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Development of a Web-Based Heavy Lifting Planning and Rigging Evaluation System for FPSO Module Decommissioning

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Abstract**—** Floating Production Storage and Offloading (FPSO) decommissioning requires complex heavy lifting operations involving large topside modules with significant weight and intricate mass distribution. The Electrical Switchgear Module (E-House), weighing over 300 tons, represents a critical lifting challenge requiring comprehensive engineering planning to ensure operational safety and load stability. Conventional lifting planning relies on manual, separate calculations that often lead to workflow inefficiencies and inconsistent engineering evaluations. This study develops an integrated web-based heavy lifting planning and rigging evaluation system to assist lifting engineers in conducting systematic and efficient lifting analysis for FPSO module decommissioning operations, with focus on determining optimal rigging configurations and evaluating maximum lifting capacity. Quantitative engineering analysis based on static load evaluation and marine lifting engineering principles was applied. The Electrical House module from FPSO Ningaloo Vision (actual weight: 303.281 tons; design load: 334.367 tons with 5% operational allowance) was analyzed under multiple lifting scenarios. The study evaluated three rigging configurations (single crane with spreader bar, dual crane without spreader bar, and single crane without spreader bar) through sling force calculation, crane capacity assessment, and Ground Bearing Pressure (GBP) evaluation. The sling angle emerged as the most sensitive parameter affecting tensile force distribution. The single crane configuration utilizing a spreader bar provided optimal performance with balanced load distribution and superior lifting stability compared to alternative configurations. The web-based system successfully integrated lifting calculations, rigging assessment, and safety evaluation into an automated platform, reducing calculation time and improving engineering consistency compared to conventional manual methods. The developed web-based system demonstrates significant potential to improve lifting planning efficiency, enhance engineering decision-making, and support standardization of heavy lifting operations in FPSO decommissioning activities. The flexible calculation methodology can be applied to similar FPSO modules, contributing to safer and more systematic offshore decommissioning operations.

Keywords—Crane Capacity, FPSO, Heavy Lifting, Lifting Engineering, Rigging Configuration, Web Application.

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I. INTRODUCTION

Floating Production Storage and Offloading (FPSO) units represent critical infrastructure in offshore oil and gas production, with operational lifespans typically ranging from 20 to 30 years [1]. As these facilities approach end-of-life, decommissioning becomes an inevitable operational challenge requiring comprehensive technical planning and execution [2]. he increasing number of aging offshore installations worldwide has led to growing attention toward safe, efficient, and environmentally responsible decommissioning strategies for offshore oil and gas facilities [3]. The decommissioning process involves the systematic removal of topside modules, structural components, and equipment, with heavy lifting operations representing one of the most critical and hazardous phases of the entire process. The FPSO decommissioning process typically comprises five distinct phases: planning and environmental assessment, system shutdown and preservation, topside module removal, hull decommissioning or conversion, and final disposal. The topside removal phase is particularly critical, as it involves systematic extraction of installed modules, equipment, and systems integrated into the FPSO structure for 20–30 years of operation, requiring precisely coordinated lifting operations, structural support management, and environmental protection measures.

Heavy lifting operations during FPSO decommissioning present substantial technical complexity and operational risk. Large topside modules including power systems, electrical distribution, and processing equipment—frequently exceed 300 tons in total weight and possess complex mass distributions that significantly complicate lifting dynamics [4]. Improper lifting planning may lead to catastrophic failures including crane overloading, sling rupture, rigging instability, excessive ground bearing pressure, equipment damage, personnel injuries, and substantial financial losses. The Electrical Switchgear Module (E-House) exemplifies these challenges. This critical component integrates electrical distribution systems, control mechanisms, and switchgear equipment necessary for FPSO electrical management, resulting in a compact structure with high weight concentration and irregular mass distribution. The module's structural characteristics and installation requirements demand meticulous lifting

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engineering analysis to ensure safe, stable, and controlled handling throughout the lifting sequence. FPSO decommissioning presents unique challenges compared to conventional offshore platform decommissioning, including spatial constraints from limited deck space that restrict crane positioning and lifting radius, dynamic vessel environments caused by sea state and wind that complicate lifting stability and timing, module weights frequently exceeding 300–400 tons with irregular mass distributions from integrated topside systems, environmental integration requiring careful disconnection of numerous process, utility, and control system connections and regulatory compliance with multiple international regulations including DNV, IMCA, and API standards that impose strict requirements on lifting operations and personnel safety [5], [6], [7].

Recent FPSO decommissioning projects in Southeast Asia and North Sea regions have demonstrated both the complexity and feasibility of large-scale module removal operations, providing valuable lessons regarding scheduling, environmental management, and cost optimization [8]. Heavy lifting in offshore environments requires adherence to rigorous engineering standards and proven operational best practices, with modern lifting engineering integrating multiple disciplinary areas including structural mechanics, rigging design, crane engineering, and operational safety management. Heavy lifting operations are governed by comprehensive engineering analyses incorporating static load analysis as the foundation of lifting design, assuming equilibrium conditions and calculating load distribution through force balance equations considering the number of lifting points, sling geometry, and load configuration. Real-world lifting operations introduce dynamic effects through acceleration, deceleration, vessel motion, and environmental loading, with safety standards typically incorporating Dynamic Amplification Factors (DAF) ranging from 1.1 to 1.25 depending on operational conditions and lift complexity [9].

Offshore lifting standards mandate multiple safety layers including equipment safety factors typically ranging from 5–6 for slings, operational safety factors generally between 1.5–2.0 applied to design loads, and additional analytical safety factors inherent in conservative engineering assumptions. Lifting operations are governed by several internationally recognized standards, including DNV-ST-N001 [5], which provides comprehensive marine operations and marine warranty requirements covering lifting analysis, weather criteria, personnel certification, and operational control; NORSOK R-003 [10], which establishes standards for the safe use of lifting equipment and rigging systems; IMCA M179 [11], which provides best-practice guidance for the management, planning, and execution of lifting operations; API RP 2A-WSD [12], which outlines recommended practices for fixed offshore platform design including lifting-related requirements; and ASME B30.9 [13], which specifies safety and performance requirements for slings and lifting devices. Additional offshore lifting requirements are addressed by DNV-ST-0378 [14], covering offshore and platform lifting appliances.

Among the most critical parameters in rigging design is sling angle configuration. The relationship between sling angle and sling tension can be expressed as $F = W / (n \times \cos\theta)$, where F represents sling tensile force, W represents lifting load, n represents the number of sling legs, and θ represents the angle between the sling and the horizontal plane. This relationship demonstrates that smaller sling angles result in substantially increased tensile forces. At a sling angle of 30°, sling tension may reach approximately 2.3 times the theoretical equal load distribution, while at 15° the tension may increase to approximately 3.9 times, highlighting the critical importance of maintaining proper rigging geometry. Spreader bars function as rigid load-distributing elements that maintain favorable sling geometry by increasing horizontal separation between lifting points. By maintaining larger sling angles, typically between 45° and 60°, spreader bars significantly reduce tensile forces compared to configurations without spreader bars, thereby improving lifting safety margins. Crane lifting capacity is not constant but varies significantly with lifting radius and boom angle. Crane load charts establish maximum permissible loads at various radii, requiring that lifting analyses verify that actual loads remain below charted capacities at the intended operating radius.

Rigging configuration refers to the arrangement of slings, shackles, spreader bars, and other hardware used to connect a load to a lifting device. The choice of rigging configuration directly affects load distribution among lifting points, sling tensile forces, component stresses, overall system stability and balance, operational safety, redundancy, and project cost. A single crane configuration with a spreader bar utilizes a rigid spreader beam to distribute load symmetrically across four lifting points, offering advantages including superior load distribution, operational stability, simplified coordination, and proven reliability, although it requires adequate deck space and spreader bar fabrication and certification. A dual crane configuration distributes the load between two crane systems, potentially reducing individual crane capacity requirements and increasing operational flexibility, but introduces synchronization challenges, coordination complexity, unequal load distribution risks, and higher operational costs. A single crane configuration without a spreader bar may reduce hardware requirements and costs, but it often results in unfavorable sling angles, increased tensile forces, reduced stability, and lower safety margins.

Crane stability during lifting operations depends not only on crane capacity but also on the ability of the supporting surface to safely distribute applied loads without excessive settlement. Ground Bearing Pressure (GBP) analysis evaluates the pressure exerted on the supporting surface using the relationship $GBP = P / A$, where P represents the applied load and A represents the effective bearing area. Crane outrigger pads and mat systems are used to distribute loads across supporting surfaces. If the calculated GBP exceeds the allowable bearing capacity, excessive settlement may occur, potentially resulting in loss of crane stability, structural imbalance, and lifting accidents. Recommended GBP limits vary depending on soil characteristics, with concrete decks typically allowing 5–10 ton/m², prepared sand and gravel 1.5–3 ton/m², and exposed soil 0.5–2 ton/m².

Recent studies have highlighted that conventional Ground Bearing Pressure calculations may not fully represent actual pressure distributions beneath crane mats and outrigger systems [15], demonstrated through finite element analysis that pressure distribution beneath lifting support systems is often non-uniform, indicating the importance of detailed GBP assessment to prevent excessive settlement and maintain crane stability during heavy lifting operations.

Recent years have witnessed increasing adoption of web-based systems and digital tools in engineering disciplines [16], [17]. These systems offer advantages including accessibility through cloud-based platforms, standardization of engineering procedures and calculation methodologies, efficiency through automated calculations, traceability via centralized documentation and audit trails, and enhanced collaboration among distributed engineering teams. Digital transformation in maritime and offshore engineering has manifested through the development of simulation tools, design optimization systems, condition monitoring platforms, and operational planning systems.

Recent developments in lifting engineering have increasingly emphasized the integration of automation technologies and decision-support systems to improve lifting safety and planning efficiency. Automated lift planning methods have been developed to support crane selection, localization, and path planning, enabling more systematic lifting operations and reducing reliance on manual engineering judgement [18]. Similarly [19] reported that crane lift planning involves complex engineering decisions that require the integration of crane capacity assessment, spatial constraints, safety considerations, and operational feasibility.

More recently, [20] demonstrated that automated lift planning systems can significantly improve safety and practicality by integrating crane configuration analysis, scheduling, and risk mitigation into a single planning framework. These studies indicate a growing trend toward digitalization and automation in lifting engineering, however, their applications remain predominantly focused on construction and modular installation projects rather than offshore decommissioning activities.

The application of visualization and digital planning technologies has also been explored in lifting engineering [21]. Demonstrated that Virtual Reality (VR) environments can improve heavy lift planning, visualization, and safety training by allowing engineers to evaluate lifting operations in immersive digital environments. Earlier, [22] developed a computerized Heavy Lift Planning System (HELPS) that utilized visualization-based engineering tools to improve lift planning reliability and reduce the limitations associated with conventional manual planning approaches. These studies provide an important foundation for the development of modern digital lifting engineering systems.

From the offshore engineering perspective, FPSO module lifting presents additional challenges due to large module weights, irregular center-of-gravity distributions, restricted deck space, and dynamic environmental conditions [4]. Emphasized that FPSO modules often involve extremely large lifting loads requiring comprehensive structural and lifting assessments to ensure operational safety throughout installation and removal activities.

Previous offshore heavy lifting studies have demonstrated that sling force distribution in multi-leg lifting arrangements is strongly influenced by lifting geometry, sling configuration, and load sharing characteristics [23]

In offshore lifting operations, rigging geometry plays a critical role in load transfer mechanisms [24] demonstrated that sling angle configuration significantly affects sling tension, safety margins, and overall lifting stability. Lower sling angles result in substantial increases in sling tension and may compromise rigging safety if not properly evaluated. Furthermore, offshore lifting standards and previous lifting engineering studies indicate that crane utilization, Dynamic Amplification Factors (DAF), working radius, and rigging configuration are among the most influential parameters affecting lifting safety and operational feasibility during heavy lifting operations [5], [7], [24].

However, integrated web-based heavy lifting planning systems that combine crane capacity analysis, sling load evaluation, rigging configuration assessment, and safety evaluation remain limited, representing a significant gap in current engineering tool availability and marine operation support systems.

While significant research has been conducted on crane lift planning, lifting optimization, structural evaluation, and rigging analysis, most previous studies have investigated these engineering aspects separately. Existing studies primarily focus on construction lift planning [18], [19], [20], structural lifting evaluation [4] or rigging safety assessment [24]. Limited research has successfully integrated crane capacity analysis, sling load evaluation, rigging configuration assessment, and Ground Bearing Pressure evaluation into a unified web-based engineering platform specifically intended for FPSO decommissioning applications. Consequently, lifting engineers often rely on multiple independent tools and manual calculations, resulting in lengthy analysis processes and potential inconsistencies in engineering decision-making.

This research addresses the identified gap by developing an integrated web-based heavy lifting planning and rigging evaluation system specifically designed for FPSO decommissioning applications. The novelty of this research lies in three main aspects. First, the system integrates crane capacity analysis, sling load evaluation, rigging configuration assessment, and Ground Bearing Pressure analysis into a unified engineering platform. Second, the developed application automatically evaluates lifting safety and operational feasibility based on user-defined lifting parameters.

Third, the proposed system provides a practical engineering decision-support tool that standardizes lifting planning procedures and reduces calculation inconsistencies commonly associated with conventional spreadsheet-based methods.

This research aims to develop an integrated web-based system for heavy lifting planning that combines crane capacity analysis, sling load evaluation, rigging configuration assessment, and Ground Bearing Pressure analysis into a unified engineering platform. The study also seeks to determine the optimal rigging configuration for the E-House module through a systematic evaluation of alternative lifting arrangements, including the effectiveness of spreader bars, different crane configurations, and load distribution characteristics. In addition, the research analyzes critical lifting parameters that influence operational safety, with particular emphasis on the sensitivity of sling angle variations and their effects on tensile force distribution and overall lifting stability. Furthermore, the study establishes a flexible calculation methodology that can be generalized and applied to similar FPSO modules and heavy lifting scenarios beyond the specific case examined. Finally, the research evaluates the efficiency improvements achieved through web-based automated analysis by comparing it with conventional manual calculation methods in terms of speed, consistency, and calculation accuracy.

II. METHOD

A. Research Method

This study applies a quantitative engineering approach based on lifting engineering calculations and static load analysis for heavy lifting operations during FPSO decommissioning activities in accordance with offshore lifting engineering practices and marine operation requirements. The research focuses on the lifting operation of the Electrical House (E-House) module on FPSO Ningaloo Vision using several lifting configurations and crane scenarios.

The developed engineering system integrates lifting calculations, rigging configuration analysis, crane capacity evaluation, and lifting safety assessment into a web-based application developed using R programming language and Shiny framework. The system is intended to assist lifting engineers in conducting lifting planning more systematically and efficiently.

B. Data Collection

The research data were obtained from technical documents, lifting engineering references, crane load charts, module dimensional data, and lifting operational parameters. The primary object used in this study is the Electrical House (E-House) module during FPSO Ningaloo Vision decommissioning operations.

The collected data include module dimensions, module weight, lifting point configuration, crane specifications, sling configuration, sling angle, and lifting operational parameters required for lifting analysis and engineering evaluation in accordance with lifting engineering requirements and offshore crane operation guidelines.

The collected data were further classified into lifting load parameters, crane operational parameters, and rigging configuration parameters. These data were used as the primary input variables for lifting calculations and engineering evaluations within the developed web-based system. The classification of operational data enables the system to process various lifting scenarios and generate engineering recommendations based on user-defined lifting conditions.

To ensure calculation consistency, all technical data were verified against project engineering documents and lifting design requirements. The verified data were subsequently utilized for crane capacity assessment, sling load analysis, lifting geometry evaluation, and Ground Bearing Pressure calculations.

TABLE 1.
MAIN LIFTING PARAMETERS AND OPERATIONAL DATA

Parameter	Value
Module Weight	303.281 tons
Design Load	334.367 tons
Sling Type	Wire Rope Sling
Crane Type	Crawler Crane
Lifting Configuration	Single / Dual Crane
Allowance Factor	5%

C. Lifting Calculation Parameters

The lifting calculations in this study were conducted using static load analysis and lifting engineering principles. The design lifting load was determined by adding lifting allowance to the actual module weight in order to account for operational uncertainty and lifting dynamic effects.

The design load calculation is expressed as:

$$DL = W \times (1 + Allowance) \quad (1)$$

where DL represents the design load and W represents the actual module weight.

The design load represents the total lifting load considered during engineering evaluation. This value includes operational allowances to account for uncertainties that may occur during lifting execution. The use of design load instead of actual module weight provides a more conservative basis for lifting safety assessment.

The use of design load with operational allowance is commonly applied in lifting engineering to account for uncertainties during lifting execution and ensure conservative lifting assessment.

The sling tensile force was calculated based on sling geometry and sling angle configuration. Sling angle significantly affects the tensile load acting on each sling leg. Smaller sling angles increase the tensile force and may reduce lifting safety margins.

The sling force calculation follows conventional sling load distribution principles described in lifting engineering standards and rigging design practices.

$$F = \frac{W}{n \sin\theta} \quad (2)$$

where F represents sling tensile force, W represents lifting load, n represents the number of sling legs, and θ represents sling angle.

The Ground Bearing Pressure (GBP) calculation was conducted to evaluate crane stability during lifting operations. The GBP is calculated as:

$$GBP = \frac{P}{A} \quad (3)$$

where GBP represents Ground Bearing Pressure, P represents the applied load, and A represents the effective bearing area.

Ground Bearing Pressure evaluation is important because excessive pressure may result in ground settlement and reduced crane stability during lifting operations. Therefore, the calculated GBP value must remain below the allowable bearing capacity of the supporting surface.

Ground Bearing Pressure assessment is widely used in crane engineering to evaluate supporting surface stability and prevent excessive ground settlement during lifting operations.

The crane capacity evaluation was performed using crane load chart analysis based on lifting radius and operational lifting conditions in accordance with offshore crane operational guidelines [7].

TABLE 2.
ENGINEERING CALCULATION PARAMETERS

Parameter	Description
DL	Design Load
W	Actual Module Weight
F	Sling Tensile Force
θ	Sling Angle
GBP	Ground Bearing Pressure
DAF	Dynamic Amplification Factor

TABLE 3.
ENGINEERING EVALUATION CRITERIA

Evaluation Parameter	Acceptance Criteria
Crane Capacity	Actual Load < Crane Capacity
Sling Force	Sling Force < WLL
Ground Bearing Pressure	GBP < Allowable GBP
Rigging Configuration	Stable
Safety Factor	> 1

D. Web-Based System Development

The web-based heavy lifting planning system developed in this study was designed to integrate lifting engineering calculations and lifting safety evaluations into a single engineering platform. The system was developed using R programming language and Shiny framework to provide an interactive and user-friendly lifting planning interface for engineering applications.

The development approach adopted in this study was informed by previous research on automated crane planning systems, lifting optimization frameworks, and digital engineering applications. Previous studies have demonstrated that automation technologies can improve lifting safety, reduce planning time, and enhance engineering consistency through systematic evaluation procedures [18], [20]. Therefore, the present study adopts a system integration approach that combines multiple lifting engineering analyses within a single web-based environment.

The Shiny framework was selected because it allows the development of interactive engineering applications without requiring extensive web programming experience. Through the integration of R and Shiny, engineering calculations can be processed dynamically based on user-defined operational parameters while maintaining computational flexibility and transparency.

The developed system consists of several integrated modules, including crane database module, lifting parameter input module, lifting calculation module, rigging evaluation module, and safety evaluation module. Each module is connected systematically to support lifting analysis and engineering decision-making during heavy lifting operations.

The crane database module functions as the primary data source for crane specifications and lifting capacities used in lifting calculations. The lifting parameter input module allows users to input operational lifting parameters such as module weight, sling angle, lifting radius, rigging configuration, and lifting geometry. The calculation module then performs lifting calculations automatically based on the provided operational parameters.

In addition, the developed system also integrates lifting safety evaluation, including crane capacity analysis, sling tensile force evaluation, and Ground Bearing Pressure (GBP) analysis. The integration of these engineering evaluations allows the developed application to provide lifting recommendations and engineering assessments more systematically compared to conventional manual calculations.

The developed application architecture follows a modular structure, allowing future expansion of engineering functions and lifting evaluation features. This modular approach improves system maintainability and enables the integration of additional lifting assessment modules for different heavy lifting scenarios.

III. RESULTS AND DISCUSSION

A. *Lifting Load Analysis*

The lifting analysis was conducted on the Electrical House (E-House) module during FPSO Ningaloo Vision decommissioning operations [25]. Based on the available technical data, the actual module weight was determined to be 303.281 tons. To account for operational uncertainty and lifting dynamic effects, a 5% lifting allowance factor was applied, resulting in a design lifting load of 334.367 tons.

The module weight was derived from the combined contribution of the structural frame and supports (45.2 tons), switchgear and electrical equipment (178.3 tons), cable trays and electrical connections (32.8 tons), HVAC and miscellaneous systems (36.9 tons), and integral ballast and reinforcement (10.181 tons). The total module weight was therefore determined to be 303.281 tons. By applying a 5% operational allowance factor in accordance with offshore lifting engineering practice, the design load increased to 334.367 tons. This design load was subsequently adopted as the governing load for sling force calculations, crane capacity evaluation, and Ground Bearing Pressure assessment throughout the study.

The lifting calculations include sling force analysis, lifting geometry evaluation, crane load analysis, and rigging configuration assessment. The design load value becomes the primary reference in determining lifting safety and evaluating crane lifting capacity during heavy lifting operations. The design load used throughout the engineering evaluation was calculated using Eq. (1), which incorporates an operational allowance to account for uncertainties during lifting execution.

The detailed module weight breakdown and resulting design load are presented in Table 4. The switchgear and electrical equipment contributed the largest portion of the total weight, accounting for approximately 59% of the overall module mass. This distribution reflects the functional role of the E-House as the primary electrical control and power distribution center of the FPSO.

The increase in lifting load from the actual module weight to the design load demonstrates the importance of incorporating operational allowances into heavy lifting planning. In practical lifting operations, the use of actual weight alone may underestimate the load acting on lifting components and crane systems. Therefore, the design load serves as a more conservative engineering basis for evaluating lifting safety.

The calculated design load of 334.367 tons became the primary parameter for all subsequent lifting evaluations, including sling load analysis, crane capacity assessment, and Ground Bearing Pressure calculations. By establishing a consistent design load basis, the engineering evaluation process can be conducted more systematically and provide a higher level of operational confidence.

The difference between the actual module weight and the design load demonstrates the importance of incorporating engineering allowances into lifting planning. The application of a design load prevents underestimation of operational loads and provides a more conservative basis for evaluating crane capacity, sling forces, and lifting safety during heavy lifting operations.

TABLE 4.
MODULE WEIGHT SUMMARY AND DESIGN LOAD CALCULATION

Parameter	Value
Structural Frame and Supports	45.2 tons
Switchgear and Electrical Equipment	178.3 tons
Cable Trays and Electrical Connections	32.8 tons
HVAC and Miscellaneous Systems	36.9 tons
Integral Ballast and Reinforcement	10.181 tons
Total Module Weight	303.281 tons
Operational Allowance	5%
Design Load	334.367 tons

B. *Sling Load and Rigging Configuration Analysis*

The sling load analysis indicates that sling angle significantly affects the tensile force acting on each sling leg. Smaller sling angles increase tensile forces and may reduce lifting safety margins during heavy lifting operations. Therefore, sling geometry and rigging configuration become critical parameters in lifting engineering evaluation. The sling tensile force acting on each sling leg was determined using Eq. (2), which relates sling force to the applied lifting load, number of sling legs, and sling angle configuration.

The results presented in Table 5 clearly demonstrate the strong influence of sling angle on tensile force distribution. Reducing the sling angle from 45° to 30° increased the sling force from 81.68 tons to 96.42 tons, representing an increase of approximately 18%. Conversely, increasing the sling angle to 60° reduced the sling force to 64.54 tons, corresponding to a reduction of approximately 21%. These findings confirm that sling angle is one of the most sensitive parameters in lifting engineering and directly affects the available safety margin of the rigging system.

Several rigging configurations were evaluated in this study, including single crane with spreader bar, dual crane without spreader bar, and single crane without spreader bar configurations. Each configuration was analyzed based on lifting stability, sling load distribution, crane capacity utilization, and operational safety considerations.

TABLE 5.
EFFECT OF SLING ANGLE ON SLING TENSILE FORCE

Sling Angle (θ)	Sling Force (tons)	Change Relative to 45°
30°	96.42	+18.0%
45°	81.68	Baseline
60°	64.54	-21.0%

The analysis results show that the single crane configuration using spreader bar provides the most optimal lifting performance because it maintains better sling geometry and more balanced load distribution compared to other evaluated configurations.

The results indicate that sling angle plays a significant role in determining the tensile force experienced by each sling leg. As the sling angle decreases, the vertical lifting force is distributed less efficiently, causing a substantial increase in sling tension. This condition may increase the risk of sling overloading and reduce the overall safety margin of the lifting system.

The use of a spreader bar was found to improve load distribution by maintaining a more favorable sling geometry and reducing excessive sling angles. Consequently, the lifting load can be transferred more effectively to the lifting components while maintaining lifting stability throughout the operation.

From an engineering perspective, the selection of rigging configuration should not only consider lifting feasibility but also operational safety, load distribution, and lifting stability. Therefore, the single crane configuration using a spreader bar was selected as the preferred lifting arrangement for the E-House lifting operation.

The superior performance of the spreader bar configuration is primarily attributed to its ability to maintain favorable sling geometry and distribute loads more evenly among lifting points. Improved load distribution reduces excessive tensile forces on individual sling legs and contributes to better lifting stability throughout the operation. Consequently, the spreader bar configuration provides a higher level of operational safety compared with alternative lifting arrangements.

The rigging configurations evaluated in this study are presented in Figure 1. The comparison includes a single crane configuration with spreader bar, a dual crane configuration, and a single crane configuration without spreader bar.

The qualitative comparison of the evaluated rigging configurations is summarized in Table 6.

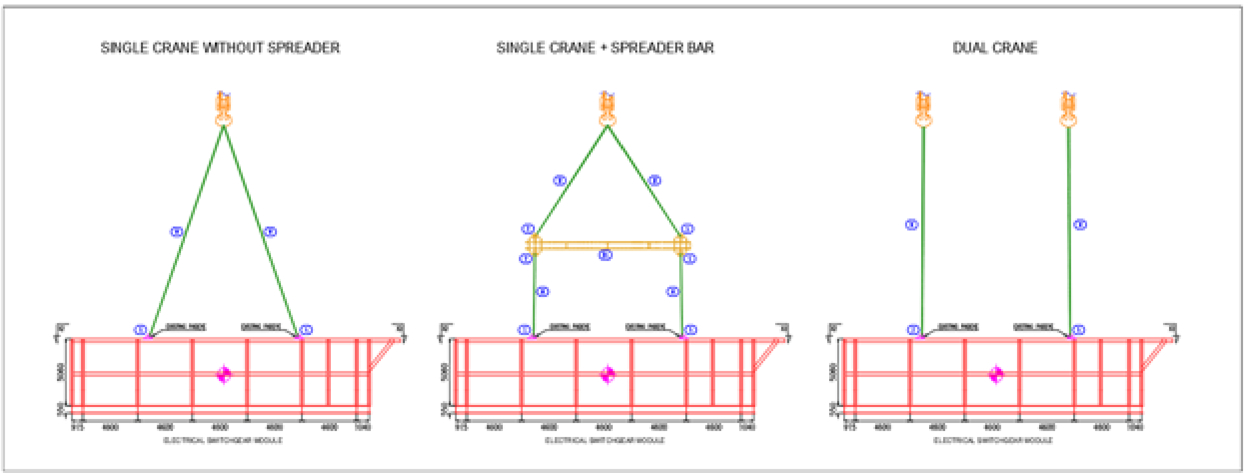

Figure 1. Comparison of Evaluated Rigging Configurations

TABLE 6.
COMPARISON OF RIGGING CONFIGURATION

Configuration	Sling Force (tons)	Safety Factor	Operational Assessment
Single Crane + Spreader Bar	81.68	3.9	Recommended
Dual Crane	95.2	2.8	Acceptable
Single Without Spreader	112.4	1.8	Not Recommended

The comparison presented in Table 5 confirms that the single-crane configuration with a spreader bar provides the most favorable lifting performance. This arrangement generated the lowest sling force and the highest safety factor among all evaluated alternatives. Conversely, the single-crane configuration without a spreader bar produced the highest sling force and the lowest safety factor, indicating reduced operational suitability. Although the dual-crane arrangement remained feasible, the additional coordination requirements and synchronization challenges reduced its overall practicality for the investigated lifting operation.

C. Crane Capacity Evaluation

Crane capacity evaluation was conducted using crane load chart analysis under several lifting scenarios and lifting radius conditions. The evaluation considers crane lifting capacity, lifting radius, lifting geometry, and total lifting load acting during lifting operations.

The evaluation also demonstrates that crane selection is not only influenced by object weight but is also strongly affected by lifting radius, rigging geometry, sling angle, and operational lifting configuration. Therefore, proper lifting planning is required to maintain operational safety during heavy lifting activities.

TABLE 7.
CRANE CAPACITY EVALUATION AT VARIOUS LIFTING RADIUS

Lifting Radius (m)	Crane Capacity (tons)	Utilization (%)	Assessment
20	580	57.6	Acceptable
25	485	69.0	Acceptable
30	365	91.6	Marginal
35	295	113.3	Not Feasible

The crane capacity evaluation results indicate a strong dependency between lifting radius and crane utilization. At lifting radii of 20 m and 25 m, crane utilization remained below 70%, providing a comfortable operational safety margin. However, increasing the lifting radius to 30 m raised utilization to 91.6%, leaving only a limited reserve capacity. At 35 m, the utilization exceeded 100%, indicating that the selected crane could no longer safely perform the lifting operation. Therefore, lifting operations should be maintained within a radius of approximately 25 m to preserve adequate safety margins and operational flexibility.

This finding highlights the importance of considering lifting geometry during crane selection. Even when the crane possesses sufficient nominal lifting capacity, unfavorable lifting geometry may result in reduced operational safety margins. Therefore, crane capacity evaluation must always be performed together with lifting radius assessment and rigging configuration analysis.

The findings emphasize that crane selection should not be based solely on nominal lifting capacity. Although the selected crawler crane possesses sufficient capacity to lift the E-House module, the available lifting capacity decreases significantly as the operating radius increases. Consequently, crane positioning becomes a critical planning parameter because excessive lifting radii may require larger crane classes despite the lifting load remaining unchanged.

The analysis also established a practical operational constraint for the investigated lifting activity. While the selected 600-ton crawler crane remained technically feasible at a 30 m lifting radius, the resulting utilization approached the upper limit of acceptable operational practice. Therefore, maintaining crane operations within a lifting radius of 20–25 m is recommended to provide additional safety margins and reduce the risk associated with unexpected operational uncertainties.

D. Ground Bearing Pressure Evaluation

Ground Bearing Pressure (GBP) analysis was performed to evaluate crane ground stability during lifting operations. The evaluation aims to determine whether the lifting ground condition remains within the allowable bearing pressure limit during crane operation [25]. The Ground Bearing Pressure values were calculated using Eq. (3), which evaluates the relationship between the applied load and the effective bearing area of the supporting surface.

The initial Ground Bearing Pressure evaluation revealed that the calculated pressure of 54.2 tons/m² substantially exceeded the allowable bearing pressure range of 8–10 tons/m². This result indicates that the supporting surface could not safely sustain the crane load without additional mitigation measures. Therefore, direct crane placement on the existing supporting structure was considered unsuitable for the planned lifting operation.

Ground Bearing Pressure analysis is essential because crane stability depends not only on crane capacity but also on the ability of the supporting surface to withstand the applied load. Excessive ground pressure may result in localized settlement, loss of crane stability, and potential lifting accidents.

TABLE 8.
GROUND BEARING PRESSURE EVALUATION RESULTS

Parameter	Value
Vertical Load	650 tons
Effective Bearing Area	12 m²
Calculated GBP	54.2 tons/m²
Allowable Bearing Pressure	8 - 10 tons/m²
Initial Assessment	Exceeds Allowable Limit

TABLE 9.
EFFECT OF LOAD DISTRIBUTION MATTING ON GBP

Condition	Effective Area (m²)	GBP (tons/m²)	Assessment
No Matting	12	54.2	Not Acceptable
Standard Matting	35	18.6	Improved but High
Reinforced Matting	55	11.8	Acceptable

The implementation of load distribution matting significantly reduced the Ground Bearing Pressure acting on the supporting surface. Standard crane matting increased the effective bearing area and reduced the pressure to 18.6 tons/m², although the value remained above the recommended limit. A reinforced matting arrangement further increased the effective bearing area and reduced the pressure to 11.8 tons/m², providing an acceptable condition for crane operation.

The Ground Bearing Pressure evaluation demonstrates that crane stability cannot be assessed solely through lifting capacity analysis. Although the selected crane satisfied the lifting load requirements, the initial bearing pressure exceeded the allowable limit and required additional mitigation measures. The use of reinforced load-distribution matting was identified as the most practical solution for reducing bearing pressure to an acceptable level while maintaining operational safety. These findings emphasize the importance of integrating ground stability assessment into heavy lifting planning and engineering decision-making.

E. Web-Based Application Implementation

The developed web-based application integrates lifting engineering calculations into a single engineering support system capable of assisting lifting engineers during lifting planning activities. The developed application consists of crane database module, lifting parameter input module, lifting calculation module, and lifting evaluation module.

The crane database module allows users to select crane specifications based on lifting operational requirements. The lifting parameter module enables users to input lifting geometry, lifting load, sling configuration, and operational parameters required for lifting analysis.

The developed system automatically performs sling load calculation, crane capacity evaluation, Ground Bearing Pressure analysis, and lifting safety assessment based on user input parameters. Compared to conventional manual calculations, the developed application provides a more systematic, integrated, and efficient lifting engineering workflow.

The developed application allows lifting engineers to evaluate multiple lifting scenarios without repeatedly performing manual calculations. Users can modify lifting parameters, crane specifications, and rigging configurations while receiving immediate engineering feedback from the system.

The integration of engineering calculations and evaluation modules into a single web-based platform reduces calculation redundancy and improves workflow efficiency. Furthermore, the developed application facilitates engineering standardization by ensuring that lifting evaluations are performed using consistent calculation procedures.

The developed application also improves engineering accessibility by enabling lifting evaluations to be performed through a centralized digital platform. Compared with spreadsheet-based calculations, the system provides a more structured workflow, facilitates rapid assessment of alternative lifting scenarios, and reduces the potential for calculation inconsistencies during engineering planning activities.

TABLE 10.
COMPARISON BETWEEN MANUAL AND WEB-BASED LIFTING ANALYSIS

Task	Manual Method	Web-Based System	Improvement
Single Scenario Analysis	45 – 60 min	2 – 3 min	95% Faster
Five Scenario Evaluation	225 – 300 min	10 – 15 min	95% Faster
Report Generation	30 – 45 min	Automated	99% Faster
Complete Workflow	6 – 8 hours	30 – 45 min	90% Faster

The comparison results demonstrate substantial efficiency improvements achieved through the developed web-based system. Tasks that traditionally required several hours of manual engineering calculations can be completed within minutes using the automated workflow. The most significant improvement was observed during multi-scenario evaluation, where engineers could rapidly assess alternative lifting configurations without repeatedly performing manual calculations. These findings indicate that the developed application not only supports engineering accuracy but also significantly enhances planning efficiency.

Calculation verification was also performed by comparing manually calculated lifting cases with system-generated results. The comparison demonstrated complete agreement in sling force calculations and crane capacity evaluations, while only negligible rounding differences were observed in Ground Bearing Pressure calculations. These results confirm the reliability of the implemented calculation algorithms and support the application's use as an engineering decision-support tool.

The main interfaces of the developed web-based application, including the crane database module, lifting parameter input module, lifting calculation module, and lifting evaluation module, are presented in Figures 2–5.

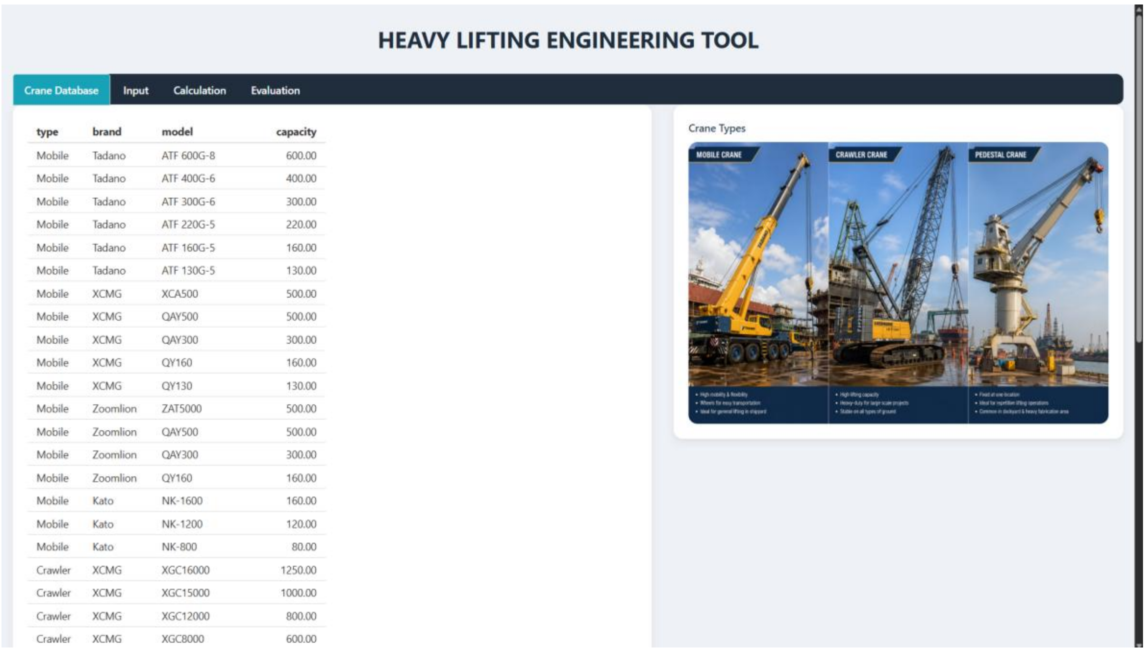

Figure 2. Crane Database Interface

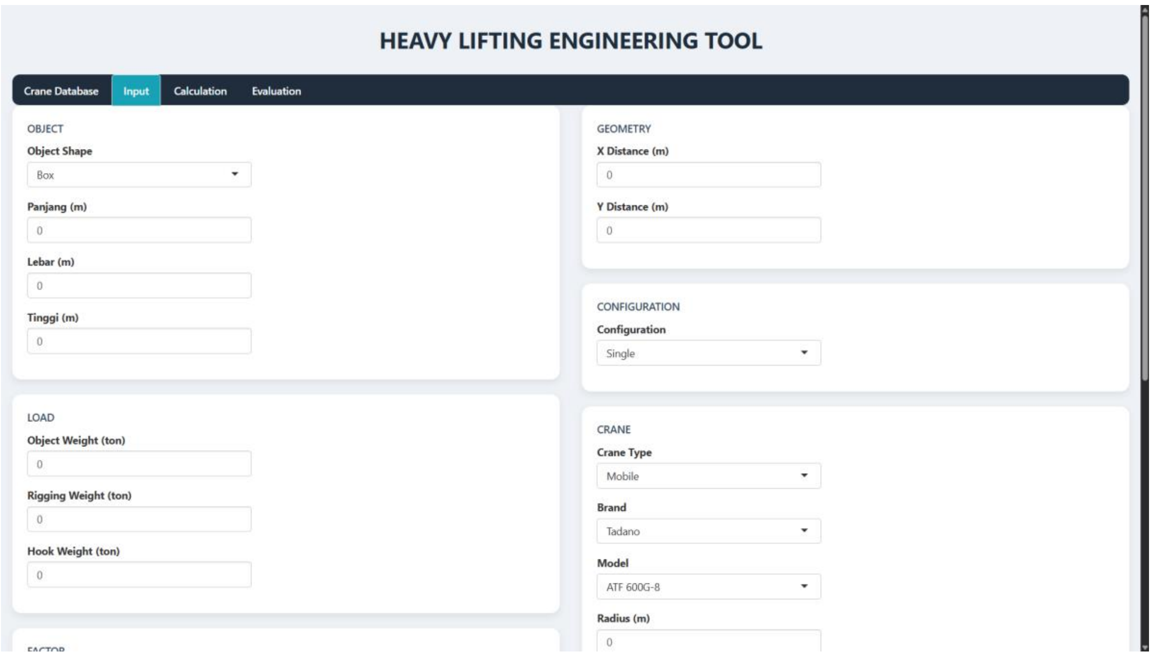

Figure 3. Lifting Parameter Input Interface

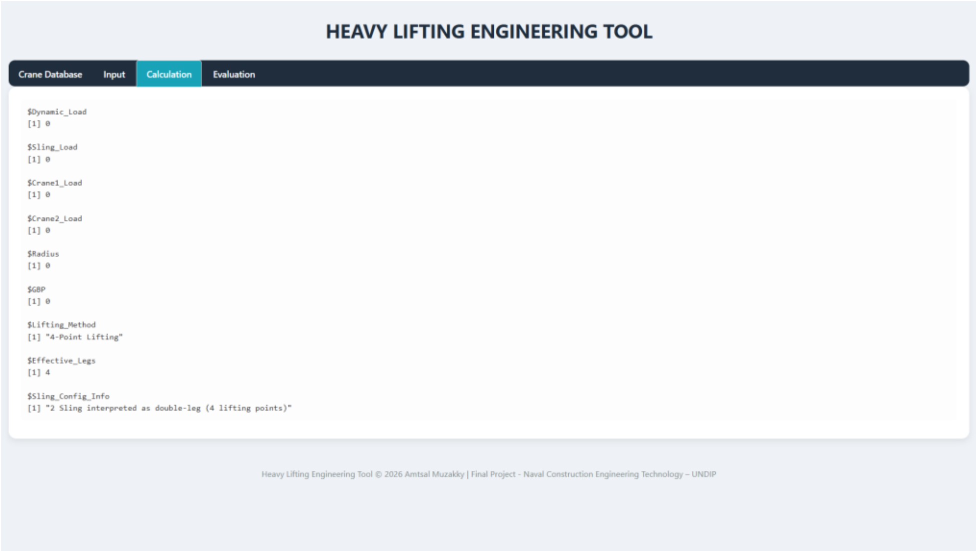

Figure 4. Lifting Calculation Interface

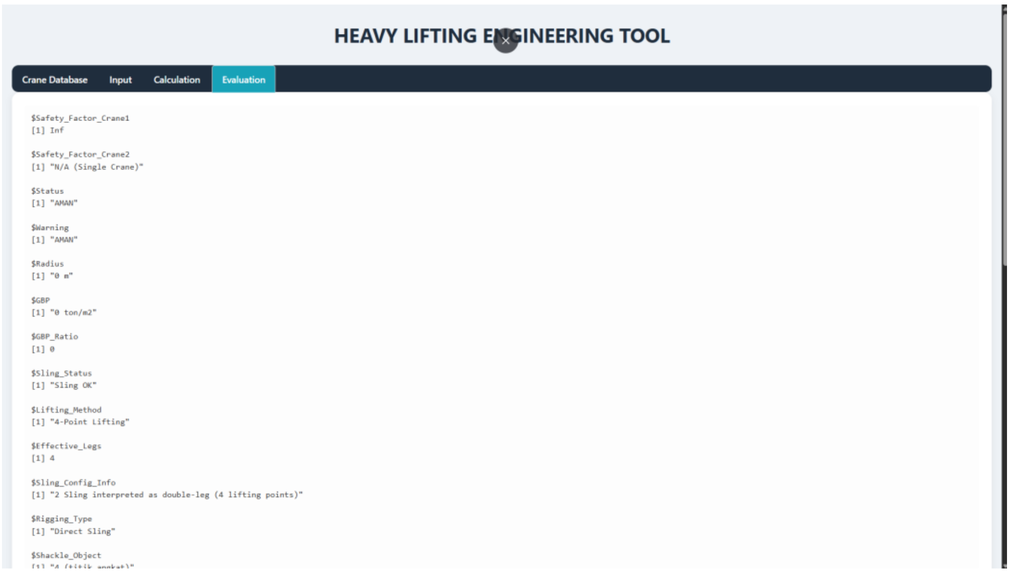

Figure 5. Lifting Evaluation Interface

F. System Evaluation and Engineering Contribution

The implementation of the developed web-based system demonstrates that lifting engineering calculations and lifting safety evaluations can be integrated into a single engineering platform. The developed application can reduce calculation inconsistencies and improve engineering efficiency during lifting planning.

The novelty of this study lies in integrating lifting engineering calculations, rigging configuration analysis, and lifting safety evaluation into a web-based engineering support system that automatically generates lifting evaluations based on operational lifting parameters.

Sensitivity analysis was conducted to evaluate the influence of key lifting parameters on overall lifting performance. The analysis revealed that sling angle represents the most sensitive parameter within the lifting system. Small reductions in sling angle produced a disproportionate increase in sling tensile force, whereas larger sling angles significantly improved load distribution and reduced rigging demand. These findings confirm the importance of maintaining appropriate sling geometry during lifting operations.

TABLE 11.
SLING ANGLE SENSITIVITY ANALYSIS

Sling Angle Range	Approximate Tension Change
Near 30°	±2.8% per 5° change
Near 45°	±1.5% per 5° change
Near 60°	±1.1% per 5° change

The sensitivity results indicate that sling force becomes increasingly sensitive at lower sling angles. Consequently, maintaining sling angles above 40° is recommended to reduce the likelihood of excessive rigging loads and preserve adequate safety margins during lifting operations.

Load distribution sensitivity was also evaluated by introducing a simulated center-of-gravity offset. The analysis demonstrated that minor load shifts generated only moderate changes in sling force distribution, indicating that the selected four-point lifting arrangement with spreader bar provides adequate tolerance against small load distribution uncertainties. This characteristic contributes positively to operational safety and lifting stability.

From an engineering perspective, this study contributes to offshore lifting and decommissioning practice by providing an integrated methodology that combines rigging analysis, crane capacity evaluation, Ground Bearing Pressure assessment, and digital decision-support capabilities within a single web-based platform. The developed approach supports engineering standardization, improves planning efficiency, and facilitates safer lifting operation preparation for FPSO module handling and similar offshore lifting applications.

IV. Conclusion

This research successfully developed an integrated web-based heavy lifting planning and rigging evaluation system for FPSO module decommissioning operations, specifically applied to the Electrical House module of FPSO Ningaloo Vision. The developed system integrates crane capacity analysis, sling load evaluation, rigging configuration assessment, and Ground Bearing Pressure analysis into a unified engineering platform accessible through a web-based interface.

The results demonstrate that sling angle is the most critical parameter affecting lifting safety and operational feasibility. The relationship between sling angle and tensile force exhibits nonlinear sensitivity, with angles below 30° producing significantly higher sling tensions and reducing operational safety margins. The findings indicate that maintaining proper rigging geometry through the use of a spreader bar is essential for ensuring safe lifting operations. Among the evaluated lifting arrangements, the single-crane configuration with a spreader bar provided the best overall performance, characterized by superior load distribution, a high safety factor of 3.9 for sling tensile force, operational simplicity, and compliance with industry regulations. This configuration significantly outperformed the dual-crane arrangement and the single-crane configuration without a spreader bar in terms of safety, operational efficiency, and economic feasibility.

The crane capacity assessment further established that lifting operations should be conducted within a lifting radius of 25 meters to maintain acceptable crane utilization levels of 70% or less. In addition, the Ground Bearing Pressure (GBP) analysis revealed that temporary load-distribution matting is required to maintain structural stability during lifting operations. The implementation of such mitigation measures may increase operational costs by approximately USD 50,000–100,000 and extend the project schedule by two to three days. Furthermore, the developed web-based system demonstrated a substantial improvement in engineering efficiency, reducing the time required for comprehensive lifting analysis from approximately six to eight hours to only thirty to forty-five minutes. The automated calculation methodology also eliminated engineering inconsistencies while maintaining full verification accuracy when compared with conventional manual calculations.

The research objectives were successfully achieved through the development of a unified web-based system that integrates multiple lifting analysis functions into a single engineering platform. The study systematically identified the optimal rigging configuration, quantified the influence of sling angle as a critical safety parameter, established a calculation methodology applicable to similar lifting scenarios, and demonstrated measurable efficiency improvements through comparison with traditional manual approaches.

The development of this web-based lifting planning system represents a significant advancement in the digital transformation of offshore engineering practices. The demonstrated reduction in analysis time, combined with enhanced consistency and standardization, indicates strong potential for industry adoption and cost reduction in future FPSO decommissioning projects. In addition, the flexible calculation methodology and modular system architecture enable application beyond the specific E-House case study, providing a general framework for planning lifting operations involving similar topside modules. The implementation of such systems across the offshore industry has the potential to reduce engineering costs and project schedules while simultaneously improving operational safety through systematic and standardized analytical procedures.

Despite these contributions, several limitations should be acknowledged. The current analysis is based on static equilibrium assumptions and does not incorporate dynamic amplification effects associated with vessel motion, transient loading, or environmental influences. The study is also limited to a single E-House module case study with specific weight distribution and structural characteristics, meaning that the identified optimal configuration may not be universally applicable to all topside modules. Furthermore, environmental loading factors such as wind, waves, and vessel motion were not explicitly considered in the analysis. The dual-crane evaluation assumes perfect synchronization between crane operators and therefore does not account for human factors or operational timing variations. In addition, although general economic considerations were discussed, a detailed project-specific cost-benefit analysis was not performed.

Future research should focus on addressing these limitations and expanding the capabilities of the developed system. Potential improvements include the integration of Dynamic Amplification Factors (DAF) to account for environmental conditions, incorporation of vessel motion models and weather-dependent operational criteria, and development of advanced optimization algorithms for evaluating alternative rigging configurations. Additional enhancements may include the application of machine learning techniques using historical lifting operation databases to predict high-risk scenarios and provide adaptive engineering recommendations. Future versions of the system could also incorporate real-time environmental monitoring, telemetry-based load monitoring, and operational decision-support functions during actual lifting activities. Moreover, integration with structural analysis, vessel stability assessment, and hydrodynamic evaluation tools could lead to the development of a comprehensive offshore decommissioning planning platform. Further validation through application to FPSO decommissioning projects in different geographical regions and across various FPSO designs would also strengthen the general applicability of the methodology.

Overall, this research demonstrates that integrated web-based engineering systems can significantly improve lifting operation planning for offshore decommissioning projects through the systematic application of established lifting engineering principles within an accessible digital platform. The developed system provides a practical tool for supporting safer, more efficient, and more consistent lifting operations while contributing to the ongoing digital transformation of marine and offshore engineering practices. Furthermore, the research establishes a foundation for future development of comprehensive offshore engineering support systems that leverage digital technologies to enhance technical decision-making, operational efficiency, and safety throughout the entire decommissioning project lifecycle. As FPSO decommissioning activities continue to increase worldwide, engineering tools such as the system developed in this study are expected to play an increasingly important role in supporting cost-effective, safe, and regulatory-compliant offshore decommissioning operations.

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