International Journal of Marine Engineering Innovation and Research, Vol. 10(1), March. 2025. 47-54
(pISSN: 2541-5972, eISSN: 2548-1479)

Jacket Structure Design Optimization to Reach Minimum Construction Cost

Aufar S.F. Sumardi[1], Daniel M. Rosyid[2]
(Received: 05 January 2025 / Revised: 19 January 2024 /Accepted: 28 January 2025 / Available Online: 21 March 2025)

Abstract—**Offshore jacket structures are essential components in platform construction, requiring optimization due to high material, fabrication, and coating costs. The objective of this research is to achieve cost-effective designs without compromising safety. The methodology employs Sequential Quadratic Programming (SQP) with a surrogate-based approach to optimize structural dimensions, while reliability is assessed using Monte Carlo Simulation to account for uncertainties. Optimization conducted in MATLAB resulted in significant improvements in the dimensional reduction of most design variables, including a 20.32% reduction in total construction costs. Material, fabrication, and coating costs decreased by 19.05%, 28.11%, and 6.14%, respectively. The reliability index (β) of critical members improved to a range of 3.12–3.29, exceeding the safety threshold of 3.09.**

Keywords— Jacket Structure, Optimization, Sequential Quadratic Programming, Surrogate Model, Monte Carlo Simulation.

I. INTRODUCTION

Indonesia, as a country rich in natural resources, has witnessed a surge in integrated construction projects over the past decade. Among these projects, the oil and gas industry are the highest value project [1]. One important factor that determines the effectiveness of construction yards is cost efficiency. According to [2], it is important to considering economic aspects, in addition to the facilities and equipment required for offshore oil and gas development, when designing platforms in Indonesia. Design efficiency directly impacts project costs, making it imperative for construction yards to optimize costs to remain competitive in the market [3]. The construction of jacket structures requires various cost considerations, with the supporting structure in the form of material volumes emerging as a significant cost component [4]. Therefore, jacket structure design optimization can substantially reduce material requirements, which in turn reduces initial construction costs and long-term operational costs [5].

Optimization algorithms play a vital role in addressing complex engineering challenges, particularly in problems with nonlinear constraints [6]. Among these, Sequential Quadratic Programming (SQP) is widely recognized for its effectiveness. As noted by [7], SQP iteratively solves approximation problems, using a quadratic estimate of the objective function and a linear approximation of constraints to guide the search direction. Its robustness and efficiency make it suitable for navigating nonlinear, constrained search spaces.

Reliability is crucial in optimizing jacket structure designs to ensure cost efficiency and safety. Reliability-Based Design Optimization (RBDO), as emphasized by [8], integrates probabilistic constraints to minimize costs while maintaining high reliability levels. This approach balances cost-effectiveness with safety, enhancing the overall performance of offshore jacket structures.

Design optimization of tubular member in jacket structures is a key challenge. This research considers total capital cost as a combination of material, fabrication, and coating costs [9]. Efficient optimization requires precise formulation of the objective function, reflecting cost reduction goals [10]. Design variables, such as nondimensional tubular geometry parameters which each component consists of a ratio between the diameter and thickness of the jacket, significantly influence structural strength, stiffness, and weight [11]. By establishing mathematical relationships between these variables and total cost, the optimization identifies an optimal configuration.

A. Offshore Jacket Structure

Offshore jackets are fixed platforms characterized by a reinforced tubular space frame that extends from the seabed to above water. This frame is engineered for structural redundancy, enabling the transfer of vertical and lateral forces to the foundation. The structure is anchored to the seabed with piles or other foundation elements to ensure stability and resistance against lateral forces over time. Above the frame, the superstructure supports operational loads, such as drilling and production equipment, living quarters, and other facilities. Offshore jackets are primarily build in shallow to medium water depths, appreciated for their robustness, versatility, and cost-effectiveness [12].

According to [13], Tubular joints are critical components of jacket structures, especially in seismic-prone regions where the design must withstand tensile or

Aufar S.F. Sumardi is with Departement of Technology Management Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: aufartrm@gmail.com.

Daniel M. Rosyid is with Departement of Ocean Engineering Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: dmrosyid@oe.its.ac.id

compressive forces caused by ground motion. Key geometric parameters include chord length, diameter, and thickness, as well as brace diameter and spacing. Non-dimensional parameters such as β (brace-to-chord diameter ratio), γ (flexibility of the chord), and τ (brace-to-chord thickness ratio) significantly influence joint efficiency and stress distribution [14]. Proper design ensures durability under concentrated stresses and punching shear, maintaining the structural integrity under diverse loading conditions.

In this research, the author conducts cost optimization of the jacket structure using a Reliability-Based Design Optimization (RBDO) approach with a Sequential Quadratic Programming (SQP)-Surrogate Based algorithm. This method incorporates design variables that include geometric parameters of tubular components, ensuring an optimal balance between cost efficiency and structural reliability. The reliability of the jacket structure is evaluated using Monte Carlo Simulation, considering failure modes from the combination of axial and bending stresses in accordance with [13].

B. Design Optimization for Offshore Jacket Structures

Reliability-Based Design Optimization (RBDO) integrates reliability constraints into the optimization process to balance cost minimization and structural safety. RBDO ensures that the structural design meets strict safety and reliability requirements [15]. This approach reduces the risk of structural failure and allows for exploring cost-effective solutions while maintaining the desired reliability index (β). For offshore jackets, the reliability index typically ranges between 3.0 and 4.0 to ensure safety under operational and extreme conditions [16].

Sequential Quadratic Programming (SQP) is a highly efficient optimization method for solving nonlinear problems with constraints. The algorithm uses the Lagrangian function to combine the objective function and constraints, iteratively solving quadratic approximations of the objective function and linearized constraints. This method enables rapid convergence to local optima while maintaining feasibility. In this research, SQP was applied with surrogate models to optimize the geometry of jacket structures, focusing on reducing costs while adhering to safety and reliability constraints [17], [18].

Surrogate models are simplified representations of complex systems that predict output responses based on input variables [19]. Kriging models, a type of surrogate model, are widely used in structural optimization due to their ability to provide accurate predictions and quantify uncertainty. By approximating the relationship between design variables and structural responses, Kriging reduces the computational cost of repeated simulations [20], [21].

The cost components of the jacket structure are determined using several constants and parameters critical for calculating material, fabrication, and coating costs. These include the density of jacket material (ρ) in kg/m^3, the number of legs (N_L), and geometric properties such as lengths ($L, L_i, L_{m,i}, L_{OSG}, L_{TP},$) and radius ($R_i$) of the jacket members. Angles ($\vartheta, \psi_{1,i}, \psi_{2,i}, \psi_{3,i}$) and cosines ($\cos\Phi_s$, $\cos\Phi_P$) are used to account for spatial and planar connections in bracings and legs. Parameters such as weldroot thickness (t_0) are essential for evaluating fabrication complexity and material usage. The diameter ratios (β, τ, γ) are utilized as design variables to optimize the geometry and structural efficiency of the jacket components. These parameters provide a detailed framework for accurately estimating the jacket structure's construction cost.

The cost optimization framework decomposes total construction costs into material, fabrication, and coating expenses. Material costs (C_1) are influenced by the weight of tubular members, with the details of the equation as follows:

$$c_1(\boldsymbol{x}) = \underbrace{2\rho N_{\mathrm{L}}\pi D_{\mathrm{L}}^2 \sum_{i=1}^{N_X}\left(\left(\frac{\beta_i\tau_i}{2\gamma_i}+\frac{\tau_i^2}{4\gamma_i^2}\right)\sqrt{\frac{L_i^2}{\cos^2(\Phi_{\mathrm{p}})}+(R_i+R_{i+1})^2\sin^2\left(\frac{\vartheta}{2}\right)}\right)}_{\text{Mass of all diagonal braces}}$$
$$+\underbrace{\rho N_{\mathrm{L}}\pi D_{\mathrm{L}}^2 \sum_{i=1}^{N_X}\left(\left(\frac{1}{2\gamma_i}+\frac{1}{4\gamma_i^2}\right)\frac{L_{m,i}}{\cos(\Phi_{\mathrm{s}})}+\left(\frac{1}{2\gamma_{i+1}}+\frac{1}{4\gamma_{i+1}^2}\right)\frac{(L_i-L_{m,i})}{\cos(\Phi_{\mathrm{s}})}\right)}_{\text{Mass of leg element}}$$
$$+\underbrace{\rho N_{\mathrm{L}}\pi D_{\mathrm{L}}^2\left(\frac{1}{2\gamma_{\mathrm{b}}}+\frac{1}{4\gamma_{\mathrm{b}}^2}\right)\frac{L_{\mathrm{OSG}}}{\cos(\Phi_{\mathrm{S}})}}_{\text{Mass of lowermost elements}}$$
$$+\underbrace{\rho N_{\mathrm{L}}\pi D_{\mathrm{L}}^2\left(\frac{1}{2\gamma}+\frac{1}{4\gamma_{\mathrm{t}}^2}\right)\frac{L_{\mathrm{TP}}}{\cos(\Phi_{\mathrm{s}})}}_{\text{Mass of uppermost leg elements}} \quad (1)$$

The fabrication costs (C_2) depend on the welding volume, with detailed equation below:

$$c_2(\boldsymbol{x}) = \underbrace{2N_{\mathrm{L}}\pi D_{\mathrm{L}}\sum_{i=1}^{N_X}\left(\beta_i\left(\frac{D_{\mathrm{L}}^2\tau_i^2}{8\gamma_i^2}+\frac{t_0D_{\mathrm{L}}\tau_i}{2\sqrt{2}\gamma_i}\right)\left(\sqrt{\frac{1}{2\sin^2(\psi_{1,i})}+\frac{1}{2}}+\sqrt{\frac{1}{2\sin^2(\psi_{2,i})}+\frac{1}{2}}+\sqrt{\frac{1}{2\sin^2(\psi_{3,i})}+\frac{1}{2}}\right)\right)}_{\text{Brace-to-brace and brace-to-leg weld volume}}$$
$$+\underbrace{N_{\mathrm{L}}\pi D_{\mathrm{L}}\sum_{i=1}^{N_X}\left(\frac{D_{\mathrm{L}}^2\min\left(\frac{1}{\gamma_i^2},\frac{1}{\gamma_{i+1}^2}\right)}{8}+\frac{D_{\mathrm{L}}t_0\min\left(\frac{1}{\gamma_i},\frac{1}{\gamma_{i+1}}\right)}{2\sqrt{2}}\right)}_{\text{Leg-to-leg weld volume}} \quad (2)$$

And coating costs are determined by the outer surface area, where the detailed equation is attached below:

$$c_3(\boldsymbol{x}) = \underbrace{2N_{\mathrm{L}}\pi D_{\mathrm{L}}\sum_{i=1}^{N_X}\left(\beta_i\sqrt{\frac{L_i^2}{\cos^2(\Phi_{\mathrm{p}})}+(R_i+R_{i+1})^2\sin^2\left(\frac{\vartheta}{2}\right)}\right)}_{\text{Outer surface area of all diagonal braces}}$$
$$+\underbrace{N_{\mathrm{L}}\pi D_{\mathrm{L}}\frac{L}{\cos(\Phi_{\mathrm{s}})}}_{\text{Outer surface area of all legs}} \quad (3)$$

By optimizing design variables such as diameters and thicknesses of the jacket's structural components, this study achieved a significant reduction in total construction costs while maintaining structural safety [9].

C. Reliability Analysis

Monte Carlo Simulation (MCS) is a robust computational method used to evaluate the reliability of structures by estimating the probability of failure under uncertain conditions [22]. This approach involves generating random samples for design variables and operational conditions based on their probability distributions. These samples are then applied to a mathematical model, often defined by a limit-state function, to determine whether the structure satisfies or violates predefined criteria [16]. In this research, MCS was implemented to evaluate the reliability of the optimized jacket structure, focusing on failure modes combining axial and bending stresses that complies with API RP 2A WSD which is given the following equation:

$$\frac{fa}{Fa} + \frac{\sqrt{f_{bx}^2 + f_{by}^2}}{Fb} \leq 1.0 \quad (4)$$

Where fa is the Axial Stress, Fa is the allowable axial stress, f_{bx} and f_{by} is the bending stress in two directions, and Fb is the allowable bending stress.

II. Method

A. Jacket Structure Data

The jacket structure analyzed is located in the Peciko Gas Field in the Mahakam Delta area with a depth of 39,358 meters. The jacket structure weighs approximately 615.788 tons and has four legs. Structural data on the study, can be seen in Table 1.

B. Environmental Data

Environmental data is critical for the design, analysis, and optimization of offshore jacket structures. This data encompasses operational conditions, storm conditions, and soil properties.

1) Operational Environmental Data
These data represent the typical conditions the structure will face during its daily operations. It includes parameters like wave height, wave period, current velocity, tidal range, and wind speed.
2) Storm Environmental Data
This category covers extreme conditions that may occur during storms, such as higher wave heights, longer wave periods, increased current velocities, and stronger winds.
3) Soil Data
Soil data is essential for understanding the interaction between the jacket's foundation and the seabed. This includes soil bearing capacity, axial stiffness, and lateral stiffness, which influence the stability and load transfer capabilities of the jacket's piles. This data ensures the foundation design supports both operational and extreme load conditions effectively.

C. Modeling the Jacket Structure using SACS

Modeling of the platform jacket is conducted to create a model of the object to be analyzed using SACS software. The structural configuration uses X-brace at the top and center and K-brace at the bottom. In addition, supporting data such as environmental data (wind, wave current), soil data, and contingency factors are also included in the modeling.

D. Validation of Jacket Structure Model

Model validation aims to ensure that the structural model accurately represents the actual structure [23]. This process employs the Mean Absolute Percentage Error (MAPE) as a parameter, comparing the weight of the modeled structure with the actual structure's weight. The MAPE equation can be seen as follows:

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| x\ 100 \quad (5)$$

Where A_t is the experimental result value at time t, F_t is the modeling result at time t, and n is the amount of data.

The acceptable error threshold for MAPE is set at no more than 10%; however, to achieve higher accuracy, this study imposes a stricter limit of 5%. If the model fails to meet these validation criteria, a review and revision of the modeling process are undertaken until the validation requirements are satisfied [24].

E. Inplace Analysis

In-place analysis is a static structural evaluation method used to assess the response of offshore jacket components under applied loads. Its primary objective is to ensure that the structure can withstand internal loads, such as equipment weights, and external loads, such as environmental forces. A key parameter for in-place analysis is the Unity Check (UC), which evaluates the

TABLE 1.
JACKET STRUCTURE DATA

Description	Remarks
Number of Jacket Leg	4
Jacket Elevation	4 (at EL: -39.77m, -25.89m, -10.39m, +4.61m from Chart Datum)
Leg Diameter	66” DIA x 0.75” WT
Leg Batter	1:10 (in Row A, B, 2); 1:1 in Row 1
Pile Penetration Deep	130m (from El. +4,895m from CD)

Figure. 1. Jacket Structure Geometry Modeling Results.

ratio of the actual stress experienced by a structural member to the allowable stress. The Unity Check formula is expressed as:

$$UC = \frac{\sigma_{actual}}{\sigma_{allow}} \quad (6)$$

Where σ_{actual} is actual stress experienced by the structure and σ_{allow} is allowable stress for the structure. The value of UC must remain below 1.0 to indicate that the structural member is operating within safe limits.

F. Optimization Process

The optimization process begins with creating a Design of Experiment (DoE) using the Latin Hypercube Sampling (LHS) method in MATLAB. This technique ensures a well-distributed sampling of the parameter space, enabling efficient exploration of possible design combinations. For this study, eight design parameters were selected, which are Outer Diameter Jacket (ODJ), Outer Diameter Bracing 1 (ODB1), Outer Diameter Bracing 2 (ODB2), Outer Diameter Bracing 3 (ODB3), Wall Thickness Jacket (WTJ), Wall Thickness Bracing 1 (WTB1), Wall Thickness Bracing 2 (WTB2), Wall Thickness Bracing 3 (WTB3). Each parameter was assigned default values, along with minimum and maximum limits based on tubular catalogs.

The generated design samples were simulated using the SACS software to evaluate the performance of each structure. Key parameters such as outer diameters (OD) and wall thicknesses (WT) were input into SACS to model the jacket structure. Structural analysis assessed various response variables, including Unity Check (UC), Punching Shear, and Slenderness Ratios.

Non-dimensional parameters such as β, τ, and γ, which describe tubular geometry, were also calculated to analyze the stability and stress distribution across various elevations. The simulation results, including response variables such as UC, Punching Shear, and Slenderness Ratios, were compiled into a matrix format. This matrix integrates design parameters (OD, WT) and response variables for further optimization. Data was processed in MATLAB to prepare it for integration into the optimization framework.

1) Training Kriging Models for the dataset

MATLAB was utilized to develop Kriging surrogate models, which approximated the complex relationship between design variables and structural responses. These models significantly reduced computational effort by replacing expensive finite element simulations with efficient predictions. The coding for the training kriging models for the dataset can be seen in Table 2.

TABLE 2.
MATLAB CODING FOR TRAIN KRIGING MODELS DATA SET

MATLAB Code

```
% Train Kriging models for UC and Punching Shear (use entire dataset)
gprMdl_UC = fitrgp(X, Y(:, 1), 'BasisFunction', 'none', 'KernelFunction', 'squaredexponential');
gprMdl_Punch = fitrgp(X, Y(:, 2), 'BasisFunction', 'none', 'KernelFunction', 'squaredexponential');
```

2) Optimization Algorithm with SQP and Nonlinear

TABLE 3.
MATLAB CODING FOR OPTIMIZATION ALGORITHM USING SQP AND NONLINEAR CONSTRAINT FUNCTION

MATLAB Code

```
% Objective function: minimize cost function
objective = @(x) costFunction(x);
% Nonlinear constraints
nonlcon = @(x) constraintFunction(x, gprMdl_UC, gprMdl_Punch, Y);
% Initial guess
x0 = (lb + ub) / 2;
% Optimization options
options = optimoptions('fmincon', 'Algorithm', 'sqp', 'Display', 'iter');
% Run optimization
[x_opt, fval] = fmincon(objective, x0, [], [], [], [], lb, ub, nonlcon, options);
%% Nonlinear Constraint Function
function [c, ceq] = constraintFunction(x, gprMdl_UC, gprMdl_Punch, Y)
    % Predict UC and Punching Shear
    UC_pred = predict(gprMdl_UC, x);
    Punch_pred = predict(gprMdl_Punch, x);
% Constraints for UC and Punching Shear
    c1 = UC_pred - 1;       % UC <= 1
    c2 = Punch_pred - 1;     % Punching Shear <= 1
% Additional constraints based on calculated values
    c3 = [beta1 - 0.5; 0.3 - beta1]; % 0.3 <= beta1 <= 0.5
    c6 = [tau1 - 1; 0.4 - tau1];     % 0.4 <= tau1 <= 1
    c9 = [gamma - 24; 10 - gamma];   % 10 <= gamma <= 24
% Slenderness constraints
    slenderness = Y(:, 10:13); % SlendernessKaki, Slenderness1, Slenderness2, Slenderness3
    c10 = max(slenderness, [], 2) - 80; % All slenderness values <= 80
```

TABLE 4.
MATLAB CODING FOR OPTIMIZATION ALGORITHM USING SQP AND NONLINEAR CONSTRAINT FUNCTION

MATLAB Code

```
% c1(x) - Material Expense
    c1 = 2 * rho * NL * pi * ODJ^2 * ...
    ((beta1 * tau1 / (2 * gamma) + tau1^2 / (4 * gamma^2)) * sqrt(L1^2 / cos(phi_p)^2 + (R1 + R2)^2 *
sin(theta)^2) + ...
     (beta2 * tau2 / (2 * gamma) + tau2^2 / (4 * gamma^2)) * sqrt(L2^2 / cos(phi_p)^2 + (R2 + R3)^2 *
sin(theta)^2) + ...
     (beta3 * tau3 / (2 * gamma) + tau3^2 / (4 * gamma^2)) * sqrt(L3^2 + (R3 + R4)^2 * sin(theta)^2))
+ ...
    rho * NL * pi * ODJ^2 * ((1/(2 * gamma) + 1/(4 * gamma^2)) * Lm1 / cos(phi_s) + ...
     (1/(2 * gamma) + 1/(4 * gamma^2)) * LOSG / cos(phi_s) + ...
     (1/(2 * gamma) + 1/(4 * gamma^2)) * LTP / cos(phi_s));

% c2(x) - Fabrication Expense
    weldVolume1 = beta1 * ((ODJ^2 * tau1^2) / (8 * gamma^2) + t0 * ODJ * tau1 / (2 * sqrt(2) * gamma))
* ...
        (sqrt(0.5 * sin(psi1_1)^2 + 0.5) + sqrt(0.5 * sin(psi3_1)^2 + 0.5));
    weldVolume2 = beta2 * ((ODJ^2 * tau2^2) / (8 * gamma^2) + t0 * ODJ * tau2 / (2 * sqrt(2) * gamma))
* ...
        (sqrt(0.5 * sin(psi1_2)^2 + 0.5) + sqrt(0.5 * sin(psi2_2)^2 + 0.5));
    weldVolume3 = beta3 * ((ODJ^2 * tau3^2) / (8 * gamma^2) + t0 * ODJ * tau3 / (2 * sqrt(2) * gamma))
* ...
        (sqrt(0.5 * sin(psi2_3)^2 + 0.5) + sqrt(0.5 * sin(psi3_3)^2 + 0.5));
    weldLegVolume = NL * pi * ODJ * ((ODJ^2 / (8 * gamma^2)) + t0 * ODJ / (2 * sqrt(2) * gamma));

    c2 = 2 * NL * pi * ODJ * (weldVolume1 + weldVolume2 + weldVolume3) + weldLegVolume;

% c3(x) - Coating Expense
    c3 = 2 * NL * pi * ODJ * ...
    (beta1 * sqrt(L1^2 / cos(phi_p)^2 + (R1 + R2)^2 * sin(theta)^2) + ...
     beta2 * sqrt(L2^2 / cos(phi_p)^2 + (R2 + R3)^2 * sin(theta)^2) + ...
     beta3 * sqrt(L3^2 + (R3 + R4)^2 * sin(theta)^2) + ...
     L / cos(phi_s));

    % Total cost
    cost = c1 + c2 + c3;
end
```

Constraint Functions

The SQP algorithm was coded to iteratively optimize design variables, such as tubular dimensions and geometry. Nonlinear constraints, derived from reliability and structural performance requirements, were integrated to ensure feasibility and safety throughout the optimization process. MATLAB coding for SQP can be seen in Table 3.

3) Objective Function Implementation

The objective function was coded to compute the total construction cost of the jacket structure. It included sub-functions for calculating material, fabrication, and coating costs, which were dynamically updated based on the optimized design variables. The objective cost function coding can be seen in Table 4.

G. Comparison of Jacket Structure Before and After Optimization

The comparison of the jacket structure before and after optimization evaluates cost efficiency, structural performance, and reliability to determine the effectiveness of the optimization process. Cost efficiency is assessed by analyzing the reduction in total construction costs (C_{Total}), including material, fabrication, and coating expenses. Structural performance improvements are highlighted through changes in Unity Check (UC) values, ensuring that stress levels remain within allowable limits (UC≤1). Reliability is evaluated by maintaining or improving the reliability index (β) to meet safety criteria, ensuring the optimized design can withstand operational and environmental loads. This comprehensive comparison demonstrates the optimization's ability to deliver a cost-effective, structurally sound, and reliable jacket structure.

III. Results and Discussion

A. Jacket Structure Model Validation

The validation of the jacket structure model was conducted using SACS 12.0 to ensure accuracy and representation of real-world conditions. As shown in Table 5, the weight difference between the original structure (20,402.17 kN) and the modeled structure (20,323.03 kN) resulted in an error of only 0.39%. This validation demonstrates that the jacket structure modeling is highly accurate. By adhering to the API RP 2A WSD standards, the structure meets widely recognized industry standards, ensuring reliability and operational efficiency. This validation confirms that further analysis can be performed with confidence that the structural model accurately represents field conditions.

B. Optimized Variable Designs

The optimization results in Table 6 shows that the optimal design variables achieved through the total cost minimization process for the jacket structure include changes in the outer diameter (OD) and wall thickness (WT) compared to the initial design. For the jacket legs, the outer diameter (ODJ) was reduced from 171.45 cm to 162.60 cm, while the wall thickness (WTJ) decreased from 3.81 cm to 3.3875 cm. For the bracings at all three elevations, the outer diameters (ODB1, ODB2, ODB3) were standardized to 48.78 cm, replacing the initial design's varied dimensions of 45.72 cm, 50.80 cm, and 60.96 cm. Similarly, the bracing wall thicknesses (WTB1, WTB2, WTB3) were unified at 1.355 cm, compared to the initial design's varying thicknesses of 1.91 cm, 1.27 cm, and 1.59 cm. Both the outer diameters and wall thicknesses of the jacket legs and bracings were reduced compared to the original design.

C. Optimized Jacket Structure Reliability

Figure 2 illustrates an overall increase in the Reliability Index (β) for all critical members after optimization. A slight decrease in reliability for one member, while still above the threshold of 3.09, is likely due to load redistribution, allocating more load to that member to optimize its design capacity. This may result from increased axial or bending forces after optimization. Additionally, changes in geometry, such as reduced diameter or wall thickness to lower weight and cost, could contribute to this reduction. Interactions between members also play a role, as changes in one member can affect force distribution in others. This decrease indicates the member is working closer to its optimal capacity without exceeding design limits, adhering to the recommended safety standards (β >3.09) based on normal reliability classification by [25].

D. Total Cost of Jacket Structure After Optimization

Based on the calculation of the unit construction cost of the jacket structure before and after optimization using MATLAB in Table 7, a significant reduction is observed in the total cost and its components, including material, fabrication, and coating costs.

The largest cost reduction was observed in fabrication unit cost (C_2), which decreased by 28.11%, followed by material unit cost (C_1) with a 19.06% reduction, and coating unit cost (C_3) with a 6.14% reduction. This significant cost reduction reflects the success of the optimization process in streamlining the jacket structure design through reductions in member dimensions (diameter and thickness) and load redistribution to optimize structural capacity.

Material costs for tubular steel were set at $4.5 per kilogram, based on raw material weight. Fabrication costs, including welding, were calculated at $1935 per cubic meter of weld volume. Coating and surface preparation costs, including anti-corrosion application, were estimated at $50 per square meter of surface area. The price of each cost component will be calculated by unit cost multiplied by the price of each cost component per unit cost as illustrated in Figure 3. These costs were sourced from online catalogs.

The total construction cost (C_{Total}) decreased significantly after optimization, from $172,254,304.52 to $137,247,754.83, achieving a savings of $35,006,549.70 or approximately 20.32%.

TABLE 5.
JACKET STRUCTURE WEIGHT VALIDATION

Jacket Structure Weight (kN)		MAPE	Remarks
Actual Weight	Modeling Weight		
20402.17	20323.03	0.39%	High Accuracy

TABLE 6.
MATLAB RUNNING RESULTS FOR OPTIMAL DESIGN VARIABLES AND PERCENTAGE REDUCTION OF DESIGN VARIABLES

Optimum Results of Design Variables from MATLAB

```
% Initial design variables
initial_design = [171.45, 45.72, 50.80, 60.96, 3.81, 1.91, 1.27, 1.59];

Optimal Design Variables (cm):
ODJ       ODB1       ODB2      ODB3      WTJ       WTB1      WTB2     WTB3
162.6000   48.7800   48.7800   48.7800    3.3875    1.3550    1.3550   1.3550

Percentage Reduction in Design Variables (%):
ODJ       ODB1       ODB2      ODB3      WTJ       WTB1      WTB2      WTB3
5.1619    -6.6929    3.9764    19.98     11.089    29.058    -6.6929    14.78
```

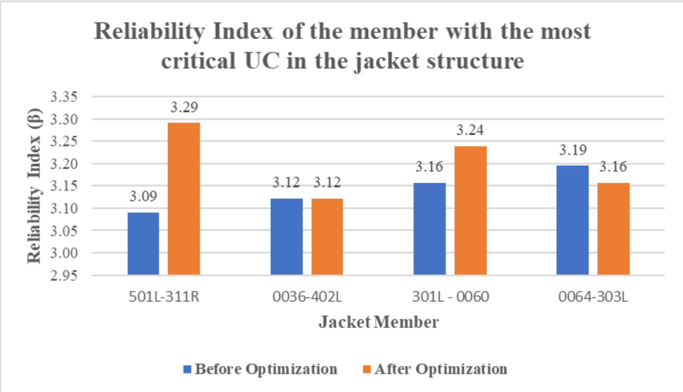

Figure. 2. Reliability Index of Members with Most Critical UC in Jacket Structure Before and After Optimization.

TABLE 7.
JACKET STRUCTURE WEIGHT VALIDATION

Optimum Results of Cost Components and Percentage Reduction in Costs from MATLAB

```
Initial Costs:
Initial c1 (Material Expense): 23911421.5121
Initial c2 (Fabrication Expense): 24780.1087
Initial c3 (Coating Expense): 334067.9477
Optimal Costs:
Optimal c1 (Material Expense): 19355107.4254
Optimal c2 (Fabrication Expense): 17814.9678
Optimal c3 (Coating Expense): 313556.1744
Percentage Reduction in Costs (c1, c2, c3) (%):
Reduction in c1: 19.055%
Reduction in c2: 28.1078%
Reduction in c3: 6.14%
```

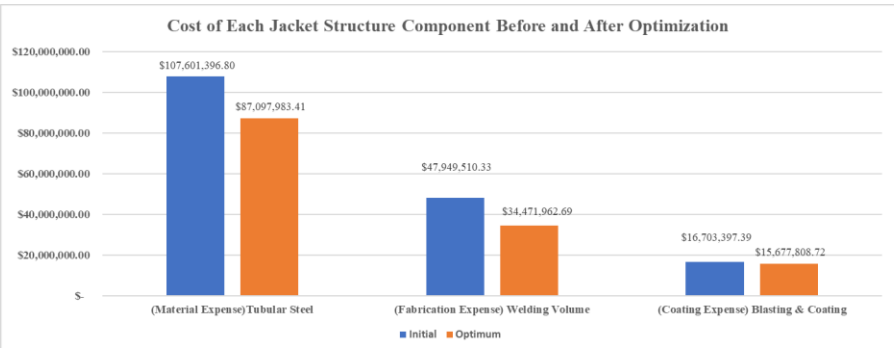

Figure. 3. Cost Per Item on Jacket Structure Before and After Optimization.

IV. Conclusion

Based on the result and discussion in the design optimization of the jacket structure to achieve minimum construction costs, the following conclusions is:

1) Optimized dimensions reduced material and fabrication costs. For jacket legs (ODJ), the diameter decreased from 171.45 cm to 162.60 cm, and thickness (WTJ) from 3.81 cm to 3.3875 cm. Bracing dimensions were standardized, with ODB1, ODB2, and ODB3 set to 48.78 cm and WTB1, WTB2, and WTB3 to 1.355 cm.
2) Total construction cost decreased by 20.32%, from 172,254,304.52 to 137,247,754.83. Material (C_1) costs dropped by 19.05%, fabrication (C_2) by 28.11%, and coating (C_3) by 6.14%.
3) The reliability index (β) increased to 3.12–3.29, above the 3.09 threshold, ensuring structural safety. The success probability remained high (>99.9%), with a failure probability below 0.09%.

The author's suggestions to enhance the design optimization process for jacket structures include increasing the sample size in Latin Hypercube Sampling (LHS) for more representative data, conducting sensitivity analysis to understand the impact of design variables on cost and reliability, and including additional costs such as labor, transportation, installation, and inspection for a more detailed total cost estimate.

Acknowledgements

The author sincerely thanks LPDP for sponsoring the Master's degree scholarship and the Department of Technology Management, ITS for their support throughout the coursework and research process.

References

[1] M. Dachyar and Sanjiwo, "Business Process Re-Engineering of Engineering Procurement Construction (EPC) Project in Oil and Gas Industry in Indonesia," *Indian Journal of Science and Technology,* vol. 11, pp. 1-8, 2018.

[2] Silvianita, F. Redana, D. M. Rosyid, D. M. Chamelia and Suntoyo, "Project Delay Analysis on Jacket Structure Construction," *Applied Mechanics and Materials,* vol. 862, no. August 2014, pp. 315-320, 2017.

[3] M. Aslam, E. Baffoe-Twum and F. Saleem, "Design Changes in Construction Projects - Causes and Impact on the Cost," *Civil Engineering Journal,* vol. 5, no. 7, pp. 1647-1655, 2019.

[4] S. Zheng, C. Li and Y. Xiao, "Efficient optimization design method of jacket structures for offshore wind turbines," *Marine Structures,* vol. 89, no. 12, p. 103372, 2023.

[5] A. A. Motlagh, N. Shabakhty and A. Kaveh, "Design optimization of jacket offshore platform considering fatigue damage using Genetic Algorithm," *Ocean Engineering,* vol. 227, no. March, p. 108869, 2021.

[6] H.-T. Thai, "Machine learning for structural engineering: A state-of-the-art review," *Structures,* vol. 38, no. 12, pp. 448-491, 2021.

[7] G. Venter, "Review of Optimization Techniques," *Encyclopedia of Aerospace Engineering,* pp. 1-12, 2010.

[8] S. Zhu, B. Keshtegar, N. Trung, Z. M. Yaseen and D. T. Bui, "Reliability-based structural design optimization: hybridized conjugate mean value approach," *Engineering with Computers,* vol. 37, no. 1, pp. 381-394, 2021.

[9] J. Häfele, R. R. Damiani, R. N. King, C. G. Gebhardt and R. Rolfes, "A systematic approach to offshore wind turbine jacket predesign and optimization: geometry, cost, and surrogate structural code check models," *Wind Energy Science,* vol. 3, no. 2, pp. 553-572, 2018.

[10] L. Birk, G. F. Clauss and J. Y. Lee, "Practical Application Of Global Optimization To The Design Of Offshore Structures," in *23rd International Conference on Offshore Mechanics and Arctic Engineering*, Vancouver, British Columbia, Canada, 2004.

[11] A. Ahrari, A. A. Atai and K. Deb, "Simultaneous topology, shape and size optimization of truss structures by fully stressed design based on evolution strategy," *Engineering Optimization ISSN:,* vol. 47, no. 8, pp. 1063-1084, 2015.

[12] F. Fu, "Chapter Eight - Design of Offshore Structures," in *Design and Analysis of Tall and Complex Structures*, Elsevier Ltd, 2018, pp. 251-293.

[13] A. P. I. (API), API Recommended Practice 2A-WSD (RP 2A-WSD), Washington, D.C: American Petroleum Institute, 2002.

[14] M. A. Lotfollahi-Yaghin and H. Ahmadi, "Effect of geometrical parameters on SCF distribution along the weld toe of tubular KT-joints under balanced axial loads," *International Journal of Fatigue journal,* vol. 32, no. 4, pp. 703-719, 2010.

[15] Y. Yu, M. Wei, J. Yu, Y. Cui, R. Gao, Z. Dong and X. Wang, "Reliability-based design method for marine structures combining topology, shape, and size optimization," *Ocean Engineering,* vol. 286, no. P1, p. 115490, 2023.

[16] S.-K. Choi, R. V. Grandhi and R. A. Canfiel, Reliability-based Structural Design, London: Springer-Verlag London Limited, 2014.

[17] K. Long, X. Wang and H. Liu, "Stress-constrained topology optimization of continuum structures subjected to harmonic force excitation using sequential quadratic programming," *Structural and Multidisciplinary Optimization,* vol. 59, no. 5, pp. 1747-1759, 2019.

[18] B. Liu, V. Grout and A. Nikolaeva, "Efficient Global Optimization of Actuator Based on a Surrogate Model Assisted Hybrid Algorithm," *IEEE Transactions On Industrial Electronics,* vol. 65, no. 7, pp. 5712-5721, 2018.

[19] C. Ren, Y. Aoues, D. Lemosse and E. S. D. Cursi, "Reliability assessment of an offshore wind turbine jacket under one ultimate limit state considering stress concentration with active learning approaches," *Ocean Engineering journal,* vol. 281, no. May, p. 114657, 2023.

[20] I. Kaymaz, "Application of kriging method to structural reliability problems," *Structural Safety,* vol. 27, no. 2, pp. 133-151, 2005.

[21] M. K. McWilliam, M. Friis-Møller, N. Pollini, K. Dykes and M. Jensen, "A surrogate model of offshore wind farm support structures for wind farm design and financial valuation," *Journal of Physics: Conference Series,* vol. 2265, no. 4, 2022.

[22] A. A. Shittu, A. Kolios and A. Mehmanparast, "A systematic review of structural reliability methods for deformation and fatigue analysis of offshore jacket structures," *Metals,* vol. 11, no. 1, pp. 1-37, 2020.

[23] I. Nabillah and I. Ranggadara, "Mean Absolute Percentage Error untuk Evaluasi Hasil Prediksi Komoditas Laut," *Journal of Information System,* vol. 5, no. 2, pp. 250-255, 2020.

[24] A. d. Myttenaere, B. Golden, B. L. Grand and F. Rossi, "Mean Absolute Percentage Error for regression models," *Neurocomputing,* vol. 192, pp. 38-48, 2016.

[25] Y. Bai, Marine Structural Design (Second Edition), The Boulevard, Langford Lane Kidlington, Oxford OX5 IGB, UK: Elsevier Ltd., 2016.