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The Impact of Operation History on Jack-up Structure Reliability

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ABSTRACT: In the Polish Baltic Sea region, jack-up structures, apart from existing offshore oil and gas offshore infrastructure, will be used for further wind farm installation. These structures usually operate under various environmental and geotechnical conditions, often in a different basin than they were designed for. Therefore, the operation history is of great importance for fatigue and reliability assessment of jack-up structures. The article first presents the construction and main components of jack-up structure, focusing on jacking system. Next, it analyses how the frequency and conditions of transit and jacking operations may impact on overall fatigue of jack-up structure and its components. In addition to time-dependent factors, such as corrosion and material degradation, the operations' history is also included in the research. The results illustrate that operational history should not be neglect in safety analysis of subsequent operations, as well as in the planning of inspections and maintenance.

1 INTRODUCTION

Offshore Infrastructure located on Polish Southern Baltic Sea have a long history, beginning in the 1960s as "Petrobaltic" for oil and gas exploration activities, intensified in May 1992 when production phase has been start. From the outset this infrastructure mostly based on jack-up platforms originally designed for different site conditions [26]. Chartering or purchasing jack-up to operate in basin other than those for which they were designed is a common practice. However many factors that have to be taken into consideration beside the standardised site assessment that impact on reliability of jack-up platform [3], [4], [21]. Especially when the design life expectancy is exceeded and lifetime extension plan is not only consider but already introduced by special survey and maintenance or even upgrades. Not only on Southern Baltic Sea, but in general platforms exceeding typical design lifetime are still in operation. In these circumstances the proper lifetime analysis and assessment is crucial to provide answer for how long particular platform can be still safely operating. As it is not directly mentioned or required by Site Specific Assessment according to ISO 19905-1, the proposed approach may be found helpful by Classification Societies and companies performing a comprehensive assessment that includes the history of transit and jacking operations in order to establish the overall state of the platform [19].

The problem of ageing of offshore structures with their equipment including history of operation, the risks that it brings and how is it related to overall reliability of jack-up offshore platform is purpose of this article study. Many papers refer to structural reliability of offshore platforms and their lifetime estimation by analysing their components fatigue [15], [36]. Authors in reference [15] perform reliability analysis of offshore platforms taking into account fatigue degradation of components, and consider different failure scenarios, including various sequences of failures and combinations of time sequences. However in practice, many accidents are related to the operation of platforms and additional circumstances such as operational and environmental conditions. According to Ibrion et al. [18] 96% of accidents occurrence were related to operation, including 13% to operation and installation, and only 4% to installation. The rate of accidents linked to jack-up on Norwegian Coastal Shelf for last 40 years is 1,25 which is not significantly high in comparison to concrete structures or jacket [18]. It should be emphasized that Southern Baltic Sea have over-representation of jack-up type platform, while concrete structures and jacket type of foundation are most common worldwide. What is also important, the majority of considered jack-up platforms operate on field for long time without change of operational site. This characteristic should be carefully considered, as there is not clear how to categorize and compare the reliability levels based on global data.

2 JACK-UP PLATFORM AND ITS RELIABILITY STRUCTURE

2.1 *Jack-up unit description and components*

In the Polish Baltic Sea area, apart from the existing oil and gas offshore infrastructures based mostly on jack-up platforms, vessels of the same type, i.e. jack-up, will also be used for subsequent wind farm installation. In the case of offshore wind farm installation vessels, a similar assumption can be made as in the case of drilling platforms. Namely, most of these vessels have been operating in various waters, which is directly related to the history of transit and jacking operations. The frequency and conditions of these operations impact on overall fatigue of jack-up structure and its reliability. Consequently, it is important for the safety of subsequent operations and can also be basis for determining the scope of inspections, repairs, or modifications to the vessel.

The construction of such offshore structures should be analysed before further study. Jack-up units consist of a buoyant hull equipped with multiple retractable legs, typically three or four, capable of raising the hull above the sea surface. For the purpose of this study typical three-legged structure with a triangular hull is presented in Figure 1.

Figure 1. Simplified 3-D model of typical three-legged jack-up hull-leg assembly (based on [28] AI generated).

In general three-legged jack-up reliability structure can be simplified to the scheme presented in Figure 2.

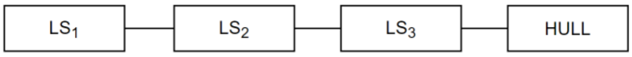

Figure 2. Simplified reliability structure of three-legged jack-up.

In Figure 2, the notation LS is used for "leg structure" that includes spud-can and jack house. Further, the reliability structure of all three legs are described and analysed depending on the platform operation mode. Each leg structure is connected to the hull, however for three-legged structure each of them must be functional, so the jack-up structure has been simplified to a series reliability structure. For other jack-ups design, the reliability structure should be redefined.

The concept of reliability has various definitions, even within the offshore industry, and different approaches to its assessment can be found. The reliability term appears at many stages of offshore projects and often refers to different issues [16]. In case of offshore object, its reliability can be formulated as the combined fulfilment of the requirements of structural integrity and operational efficiency of systems while maintaining a sufficient level of serviceability, maintainability, availability and quality that ensures the safety of people on board, the environment and performs the designed function with a reasonable degree of certainty.

In the literature review on jack-up reliability analysis [10], the authors point out that results of failure probability analysis largely depend on the method used apart from factors included in the reliability analysis. By applying different methods and approaches to structural reliability analysis, the authors conclude that their choice depends mainly on the way of treating and understanding uncertainties in reliability assessment. In reliability analysis, taking into account deterioration and degradation of structure/system and its components in time, uncertainties can refer to various aspects. Future studies on proposed in this article approach will focus on methods to reduce these uncertainties.

Referring to the classical reliability theory of two-state systems, the reliability is defined as the probability or likelihood that the system will be failed or damaged. Following this definition and considering the probability of failure over time, the reliability function of a system R(t), t $\geqslant$ 0, is defined [23] as the probability that the time to system failure, i.e. its lifetime, is not shorter than t:

$$R(t) = P(T_F \geq t), t \geq 0, \quad (1)$$

where T_F denotes random variable representing the system lifetime.

In the reliability analysis of offshore units, it is crucial not only to determine their design lifetime and the time period of system failure but also to estimate the period during which the offshore unit can be safely operated under specific conditions [2], [12]. This goal can be achieved in various ways, taking into account operating cycles and conditions data. For example, by determining the moment at which the unit's reliability is most likely to exceed a certain acceptable threshold, beyond which operation may be unsafe. In that sense, Jensen [20] estimates the average value of the expected fatigue damage rate and the probability that the expected fatigue damage rate D exceeds predetermined threshold D_T, by using the Cornell reliability index β:

$$P\left(D > D_T\right) = \Phi\left(-\beta\right). \tag{2}$$

Cornell reliability index [9] is widely used in literature to evaluate the reliability of offshore units [10], [15], [22], [36]. Nevertheless, in this paper we propose to use the reliability function to analyze the reliability of offshore platforms, which allows to consider the reliability value depending on the time and operation mode of the platform. Moreover, a multi-state approach to reliability analysis, described in Subsection 2.3, is proposed to consider the probability of platform being in a specific reliability state. Such reliability state can correspond to the offshore unit condition, including fatigue level of its structure and main components, related to its operational history.

Consequently, we apply the formula (1), to evaluate the reliability of jack-up unit. Considering reliability structure of a three-legged jack-up platform, we conclude that it is working when all its main subsystems (platform legs and connected equipment) and the hull are functional for designated task (operation mode). Thus, a basic reliability structure of platform is a series reliability structure, presented in Figure 2. The remaining components have been omitted in the reliability structure due to their negligible influence on the platform reliability in the considered scope, i.e., maintaining the pontoon structure in a specific position or not contributing to the operating mode. We focus on mechanical integrity and omit other equally important platform functions for simplicity, to demonstrate the motivation behind the proposed approach, which could be expanded to include additional functionalities in the future.

Taking into account the above conclusion, the reliability function of jack-up system is given by the following formula:

$$\boldsymbol{R}_{S_{jack-up}}\left(t\right) = R_{Leg1_{jack-up}}\left(t\right) \cdot R_{Leg2_{jack-up}}\left(t\right) \cdot R_{Leg3_{jack-up}}\left(t\right) \cdot R_{Hull}\left(t\right), t \geq 0, \tag{3}$$

where $R_{Leg1_{jack}}\left(t\right), R_{Leg2_{jack}}\left(t\right), R_{Leg3_{jack}}\left(t\right)$ denote the reliability functions of jack-up legs in jacking system and $R_{Hull}\left(t\right)$ denotes the hull's reliability function.

Jack-up structure (Figure 3) with particular emphasis on the jacking system can be divided into the following main components [1], [21], [25]:

- Hull – buoyant, watertight structure that contains ballast tanks and supports the legs, jacking system and equipment (mostly drilling for O&G purposes and Heavy Lift for Offshore Wind purposes). The hull floats during transportation and can be jacked up to elevate the rig above the water surface for drilling or crane operations. The hull's strength is crucial due to the high loads imposed by the legs and jacking systems.
- Leg Structure – in terms of reliability structure – it contains all parts (except the hull described above that connects all legs) that can be assigned to each leg individually:
- Jackhouse – machinery space on a jack-up platform or vessel, housing the jacking system that elevates and lowers the platform's hull using movable legs (Figure 3). Jackhouse is from one side welded to hull structure and from the other connected to legs by rack chocks and/or pinions (depending on the operation mode and design).
- Legs – they support the hull when elevated, providing stability under lateral loads. Two type of legs are commonly used: trussed with triangle or square shape and round – depending on the jack-up design.
- Racks – critical components in a leg structure with direct contact with pinions of jacking gearbox as well as with yokes of rack chock system. Legs depending on their type have welded one or more racks.
- Rack chocks – components that provide a secure mechanical lock, ensuring the platform's weight is safely transferred to the legs during static holding. The rack chock system operates independently of the jacking system. This separation allows the jacking pinions to be unloaded or declutch once the hull is locked with the rack chocks, increasing safety and reducing wear on the jacking components. Most of designs utilize them.
- Horizontal and Vertical Jacks – components for moving and positioning rack chocks.
- Locking Mechanisms – self-locking mechanisms that hold the rack chocks in position. This mechanical locking minimizes or eliminates the need for continuous hydraulic pressure to maintain the locked position, increasing reliability and safety even in the event of a power loss. Variable solutions are available.
- Jacking Pinions – large gear wheels with teeth that mesh precisely with the racks. These gears are almost always seven-toothed, as this is the fewest number of teeth that can be used to achieve a contact ratio of >1. The rotating pinions engage the rack teeth and convert rotational motion into vertical movement, thereby raising or lowering the hull relative to the legs. Supported by heavy-duty bearings, the pinions support the platform's weight during jacking, allowing for stable and controlled elevation or lowering.
- Jacking Motors – low-speed and high-torque hydraulic or electric motors with gearboxes installed on jacking houses, used to lift or lower the entire platform. The force is transferred via jacking pinions.
- Spudcans – base structures welded to the lower part of the leg structure that penetrates the seabed. These are critical components for ensuring stability during offshore operations and are, in most cases, designed for installation on the seabed.

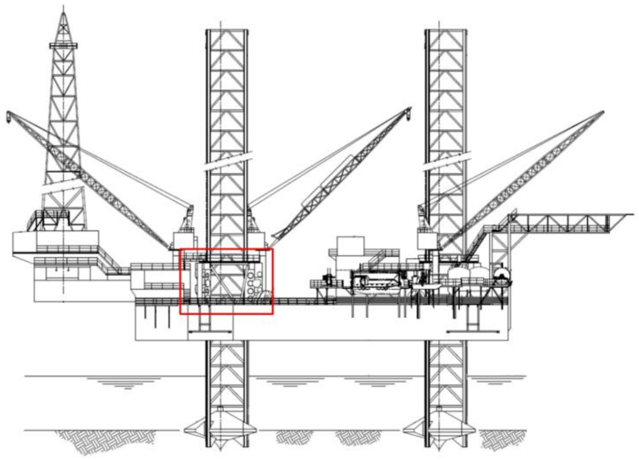

Figure 3. Side view of three-legged jack-up platform with the jacking house marked in the frame (based on [33]).

To better illustrate the jacking system's construction, described above components are show in exemplary representative scheme in Figure 4, from actual design project that can be found on one of jack-up platforms in the Baltic Sea.

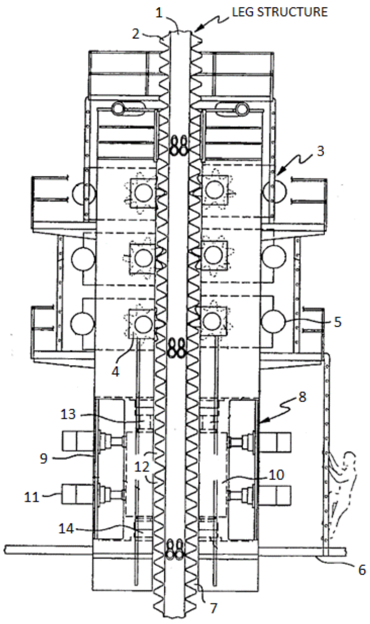

Figure 4. Schematic view of a jacking system (based on [37]). Legend: 1 – Chord Rack; 2 – Teeth; 3 – Jacking System; 4 – Pinion; 5 – Elevating Jack Drive Motor; 6 – Deck Level; 7 – Leg Well in Hull; 8 – Rack Chock System; 9 – Rack Chock Assembly; 10 – Chock; 11 – Horizontal Screw Jack; 12 – Teeth match with Chock; 13 – Upper Vertical Screw Jack; 14 – Lower Vertical Screw Jack

The above scheme of a jacking system shows a view of one rack of the jack-up leg. In the example considered, a triangular-shaped trussed leg with three double-sided rack and pinion subsystems was designed. In that configuration, each leg has twelve pinions that support the pontoon's weight during jacking operations, including holding the preload, which can result in approximately 60% greater load per pinion than during a normal jacking. Six rack chocks per leg hold the pontoon's weight during platform operation.

2.2 *Jack-up unit operations*

Jack-up type vessels are highly versatile mobile offshore platforms that serve multiple critical purposes across various industries, particularly in the energy, marine construction, and offshore sectors [3], [7], [13]. These self-elevating platforms have become indispensable tools for operations in shallow waters where stability and accessibility are paramount. To properly describe and estimate reliability of jack-up unit, basic operations, that are characteristic for this type of units, have to be characterized [10]:

– transit – during this operation, legs are elevated above the pontoon with spud-cans positioned close to the pontoon, and rack-chocks secure legs against movement. There are two types of towing: wet and dry towing for units without propulsion, illustrated in Figure 5.
– jacking – during this operation, the rack-chock system is disengaged and the entire load rests on pinions. In this state, the platform can be transited from the afloat to the elevated position and from the elevated to the afloat position. This is the most critical operation, associated with numerous risks.
– elevated position – in this position, the spud-cans stand on the seabed and the rack-chock system is engaged transferring the entire load bypassing jacking system.

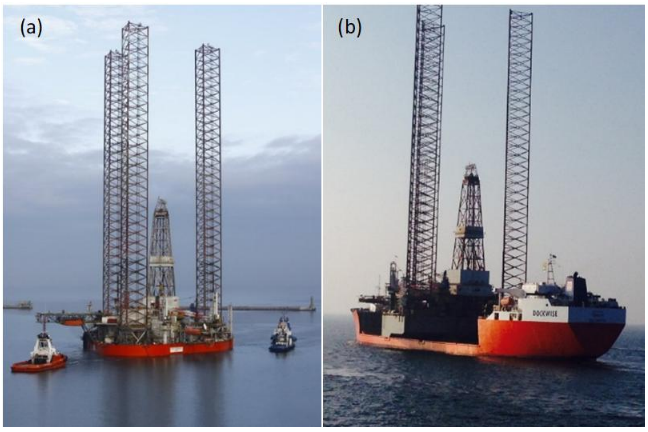

Figure 5. (a) Wet towing of Lotos Petrobaltic (photo J. Bogucki) [38], (b) Dry towing of Lotos Petrobaltic [39].

Depending on the operations performed, the contribution and fatigue of the components, listed in Subsection 2.1, during jack-up platform's operation may vary. Thus, taking into account the reliability structure of jack-up platform, the following four modes have been distinguished for consistency in the analysis:

– jacking mode – includes components active during the elevating or lowering of platform,
– wet towing mode – includes components active during the towing in buoyancy condition – see Figure 5a,
– dry towing mode – includes components active during the towing on barge – see Figure 5b,
– operation mode – includes components that are active during operation, i.e. in the elevated position.

In our research, we point out that the reliability structure of a jack-up platform depends on its operating condition. Consequently, the reliability function of a jack-up unit regarding different modes takes the form:

$$\boldsymbol{R}_{S_{jack-up}}(t) = P\left(T_{M_{jacking}}\right) \cdot \boldsymbol{R}_{S_{jack-up}}^{M_{jacking}}(t) + P\left(T_{M_{WetT}}\right) \cdot \boldsymbol{R}_{S_{jack-up}}^{M_{WetT}}(t) + P\left(T_{M_{DryT}}\right) \cdot \boldsymbol{R}_{S_{jack-up}}^{M_{DryT}}(t) + P\left(T_{M_{Oper}}\right) \cdot \boldsymbol{R}_{S_{jack-up}}^{M_{Oper}}(t), t \geq 0, \quad (4)$$

where:

$P(T_{MJacking})$ – probability of jack-up platform jacking mode,

$P(T_{MWetT})$ – probability of jack-up platform wet towing mode,

$P(T_{MDryT})$ – probability of jack-up platform dry towing mode,

$P(T_{MOper})$ – probability of jack-up platform operation (elevated) mode,

and $\boldsymbol{R}_{S_{jack-up}}^{M_{jacking}}(t), \boldsymbol{R}_{S_{jack-up}}^{M_{WetT}}(t), \boldsymbol{R}_{S_{jack-up}}^{M_{DryT}}(t), \boldsymbol{R}_{S_{jack-up}}^{M_{Oper}}(t)$ denote reliability function of a jack-up unit in the jacking mode, wet towing mode, dry towing mode and operation mode, respectively.

In the remainder of this paper, based on the knowledge of experts and platform operators, we determine the aforementioned probabilities of the platform's being in specific operational modes. In further research analysis, we plan to conduct a detailed analysis of the system's operation process, including the realizations of transition times between operational states and a detailed assessment of impact factors.

2.3 *Multi-state approach to platform reliability*

Analyzing the moment when a certain level is exceeded, above which system operation may be dangerous and pose a threat to people and the environment, instead of determining only the time to system failure, may be important from the practical perspective in platform reliability analysis. Therefore, in this paper, we propose a multi-state approach to the reliability analysis [6], [8], [14], [23] of platform structures, distinguishing reliability states s_0, s_1, s_2, … s_i, …, s_N related to the platform's condition, e.g., corrosion, age, wear, fatigue. Accordingly, we distinguish several reliability states of the platform and, from among them, we identify the state above which further operation of the platform may be dangerous. This approach can also be used to determine the state, exceeding which indicates the need for maintenance and repair. In further reliability analysis in this paper, we distinguish the following four reliability states for a jack-up unit:

- s_0- unit failure state, the system cannot be operated,
- s_1- critical system state, the system should not be used due to corrosion, material fatigue or other factors, as its operation may pose a threat to the environment and/or the life and health of people operating the system,
- s_2- system reliability state indicating partial wear, fatigue, corrosion or other factors, but enabling safe operation of the system,
- s_3- system full reliability state.

In this approach, the reliability function of multi-state jack-up unit is defined by the vector [6], [23], [24]:

$$\boldsymbol{R}_{S_{jack-up}}(t,\cdot) = \left[\boldsymbol{R}_{S_{jack-up}}(t,s_0), \boldsymbol{R}_{S_{jack-up}}(t,s_1), \boldsymbol{R}_{S_{jack-up}}(t,s_2), \boldsymbol{R}_{S_{jack-up}}(t,s_3)\right], t \geq 0, \quad (5)$$

where its coordinates are defined as the probability that the time until the system exceeds fixed conditions is not less than t, that is:

$$\boldsymbol{R}_{S_{jack-up}}(t,s_i) = P\left(\boldsymbol{T}_{S_{jack-up}}(s_i) \geq t\right), i = 0,1,2,3, \quad (6)$$

where $T_{Sjack-up}(s_i)$ is a random variable representing the time until the unit exceeds the conditions defined by s_i state and the associated safety level of the offshore structure.

Furthermore, considering the reliability structure presented in Figure 2 and formula (3), the multi-state reliability function of the jack-up unit takes form of the vector:

$$\boldsymbol{R}_{S_{jack-up}}(t,\cdot) = \left[1, \boldsymbol{R}_{S_{jack-up}}(t,s_1), \boldsymbol{R}_{S_{jack-up}}(t,s_2), \boldsymbol{R}_{S_{jack-up}}(t,s_3)\right], t \geq 0, \quad (7)$$

where its coordinates are given by:

$$\boldsymbol{R}_{S_{jack-up}}(t,s_i) = R_{Leg1_{jack-up}}(t,s_i) \cdot R_{Leg2_{jack-up}}(t,s_i) \cdot R_{Leg3_{jack-up}}(t,s_i) \cdot R_{Hull}(t), i = 1,2,3 \quad (8)$$

where $R_{Leg1_{jack}}(t,s_i), R_{Leg2_{jack}}(t,s_i), R_{Leg3_{jack}}(t,s_i)$ denote the reliability function coordinates of the jack-up system leg. With these notations, the reliability function coordinate $R_{Leg1_{jack}}(t,s_i)$ is defined as the probability that single jack-up system leg is in the reliability state s_i or better in terms of reliability at time t.

During the design phase, it is assumed that all three legs in a jacking system have the same reliability parameters and reliability function. Therefore, in this section, for notational simplicity, we consider the reliability structure of jack-up system under this assumption and determine the reliability function of a single leg in the jack-up system.

In that case, formula (8) for the reliability function coordinates of jack-up system structure, assuming the identical structure of jack-up system leg, takes the form:

$$\boldsymbol{R}_{S_{jack-up}}(t,s_i) = \left[R_{Leg_{jack-up}}(t,s_i)\right]^3 \cdot R_{Hull}(t), t \geq 0, i = 1,2,3, \quad (9)$$

where $R_{Leg_{jack}}(t,s_i)$ denotes the reliability function coordinate of single leg jacking system for the reliability state s_i, i=1,2,3. In further analysis, taking into account the operation history of the jack-up platform and its influence on the platform reliability, we consider the possibility of different reliability structures of jack-up legs in different operating modes of jack-up unit and the possibility of differential impact on individual platform legs. Therefore, in Section 3, we consider the jack-up platform as a heterogeneous system and conduct the reliability analysis of each platform leg separately.

3 TOWING AND JACKING HISTORY AND ITS IMPACT ON JACK-UP PLATFORM RELIABILITY

Jack-up platforms experience damage accumulation due to fluctuating loads, leading to fatigue failure when damage exceeds critical levels. Environmental conditions, including wind and wave forces, contribute to structural fatigue and can exacerbate degradation [2], [31], [34], [35]. The reliability of jacking systems must consider time-dependent factors, such as corrosion and material degradation, which affect the structural resistance over time [12], [32]. Advanced reliability assessment methods, including Monte Carlo simulations, can predict failure probabilities by taking into account uncertainty in loading and material characteristics [10], [20]. The mobility of jack-up platforms requires the ability to adapt to changing operating conditions, which can lead to increased wear and potential failure modes. Regular inspections and maintenance are crucial to assessing the remaining fatigue strength and ensuring the reliability of the platform throughout its operational life. As an example, Table 1 presents factors that can affect the platform reliability in jacking mode (from highest to lowest).

Table 1. Selected factors influencing the platform reliability in jacking mode.

Impact Factor Q_1	Jacking system mechanical condition factor
Impact Factor Q_2	Foundation and soil interaction factor
Impact Factor Q_3	Load distribution and structural response factor
Impact Factor Q_4	Operational control factor

Each operating mode contributes unique damage patterns to the overall structural integrity. According to research results and literature, different operating modes activate distinct failure mechanisms:

– Jacking Mode – concentrates mechanical stress on the jacking system components, with the rack-pinion interfaces experiencing peak load conditions.
– Operation Mode – subjects leg structures to cyclic environmental loading, following traditional fatigue models for offshore platforms.
– Towing Modes – introduce dynamic loading conditions not occurring in stationary operations, with quite a significant impact from hull-leg interactions near spudcan [29], [30].

There are many influence factors that vary for each operating mode. For example, the Jacking System Mechanical Condition Factor (hereinafter referred to as the impact factor Q1 for jacking operations) is a dimensionless parameter that quantifies the mechanical health and performance degradation of the jacking system during jack-up platform operations. The calculation begins with an assessment of the individual mechanical components of the jacking system, taking into account load-dependent factors based on the operating conditions, wear and degradation assessment, and the Weibull distribution for component reliability.

The fatigue life of a jack-up structure, including the jacking system, depends on operational strategy which determines, for example, the frequency and conditions of towing (dry or wet towing type). Therefore, considering the influence of jacking, operation, and towing history, is necessary for accurately assessing the reliability and lifetime of aging platforms. The main thesis of this paper is that jacking and towing operations have a measurable, cumulative impact on platform reliability, which must be incorporated into modern assessment methodologies.

3.1 *Fatigue damage process*

Jack-up platforms are designed to operate in transit, preloading, and operational conditions, all of which can contribute to fatigue damage [29]. Fatigue analysis of offshore structures is often based on S-N data as recommended for example by DNV document on fatigue design of offshore steel structures practices [11]. The guideline indicates that in fatigue analysis nominal S-N curves can be applied, however in case of exceeding the inherent S-N data in fabrication tolerances, additional stress analysis for butt welds and cruciform joints is required. Finite Element Models (FEM) are often used to conduct dynamic analysis in the time domain, and the Palmgren-Miner rule, also known as Miner's linear cumulative damage rule, is applied in engineering to estimate the fatigue damage of structures subjected to variable amplitude stress cycles. It is particularly relevant for offshore structures like jack-up platforms, which experience fluctuating stresses due to environmental loads such as waves, wind, and currents [29], [30].

The Palmgren-Miner rule assumes that fatigue damage accumulates linearly with each stress cycle, irrespective of the loading sequence. The fatigue damage D is calculated as the sum of the ratios of applied stress cycles to the number of cycles to failure at a given stress level:

$$D = \sum_{b=1}^{B} D_b \tag{10}$$

where B denotes number of stress blocks and the total stress range spectrum is discretized into a certain number of blocks.

The fatigue damage of the b-th stress block is given by:

$$D_b = \frac{n_b}{N_b} \tag{11}$$

where n_b is the number of stress cycles occurring in the stress range S_b, and N_b is the number of cycles to failure in the stress range S_b, determined from the material's S-N curve.

Despite its widespread use in engineering design [15], [29], [30], [36], Miner’s rule has several key limitations that the authors are aware of, such as the lack of load sequence effect, linear damage summation, ignoring the mean stress and environmental influence, scatter and statistical variability, and limited applicability to constant - amplitude S-N data [5], [17], [27].

In this paper, we focus on the primary fatigue data of offshore structure based on S-N data for reliability analysis. Nevertheless, due to the specific nature of jack-up platform operations and the influence of towing and jacking operations on the actual structure state, the history of structure's operation is included in its reliability analysis. Thus, we propose to apply a multi-state approach and determine the reliability function of offshore structure, taking into account the operation process of jack-up platform. We consider the influence of towing and jacking history on the jack-up structure reliability, based on the fatigue damage ratio introduced by the Palmgren-Miner rule. We assume that the impact factors can take different values for different reliability states s_i, i=1,2,3, and operating modes i.e. jacking mode, wet towing mode, operation mode and dry towing mode. Additionally, we assume that the operating history may deteriorate the component condition more than expected. However, due to natural fatigue and other factors, such as corrosion, the reliability parameters cannot be better than designed. With these assumptions, we propose the impact factor of jacking history on platform reliability in the following basic form:

$$Q_1\left(T,s_i\right)^{M_{jacking}} = min\left\{\frac{N^{Mj}\left(T,s_i\right)}{n^{Mj}\left(T,s_i\right)},1\right\},\ \ i=1,2,3, \tag{12}$$

where $N^{Mj}(T,s_i)$ is the number of operations designed for the offshore structure component, being in a reliability state s_i, in the jacking mode during operational time T, and $n^{Mj}(T,s_i)$ denotes the number of operations carried out in the jacking mode during operational time T, in which the offshore structure component was in the reliability state s_i.

Similarly, the influence of the platform's operational history in other operating modes on the conditional reliability function coordinates of jack-up platform in particular modes is considered. That way, the impact factors of operation history in wet towing, dry towing and operation modes are proposed and included in the further reliability analysis.

The number of permissible jacking up and down cycles during the design life of a jack-up platform or vessel is not universally fixed but depends on the design criteria, operational profile, and fatigue factors specific to each unit. Jack-up platforms are typically designed for a service life of 25 years, during which the jacking system - including the pinions, racks, and structural components - is expected to perform reliably under repeated jacking operations. The jacking system and leg structures are subject to fatigue from cyclic loading resulting from jacking operations, environmental forces, and operational conditions. The number of jacking cycles is limited by a fatigue life assessment that takes into account the stresses during jacking up/down and the dynamic environment. Some design parameters for the jack-up unit of drill type, analyzed in this paper, are given in Table 2. These parameters, which relate to the actual wear rate of a platform, can be used as a basis for estimating the operational history impact factor.

Table 2. Selected design parameters of conventional full size jack-up drilling unit.

Design number of jacking on site cycles per year (typical)	Around 10
Assumed number of preload and level cycles per jacking (typical)	2
Jacking time in 20 years of exploitation (estimation)	Around 320 hours

In a more advanced version, we can consider various type factors in each operational mode, for example those indicated in Table 1, influencing the reliability parameters of components. In such a case, these factors Q_1, Q_2, $\cdots$, Q_l, , $l \in$ N, are considered with coefficient weights w_1, w_2, …, w_l, satisfying the condition $\sum_{k=1} w_k = 1$. Taking into account the multi-state approach to reliability analysis, proposed in this paper, these factors can take different values for various reliability states s_i, i=1,2,3. Under such assumptions, the factor of influence on the jack-up unit reliability in any mode can be given by the following formula:

$$Q\left(T,s_i\right)^{Mode} = min\left\{w_1\cdot Q_1\left(T,s_i\right)^{Mode} + w_2\cdot Q_2\left(T,s_i\right)^{Mode} + \cdots + w_l\cdot Q_l\left(T,s_i\right)^{Mode},1\right\}, i=1,2,3. \tag{13}$$

The maximum value of impact factor can be 1, since we assume that the reliability of offshore unit cannot be better than it was designed for. Next, the coordinates of the jack-up platform reliability function are multiplied by these factors to take into account the negative impact of the operation history on offshore structure reliability. In particular, for a jack-up unit in jacking mode, regarding the four factors listed in Table 1, formula (13) can be transformed as follows:

$$Q\left(T,s_i\right)^{M_{jacking}} = min\left\{w_1\cdot Q_1\left(T,s_i\right)^{M_{jacking}} + w_2\cdot Q_2\left(T,s_i\right)^{M_{jacking}} + w_3\cdot Q_3\left(T,s_i\right)^{M_{jacking}} + w_4\cdot Q_4\left(T,s_i\right)^{M_{jacking}},1\right\}$$

i=1,2,3, (14)

where the factor $Q_1(T,s_i)^{M_{jacking}}$ can be estimated from formula (12).

3.2 *Impact of operation history on offshore structure reliability*

This paper presents a modified approach to platform reliability analysis, taking into account its operational history, unlike most papers that consider only the system structure and design parameters. Since this paper is the first stage of this research, we have adopted impact factor values based on expert opinion. In our future research, we plan to consider the operating process and history of jack-up platform in details, taking into account the number of operations of a given type, their duration, external conditions (including geological and environmental conditions), and operational frequency characteristics, to determine their impact on the actual fatigue level and reliability of the jack-up unit. The purpose of this article is to illustrate and highlight how considering the platform's operational history can impact the reliability of the entire unit and can be crucial for the safe operation of the jack-up unit.

Moreover, when analyzing the operating process of the jack-up unit, experts and operators have paid attention to the possibility of uneven fatigue and reliability level of each platform leg during operation. For example, in practice, the bow leg may be more loaded and subject to greater stress. and therefore, over time, have lower reliability parameters than the stern legs, due to geological conditions and related foundation of the unit and the depth of the platform legs. For that reason, we propose to consider three different impact factors, based on formula (10) or (11), which can take different values for each leg of the platform, i.e. $Q(T,s_i)^{M_{jacking}}_{Leg1_{jack-up}}$, $Q(T,s_i)^{M_{jacking}}_{Leg2_{jack-up}}$, $Q(T,s_i)^{M_{jacking}}_{Leg3_{jack-up}}$. Similarly, we can distinguish the impact factors of each leg on platform in other operating modes, i.e. $Q(T,s_i)^{M_{WetT}}_{Leg1_{jack-up}}$, $Q(T,s_i)^{M_{WetT}}_{Leg2_{jack-up}}$, $Q(T,s_i)^{M_{WetT}}_{Leg3_{jack-up}}$ for wet towing mode, and in further analysis for dry towing mode and operation mode.

The reliability function coordinates of the jack-up system structure in jacking mode, taking into account different reliability states s_i, i=1,2,3, and the impact of jacking history on its reliability, can be determined from the formula:

$$\tilde{\boldsymbol{R}}_{S_{jack-up}}^{M_{jacking}}(t,s_i)=Q(T,s_i)_{Leg1_{jack-up}}^{M_{jacking}}\cdot R_{Leg1_{jack-up}}^{M_{jacking}}(t,s_i)\cdot Q(T,s_i)_{Leg2_{jack-up}}^{M_{jacking}}\cdot R_{Leg2_{jack-up}}^{M_{jacking}}(t,s_i)\cdot Q(T,s_i)_{Leg3_{jack-up}}^{M_{jacking}}\cdot R_{Leg3_{jack-up}}^{M_{jacking}}(t,s_i)\cdot R_{Hull}(t),\ t\ge 0, i=1,2,3. \quad (15)$$

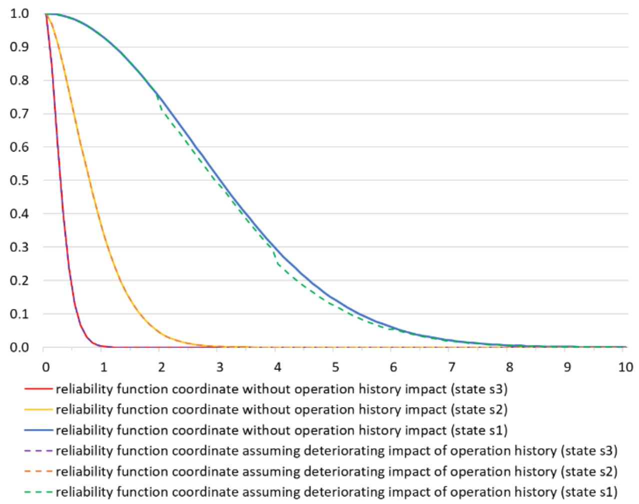

Figure 6. The reliability function coordinates of the jack-up unit in jacking mode, with and without the impact of operation history.

Figure 6 illustrates the influence of jacking history on the reliability of jack-up platform compared to the results without this influence. In this paper, the impact of the operating history is assumed to be relatively small with respect to the design fatigue limits, and the impact factor $Q(T,s_i)^{M_{jacking}}$, $i = 1, 2, 3$, ranges from 0.94 to 1, where value 1 means no negative impact of the jacking history and loading on the system beyond the design limit. For other operating modes, the influence factors range from 0.96 to 1.

Similarly, the reliability function coordinates of the jack-up system structure in wet towing mode, taking into account different reliability states s_i, i=1,2,3, and the impact of towing history on its reliability, are given by:

$$\tilde{\boldsymbol{R}}_{S_{jack-up}}^{M_{WetT}}(t,s_i)=Q(T,s_i)_{Leg1_{jack-up}}^{M_{WetT}}\cdot R_{Leg1_{jack-up}}^{M_{WetT}}(t,s_i)\cdot Q(T,s_i)_{Leg2_{jack-up}}^{M_{WetT}}\cdot R_{Leg2_{jack-up}}^{M_{WetT}}(t,s_i)\cdot Q(T,s_i)_{Leg3_{jack-up}}^{M_{WetT}}\cdot R_{Leg3_{jack-up}}^{M_{WetT}}(t,s_i)\cdot Q(T,s_i)_{Hull}^{M_{WetT}}\cdot R_{Hull}^{M_{WetT}}(t),\ t\ge 0, i=1,2,3, \quad (16)$$

and during operation mode and dry towing mode, respectively:

$$\tilde{\boldsymbol{R}}_{S_{jack-up}}^{M_{DryT}}(t,s_i)=Q(T,s_i)_{Leg1_{jack-up}}^{M_{DryT}}\cdot R_{Leg1_{jack-up}}^{M_{DryT}}(t,s_i)\cdot Q(T,s_i)_{Leg2_{jack-up}}^{M_{DryT}}\cdot R_{Leg2_{jack-up}}^{M_{DryT}}(t,s_i)\cdot Q(T,s_i)_{Leg3_{jack-up}}^{M_{DryT}}\cdot R_{Leg3_{jack-up}}^{M_{DryT}}(t,s_i)\cdot R_{Hull}(t),\ t\ge 0, i=1,2,3, \quad (17)$$

$$\tilde{\boldsymbol{R}}_{S_{jack-up}}^{M_{Oper}}(t,s_i)=Q(T,s_i)_{Leg1_{jack-up}}^{M_{Oper}}\cdot R_{Leg1_{jack-up}}^{M_{Oper}}(t,s_i)\cdot Q(T,s_i)_{Leg2_{jack-up}}^{M_{Oper}}\cdot R_{Leg2_{jack-up}}^{M_{Oper}}(t,s_i)\cdot Q(T,s_i)_{Leg3_{jack-up}}^{M_{Oper}}\cdot R_{Leg3_{jack-up}}^{M_{Oper}}(t,s_i)\cdot R_{Hull}(t), t\ge 0, i=1,2,3. \quad (18)$$

The graphs of reliability function coordinates of the jack-up unit during wet towing, dry towing and operation modes, based on formulae (16)-(18), are shown in Figures 7, 8 and 9, respectively.

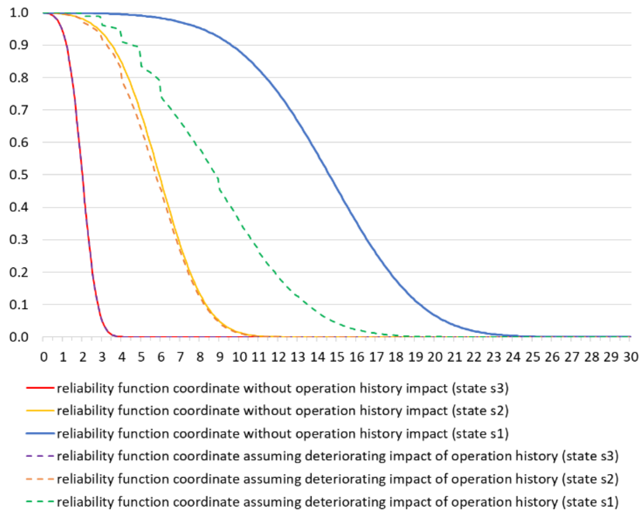

Figure 7. The reliability function coordinates of the jack-up unit in wet towing mode, with and without the impact of operation history.

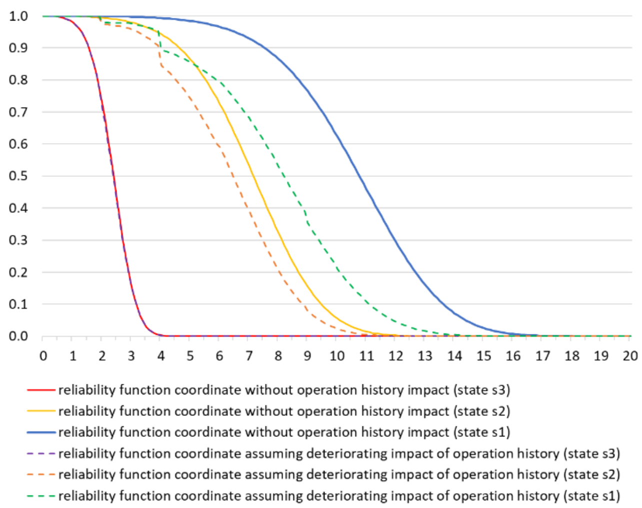

Figure 8. The reliability function coordinates of the jack-up unit in dry towing mode, with and without the impact of operation history.

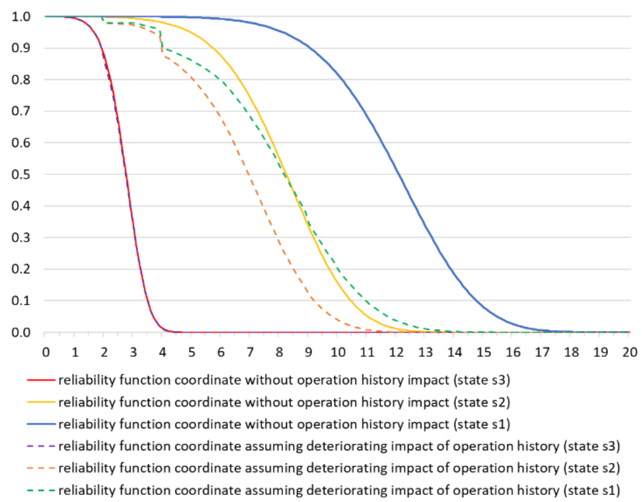

Figure 9. The reliability function coordinates of the jack-up unit in operation mode, with and without the impact of operation history.

Taking into account the operation history and its impact factors, including jacking and towing operations, the reliability function of jack-up unit, based on formula (7) and assuming multi-state approach to platform reliability analysis, is given by the vector:

$$\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,\cdot) = \left[1, \tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_1), \tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_2), \tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_3)\right], t \ge 0, \quad (19)$$

where its coordinates, considering the platform operation process, can be determined from the following formula:

$$\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_i) = P\left(T_{M_{jacking}}\right) \cdot \tilde{\boldsymbol{R}}^{M_{jacking}}_{S_{jack-up}}(t,s_i) + P\left(T_{M_{WetT}}\right) \cdot \tilde{\boldsymbol{R}}^{M_{WetT}}_{S_{jack-up}}(t,s_i) + P\left(T_{M_{DryT}}\right) \cdot \tilde{\boldsymbol{R}}^{M_{DryT}}_{S_{jack-up}}(t,s_i) + P\left(T_{M_{Oper}}\right) \cdot \tilde{\boldsymbol{R}}^{M_{Oper}}_{S_{jack-up}}(t,s_i),\ i = 1,2,3, \quad (20)$$

and conditional reliability function coordinates in particular operating modes are given by formulae (15)-(18), respectively.

Figure 10 presents the coordinates of the unconditional reliability function of the platform when the operating history and its impact on the jack-up platform reliability are taken into account, based on formulae (20) and (15)-(18), and without taking into account such influence.

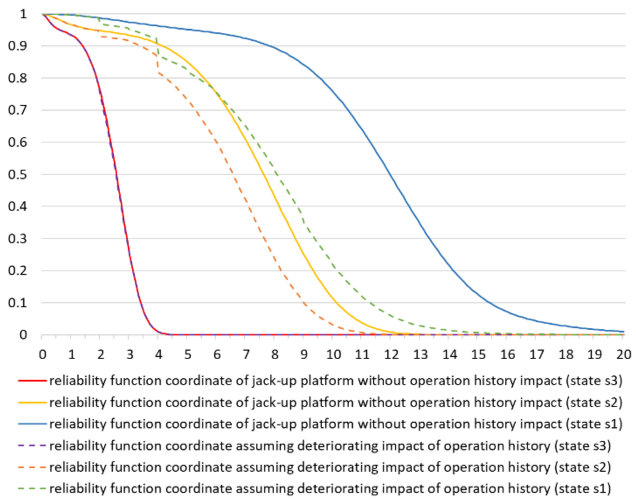

Figure 10. The coordinates of the unconditional reliability function of jack-up unit, taking into account the impact of its operation history and without such influence.

The values of reliability function coordinates at the moment t represent the probability that the time to system exceeding certain reliability and safety conditions is not less than t. Reversing this relationship, by using the inverse function of the coordinate, we can determine the moment when the reliability function coordinate of jack-up unit exceeds some fixed level, e.g. 0.8. Let's denote:

$$\tilde{\boldsymbol{r}}_1(t) = \tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_1), t \ge 0, \quad (21)$$

and consequently by using its inverse function, if such exists, we can determine the moment when the probability of jack-up platform failure exceeds certain level, from the following formula:

$$\tilde{\tau}_1 = \tilde{\boldsymbol{r}}_1^{-1}(p), \text{, where } p \in \langle 0;1 \rangle. \quad (22)$$

Consequently, we can determine the moment when the values of reliability function coordinates $\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_2)$ and $\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_3)$ fall below a certain level $p \in \langle 0;1 \rangle$ according to the formulae:

$$\tilde{\tau}_2 = \tilde{\boldsymbol{r}}_2^{-1}(p), \text{ where } \tilde{\boldsymbol{r}}_2(t) = \tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_2), t \ge 0, \quad (23)$$

and

$$\tilde{\tau}_3 = \tilde{\boldsymbol{r}}_3^{-1}(p), \text{ where } \tilde{\boldsymbol{r}}_3(t) = \tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_3), t \ge 0. \quad (24)$$

Tables 3, 4, 5 present the results of moments $\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\tau}_3$, when the values of reliability function coordinates $\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_1)$, $\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_2)$ and $\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_3)$, respectively, fall below a certain level p. They are determined from formulae (22)-(24) for the jack-up unit taking into account the impact of its operating history on reliability. Similarly, the moments τ_1, τ_2, τ_3, when the coordinates of unconditional reliability function fall below a certain level p, for the jack-up unit without taking into account such influence, are determined and given in Tables 3, 4, 5, respectively.

Table 3. Moments τ_1 and $\tilde{\tau}_1$ of exceeding the probability level by the coordinates of unconditional reliability function of the jack-up unit.

Level of probability p	Moments of exceeding the probability level p (in years)		
	τ_1	$\tilde{\tau}_1$	difference
0.9	7.9	4.0	49%
0.8	9.6	5.4	44%
0.7	10.6	6.6	38%
0.6	11.3	7.4	35%
0.5	12.0	8.1	33%
0.4	12.7	8.8	31%

Table 4. Moments τ_2 and $\tilde{\tau}_2$ of exceeding the probability level by the coordinates of unconditional reliability function of the jack-up unit.

Level of probability p	Moments of exceeding the probability level p (in years)		
	τ_2	$\tilde{\tau}_2$	difference
0.9	4.2	3.4	19%
0.8	5.6	4.3	23%
0.7	6.4	5.3	17%
0.6	7.1	6.0	15%
0.5	7.6	6.6	13%
0.4	8.2	7.1	13%

Table 5. Moments τ_3 and $\tilde{\tau}_3$ of exceeding the probability level by the coordinates of unconditional reliability function of the jack-up unit.

Level of probability p	Moments of exceeding the probability level p (in years)		
	τ_3	$\tilde{\tau}_3$	difference
0.9	1.4	1.4	0%
0.8	1.9	1.9	0%
0.7	2.2	2.1	5%
0.6	2.4	2.3	4%
0.5	2.6	2.6	0%
0.4	2.8	2.7	4%

Based on the results presented in this section, it can be concluded that the most significant difference occurs between the values of reliability function coordinates $\tilde{\boldsymbol{R}}_{S_{jack-up}}(t,s_1)$, taking into account the influence of platform's operation history, and $\boldsymbol{R}_{S_{jack-up}}(t,s_1)$ without such influence. This means that the impact of operation history on the jack-up platform reliability is crucial in the long term when comparing the platform's lifetimes, i.e. times of system being in the reliability states s_1, s_2 or s_3. Comparing the moments at which the reliability function coordinates exceed the predefined probability levels (Tables 3, 4, 5), corresponding to the time the system spends in the reliability states s_1, s_2 or s_3, the differences range from approximately 30% to 50%. For the probability that the platform is in the reliability states s_2 or s_3, the differences between the moments of exceeding the probability levels range from 13% to 23%, and for the probability that the platform is in the reliability state s_3 of full system reliability, these differences are negligible (up to 5%). From these results, it can be clearly shown that operational history has a deterministic effect on the jack-up platform reliability, and the scale of this effect is critically dependent on the current degradation state of platform. For aged platforms exhibiting degraded reliability states (s_2 or s_1) – characterized by accumulated mechanical wear, fatigue damage, or corrosion – the operational history becomes a primary factor in determining reliability, where additional operations beyond the original design parameters or exposure to adverse operating conditions can accelerate catastrophic reliability degradation.

This phenomenon is revealed in the non-linear relationship between cumulative damage and operational stress, where platforms with pre-existing degradation show increased sensitivity to changes in operational history. In particular, when jack-up platforms show partial wear of critical components (jacking systems, structural connections, foundation interfaces), fatigue crack propagation, or signs of progressive corrosion, subsequent operating modes – especially jacking operations, transit conditions, or extended operational periods – can trigger accelerated degradation mechanisms that fundamentally compromise the platform's integrity. The key finding illustrates that the influence of operational history follows a threshold-dependent model: platforms maintaining a full reliability state ($R \geqslant 0.95$) indicate resilience to operational variations, with only a slight degradation in reliability under unfavourable conditions. In contrast, platforms in a state of reduced reliability ($R < 0.95$) present exponential sensitivity to operational history, where identical operational sequences can yield significantly different reliability results depending on the baseline level of platform degradation. This threshold behaviour validates the need for history-dependent reliability assessment methodologies, as traditional approaches that assume operational independence generally underestimate failure probabilities for aged platforms while potentially over-conservatizing assessments for platforms in excellent condition. Thus, the operating mode impact factor model provides the essential analytical framework to distinguish platforms requiring intensive historical evaluation from those suitable for conventional reliability assessment approaches.

4 CONCLUSIONS

The paper illustrates the relationship between operating conditions and overall fatigue of a typical jack-up structure in the context of the safety of future operations. The results obtained show that operational history has a significant impact on the reliability of a jack-up structure. That can be crucial in lifetime assessment and correction of estimated design lifetime. Moreover, the detailed analysis of reliability of individual legs and their fatigue is extremely important, which from the point of view of operational safety is more realistic and can provide a more sustainable approach to maintenance and repairs – which will be included as an additional impact factor in our future studies. This multi-modal operational framework represents a paradigm shift from traditional static reliability analysis to dynamic, history-dependent assessment methodologies. In our future research, we plan to analyse the reliability impact factors for each components depending on the operating mode, as a multidisciplinary approach that could help develop a supportive tool for lifetime assessment of offshore structures.

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