requirements. Topology optimization is carried out with the largest volume ratio of 70% and the smallest volume ratio of 15%. The topology optimization results based on volume ratio can be seen in Figure 5.

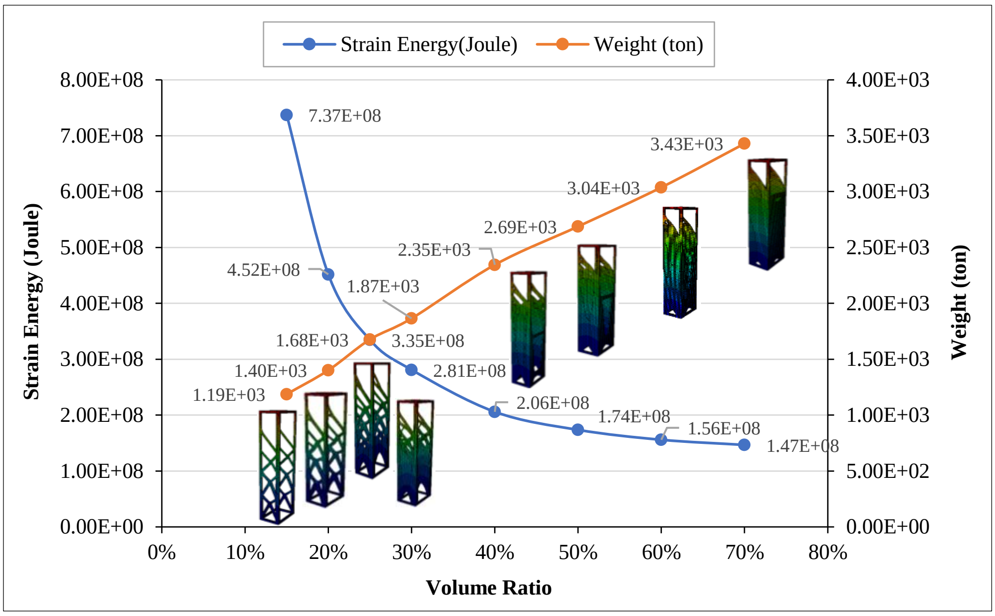

Figure 5. Topology optimization results with volume ratio

Figure 5 shows the volume-ratio topology optimization was performed using ABAQUS. The optimization results show that the greater the volume ratio, the greater the weight and stiffness; conversely, the smaller the volume ratio, the lighter the structure but with less stiffness. The optimal result was obtained at a volume ratio of 15% with a jacket structure model consisting of 3 X brace columns and one single diagonal brace column. A minimum volume is selected to determine the lightest that still meets the jacket structure serviceability limit-state requirements. The resulting topology model is, of course, an interpretation of the objective function applied to topology optimization, namely, minimizing strain energy. The detailed topology optimization model is shown in Figure 6.

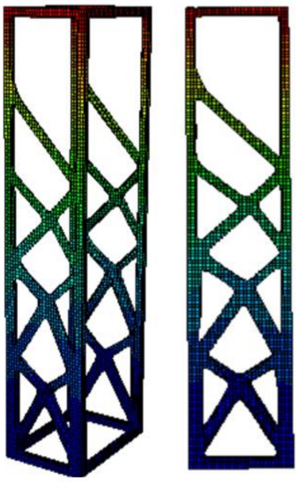

Figure 6. Topology optimizations result jacket model

3.2. Shape Optimization Result

The topology optimization results produced by numerical software certainly do not provide a perfect model. Hence, it is very necessary to improve the position of the joint layout of the structure, so that in this study, shape optimization is carried out to minimize the working stress on the structure by changing the joint layout and applying tubular dimensions to the optimized structure model. The results of shape optimization can be seen in Figure 7.

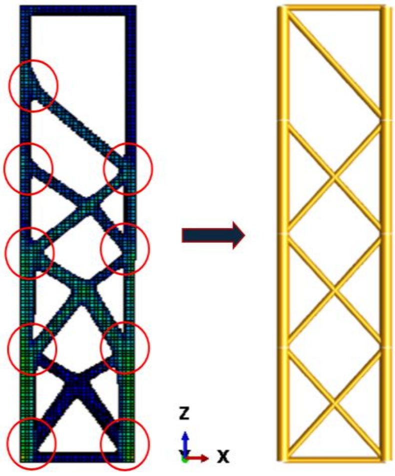

Figure 7. Shape optimizing process

Figure 7 shows a shape optimization process that changes the layout model and cross-section of the jacket from a solid material model resulting from topological optimization to a tubular structure. Shape optimization is performed to improve the jacket model to meet the jacket platform's requirements and criteria. Shape optimization aims to minimize the volume of topological jacket models with dimensions and shapes that do not yet resemble the tubular profiles commonly used in jacket structures. The application of the diameter and thickness of the jacket structure as a result of topological optimization using the dimensions of the reference jacket structure used in this study. Shape optimization is done using SACS software. After the shape optimization is completed by improving the join layout, an in-place analysis is performed. The analysis results showed that the maximum UC in the shape optimization structure model was still very small, 0.21, less than the UC of the structure model used as a reference. The optimization carried out provides a stronger structural model. Based on the shape optimization analysis results, further optimization can be carried out, especially reliability-based size optimization, as the jacket structure still has a UC value that is small.

3.3. Size Optimization Result

Size optimization was carried out on the structure resulting from shape optimization by applying the reliability-based design optimization (RBDO) method. Size optimization was done using the surrogate model method by applying the kriging model, SQP, and using Monte Carlo simulation for reliability analysis. The purpose of the function to be achieved is to minimize the weight of the jacket structure with variable design thickness and member diameter of the jacket structure. The results of RBDO can be seen in Table 5.

Table 5. Size optimization results

Design variables	Member group	Initial dimensions (m)	Optimization results (m)	Optimization ratio (%)
OD_c	KKI	1.097	0.7501	31.62
OD_{b1}	DB	0.559	0.35	37.39
OD_{b2}	VR	0.508	0.35	31.10
OD_{b3}	HZ	0.457	0.33	27.79
t_c	KKI	0.04	0.014	65.00
t_{b1}	DB	0.0127	0.008	37.01
t_{b2}	VR	0.0127	0.008	37.01
t_{b3}	HZ	0.0127	0.0127	0

Table 5 presents the detailed results of the size optimization, demonstrating the variation in diameter and thickness reductions among structural members. Overall, the majority of members exhibit decreases in both outer diameter and wall thickness, indicating that the optimization framework effectively identifies and removes excess material while maintaining structural integrity. The most pronounced reduction is observed in the chord thickness, with a volume reduction ratio of 65%. This substantial decrease suggests that the initial configuration was conservative in certain chord segments, allowing material redistribution without compromising performance. The design variables t_{b1} and t_{b2} are reduced by 37.01%, whereas t_{b3} remains unchanged (0%). The unchanged value of t_{b3} indicates that this particular member functions as a critical load-bearing component within the structural load path. Any further reduction in its thickness would likely lead to constraint violations, particularly in terms of stress utilization or buckling resistance. Regarding the diameter variables, the optimization ratios are relatively uniform across members, indicating a balanced redistribution of stiffness throughout the global structural system. The largest diameter reduction is observed in OD_{b1} (37.39%), while the smallest occurs in OD_{b3} (27.79%). The comparatively lower reduction in OD_{b3} further supports its role as a structurally governing member, where geometric reduction is limited by strength or stability constraints.

In addition to the quantitative results presented in Table 5, the predictive ability of the substitute model is evaluated using the coefficient of determination (R^2) as presented in Figure 8.

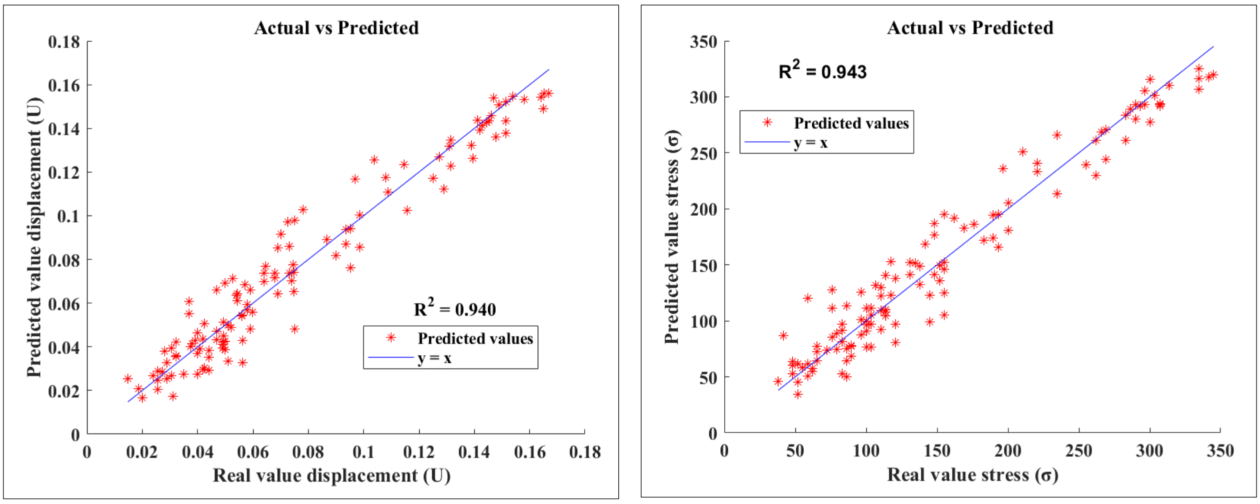

Figure 8. Validation of surrogate model accuracy through actual versus predicted comparisons for displacement and stress responses, demonstrating high R² values

Figure 8 shows that the R^2 values are 0.940 for the displacement response and 0.943 for the stress response. The validation shows a very strong correlation, with R^2 values greater than 0.90 generally considered very satisfactory for nonlinear structural optimization problems, especially in offshore jacket systems, where geometric parameters significantly affect stiffness and load redistribution. R^2 = 0.943 for stress indicates that 94.3% of the variance in the actual stress response was captured by the surrogate model. Similarly, R^2 = 0.940 for displacement confirms that 94% of structural deformation behavior is accurately represented. In the Actual versus Predicted plot, this level of agreement is reflected by the grouping of data points near the 45° diagonal line, indicating minimal prediction deviation. Slightly higher R^2 values for stress compared to displacement suggest that the replacement model captures stress-related nonlinear behavior slightly better than global displacement behavior. This can happen because the displacement response is affected by the cumulative stiffness contribution of multiple interconnected members, thus making it a bit more complex to estimate.

The optimized configuration achieves a final structural weight of 1826.10 kN, representing a significant improvement in material efficiency. Reliability analysis yields a probability of failure (PoF) of 0.00093, corresponding to a reliability index of β = 3.11. This reliability level satisfies commonly accepted offshore structural safety criteria, indicating that the substantial weight reduction is achieved without compromising structural safety. Collectively, these results confirm that the proposed size optimization framework successfully balances material efficiency and reliability performance by targeting adjustments to critical and non-critical members.

After the size-optimization results are obtained, the ratio of the ranges of the non-dimensional parameters for tubular geometry, buckling limit, and slimness ratio is then evaluated. This is done to evaluate the RBDO model and determine whether it meets the criteria for rule-based design in a jacket platform. The results of the RBDO jacket structure evaluation are shown in Tables 6 and 7.

Table 6. Results of evaluation of the range of non-dimensional parameters of tubular geometry

Member Group	β_t	τ_t	γ_t
	$0,3 \le \left(\beta_t = \frac{OD_{bi}}{OD_{ci}}\right) \le 0,5$	$0,4 \le \left(\tau_t = \frac{t_{bi}}{t_{ci}}\right) \le 1,0$	$10 \le \left(\gamma_t = \frac{OD}{2t}\right) \le 50$
DB	0.47	0.57	21.88
VR	0.47	0.57	21.88
HZ	0.44	0.91	12.99

Table 7. Results of the evaluation of the buckling limit and the slimming ratio

Member Group	**D/t**	**KL/r**
	$2,0 \le \frac{OD_i}{t_i} \le 60$	$\frac{kL}{0,35OD_i} \le 80$
KKI	53.58	32.38
DB	43.75	74.04
VR	43.75	74.04
HZ	25.98	77.92

Table 6 presents the results of the evaluation of the non-dimensional parameters of tubular geometry in the reliability-based design optimization (RBDO) jacket, which are required by API RP 2A WSD and are generally used in the design of platform jacket structures. The results of the evaluation in Table 6 show that the optimization results in the form of diameter and thickness of the RBDO jacket structure have met the requirements.

Table 7 presents the results of evaluating the buckling limit and sleekness ratio of the jacket structure after size optimization, in accordance with the rule recommended by API RP 2A WSD for the platform jacket structure. This evaluation is important because if the structure does not meet the criteria, the risk of jacket buckling failure is high. The results of the evaluation in Table 5 show that the results of the size optimization in the form of diameter and thickness of the RBDO jacket structure are appropriate and meet the recommended criteria.

3.4. Weight Comparison of Reference Structure and Optimization Results Models

A comparative evaluation of the structural weight obtained from topology, shape, and size optimization is conducted to assess the effectiveness of each optimization stage. Variation in weight reduction serves as a quantitative indicator of the structural efficiency achieved by the applied optimization framework. The comparison between the optimized configurations and the reference model is illustrated in Figure 9.

Figure 9 compares the weight of the reference model with that of the RBDO-optimized model. It can be seen in the graph of the difference in the weight of the two jacket models that the weight of the reference jacket is 3944.79 kN, while the RBDO topology optimization jacket model is 1826.1 kN, where there is a decrease of more than half of the weight of the reference jacket model, which is 2118.69 kN or 53.71%. These results show that the structural model resulting from the RBDO topology optimization has a lighter structure than the jacket structure used as a reference in this study.

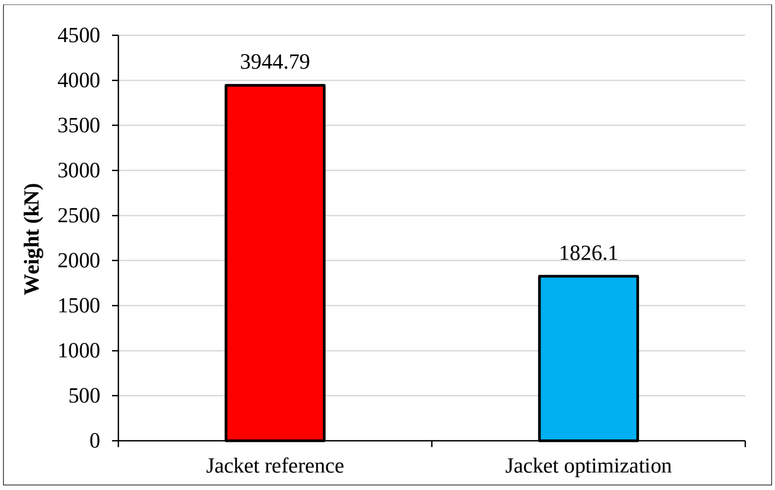

Figure 9. Weight comparison of jacket models

To contextualize the effectiveness of the proposed framework, the results are compared with those reported by Tian et al. (2022) [43], in which topology optimization was applied to a jacket support structure for offshore wind turbines. Their study reported a maximum volume reduction of 38.24% relative to the initial design. In the present study, the combined application of topology, shape, and reliability-based size optimization resulted in a 53.71% reduction in structural weight compared to the reference configuration. Although a higher reduction is observed, this difference may be attributed to variations in structural configuration, loading conditions, optimization constraints, and objective functions.

3.5. Validation of the RBDO Jacket Model with In-place Analysis

Verification of the jacket structure model is carried out to ensure that the resulting model meets the requirements of the jacket structure strength. This model is verified by in-place analysis using finite element software. The calculation of the maximum UC is carried out after the results of the size optimization are completed, and the value of the objective function has been obtained, where the structural dimensions have met the requirements of the predetermined limits. The modelling of the jacket structure is carried out using the dimensions of the size optimization result. After the jacket structure is modelled, an analysis is carried out using SACS software, which aims to verify the jacket model from the size optimization results and whether the UC of the jacket model still meets the requirements. The UC Equation is as follows:

$$\mathrm{UC} = \frac{\sigma_a}{\sigma_I} \leq 1 \tag{14}$$

where, σ_a is the maximum stress value that works on the structure and σ_i is the allowed material tension. UC is the unity check member of the structure, where the value must be smaller than or a maximum of 1. The results of the in-place analysis that has been carried out on the RBDO topology jacket model can be seen in Figure 10.

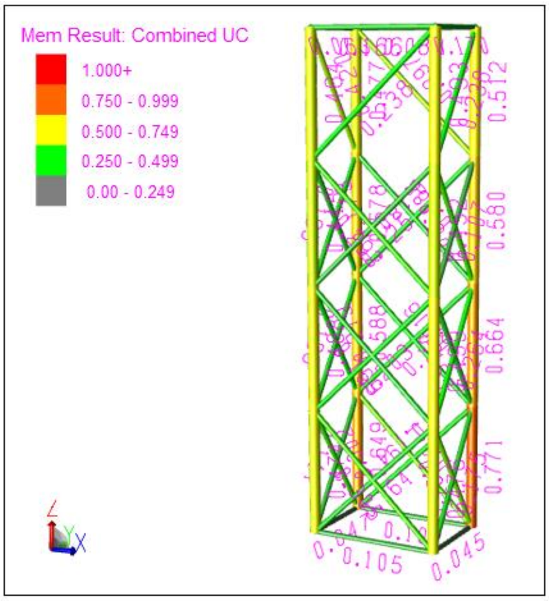

Figure 10. In-place analysis results for the topology RBDO jacket model

Figure 10 presents the results of the in-place structural analysis of the RBDO-optimized jacket model conducted using SACS. The contour plot illustrates the distribution of the unity check (UC) under the governing environmental and operational load combinations. The absence of red zones in the model indicates that no structural member exceeds the allowable limit ($UC \leq 1.0$), confirming that the optimized configuration satisfies the strength requirements prescribed by offshore design standards. The maximum UC value of 0.77 is observed in the leg members, represented by an orange gradient. This demonstrates that the critical members operate at approximately 77% of their allowable capacity, indicating an efficient yet safe level of structural utilization.

From a reliability-based design perspective, achieving a maximum UC below unity while remaining close to the allowable threshold represents an optimal balance between structural safety and material efficiency. The concentration of higher UC values in the leg region is mechanically consistent, as the legs primarily resist combined axial compression, bending moments, and environmental lateral loads induced by wave and current actions. Importantly, the absence of overstressed elements confirms that the reliability constraints imposed during the RBDO process effectively controlled structural performance while enabling weight reduction. Therefore, the in-place analysis validates that the optimized size configuration not only reduces material usage but also preserves global stability and code compliance, demonstrating the robustness and practical feasibility of the proposed optimization framework for offshore jacket structures.

4. Conclusion

This study introduces a unified reliability-based framework for the optimization of the topology, shape, and size of non-battered four-legged offshore platform jackets. This approach addresses the need for a lightweight, structurally reliable offshore structure under combined environmental loads. Topology optimization using the SIMP method identifies the optimal material distribution and the dominant load path. The conceptual layout is refined into a tubular configuration that can be built and evaluated through on-site structural analysis with SACS. The optimized design meets the requirements of the API code RP 2A-WSD, achieving a maximum unit check value of 0.77, indicating efficient use of structural members without excessive stress. Reliability-based size optimization further improves efficiency by incorporating probabilistic constraints. Kriging replacement models with sequential quadratic programming enable accurate predictions of voltage and displacement while reducing computational costs. The final design reduced the total structural weight by 53.71%, from 3944.79 kN to 1826.10 kN. Substitute validation shows strong predictive accuracy, with a determination coefficient above 0.94. The reliability assessment resulted in a probability of failure 0.00093 and a reliability index of $\beta = 3.11$, meeting offshore safety standards.

A major contribution of this study is the systematic integration of topology optimization and reliability-based size optimization for non-battered vertical jacket configurations, an area that is still unexplored in offshore structural design. The proposed framework demonstrates that significant weight savings can be achieved while maintaining structural reliability, offering a robust and efficient strategy for the development of next-generation offshore platforms.

5. Declarations

5.1. Author Contributions

Conceptualization, A.A., R.W.P., and D.M.R.; methodology, A.A., R.W.P., and D.M.R.; software, A.A.; validation, A.A. and R.W.P.; formal analysis, A.A.; investigation, A.A. and R.W.P.; resources, A.A.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A., R.W.P., and D.M.R.; visualization, A.A. and R.W.P.; supervision, R.W.P. and D.M.R. All authors have read and agreed to the published.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding and Acknowledgments

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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