Journal of Safety Science and Resilience 3 (2022) 153–168

Science Press

Contents lists available at ScienceDirect

Journal of Safety Science and Resilience

journal homepage: http://www.keaipublishing.com/en/journals/journal-of-safety-science-and-resilience/

Offshore system safety and operational challenges in harsh Arctic operations

Sidum Adumene[a,*], Hope Ikue-John[b]

[a] School of Ocean Technology, Marine Institute, Memorial University, St. John's, NL A1C 5R3, Canada
[b] Department of Marine Engineering and Naval Architecture, Akwa Ibom State University, Nigeria

ARTICLE INFO

Keywords:
Critical offshore infrastructure
Harsh arctic operations
Metocean
Resilient design
Safety
Digitalization

ABSTRACT

Offshore oil and gas drilling operations are going to remote and harsh arctic environments with demands for heightened safety and resilience of operational facilities. The remote and harsh environment is characterized by extreme waves, wind, storms, currents, ice, and fog that hinder drilling operations and cause structural failures of critical offshore infrastructures. The risk, safety, reliability, and integrity challenges in harsh environment operations are critically high, and a comprehensive understanding of these factors will aid operations and protect the investment. The dynamics, environmental constraints, and the associated risk of the critical offshore infrastructures for safe design, installation, and operations are reviewed to identify the current state of knowledge. This paper introduces a systematic review of harsh environment characterization by exploring the metocean phenomena prevalent in harsh environments and their effects on the floating offshore structures performance and supporting systems. The dynamics of the floating systems are described by their six degrees of freedom and their associated risk scenarios. The systematic methodology further explores the qualitative, quantitative, and consequences modeling techniques for risk analysis of floating offshore systems in a harsh environment. While presenting the current state of knowledge, the study also emphasizes a way forward for sustainable offshore operations. The study shows that the current state of knowledge is inexhaustive and will require further research to develop a design that minimizes interruption during remote harsh offshore operations. Resilient innovation, IoT and digitalization provide opportunities to fill some of the challenges of remote Arctic offshore operations.

1. Introduction

Drilling operations in the remote harsh environment present diverse technical, operational, and logistics challenges to oil and gas development. These challenges include but are not limited to catastrophic accidents, operational downtime, system failures, and occupational risk. Therefore, consideration should be given to understanding the technical issues associated with remote deep-water operations, especially with machines and resources [1]. Understanding the operational dynamics of the system and its performance in harsh environments is a fundamental key to sustainable oil and gas field development.

In remote harsh environment operations, the metocean (environmental) factors are complex, resulting in severe consequences for drilling facilities and personnel in extreme scenarios [1]. Data gathering for the operation of the floating system in an extreme and harsh environment is limited to enable timely prediction, design, and detection of structural failures, safety assessments, and predictions of performance degradation and the remaining structural life of the systems [2]. The high-tech development of real-time monitoring and data gathering equipment for harsh environment offshore operation is still evolving. The complex environmental loads adversely affect the subsea facilities, including riser and mooring systems, resulting in a complicated failure phenomenon. Understanding the processes, dynamics, and risk involved in the remote harsh environment operation is key to safe operation and good modeling, particularly in developing resilience and emergency response models. These models are useful and critical in data gathering and help to better predict the possible accident scenarios in the course of operation. Proneness and accuracy are crucial for effective response in offshore operations.

The current study presents the state of knowledge and understanding of the challenges in remote harsh offshore operations, which include the environment, structural dynamics, operational risk, safety, and logistics challenges. There exists limited knowledge in actual system design and predictions that will minimize interruption and optimize operations. A systematic methodology is used to explore various effects of the operational dynamics on system performance and operational risk in harsh offshore operations. A way forward for sustainable offshore operations in the remote harsh arctic environment is presented.

The remaining sections of the paper are structured thus: section 2 of the research characterizes the harsh environment and recent models for prediction. Section 3 presents offshore system dynamics challenges in remote arctic operations. Section 4 focuses on operational risk and

* Corresponding author.
E-mail address: sadumene@mun.ca (S. Adumene).

https://doi.org/10.1016/j.jnlssr.2022.02.001
Received 8 November 2021; Received in revised form 26 January 2022; Accepted 7 February 2022

safety challenges. Section 5 explores knowledge gaps and research opportunities, while section 6 concludes the paper.

2. Harsh offshore environment characterization

The remote and harsh operating environment is commonly described as extremely low temperatures, winds, waves, snowdrifts, polar low pressures, atmospheric and sea-spray icing, sea-ice induced vibrations, seasonal darkness, and poor visibility due to fog and snowstorms, etc. Since the reliability performance of Arctic oil and gas facilities is adversely affected by such an environment [3,4], a proper understanding of its effect on facility integrity is crucial to sustaining operation from the design stage.

The characteristics of these areas like remoteness, lack of infrastructure, icing events, sea ice conditions, and harsh climatic conditions intensify these challenges. This should be attributed to high uncertainties and operational risks [3]. The risk has an adverse effect on the environment in the case of an accident during operation. The remoteness causes long supply routes vulnerability and interruption due to sea ice conditions, fog, long periods of darkness, and other weather phenomena [5]. Polar Low is also a critical phenomenon that affects offshore operations in remote arctic environments. The formation results from intense mesoscale cyclones with less than 1000 km horizontal extensiveness. The cyclone's formation process is rapid and difficult to predict clearly in such a harsh environment. It is characterized by sudden weather changes with snowfall and a rapid increase in wind speed. Research shows that the wind generates sea spray in a harsh environment; the sea spray causes microbial growth in drilling and production facilities [6].

The challenging environment, sea ice, icebergs, and fog are critical environmental conditions that affect offshore operations [7]. For the Barents Sea, it is reported that ice formation can be up to 2 m thick for unreformed first-year ice and 3–5 m for a multi-year period [8]. The foregoing shows that waves, wind, storms, and ice are prevailing elements of a remote and harsh environment that describe the metocean characteristic of a region of operations.

2.1. Metocean (loads) challenges

Metocean analysis presents the interaction of the various natural phenomenon associated with ocean dynamics. These phenomena include waves, wind, storms, currents, and tides and are measured using hi-tech equipment to form a data bank for operation (generally, with a 100-year return period). These data are used to predict future analysis. These data are presented using a probability of exceedance to describe the extreme value for a given period.

2.1.1. Wind load effects

The wind is one of the environmental loads that the floating system experiences in harsh environment operations. Wind speed and direction of propagation affect the floating system responses during the drilling operation. Critical wind speed affects other support operations such as crane and helicopter operations, especially during remote harsh drilling operations [2]. Actual data gathering and prediction of wind projection in such an environment are crucial in the risk-based analysis for such operations. The safety of the offshore system, personnel, and operational facilities suffer adverse effects due to the wind load on the structure [9]. Most times, the results are rocking, slamming, flooding of the deck, and acceleration of the state of excitation. Lateral rolling is associated with wind-induced loading on ships. Zangeneh et al. [10] present the effect of wind loads on structure response in a harsh sea state. The result shows that the heading instability associated with the floating structure decreases at a certain wind speed with a wavelength ratio greater than 1.17. This prediction of the operating envelope will guarantee safe operation in extreme wind conditions. Continuous research is needed to better understand this criterion at its maximum occurring speed, permissible limits, and probability of occurrence to guide the drillship operation prediction, especially in a harsh environment.

2.1.2. Waves load effects

In offshore operation, wave modeling is generally defined by wave height and period and is used to design and predict the dynamic insensitivity of the offshore system. The pre-known wave pattern is for a 100-year return period analysis of the wave data. For practical modeling, the wave data for the period are collected at different wavelets and combined in random phases [11]. The waves are represented in an infinite number of sinusoidal wavelets with different frequencies and directions. The wave spectrum is used to plot the distribution of these wavelets against frequency and orientation [12]. Statistical tools are commonly used to describe the random nature of ocean surfaces. These statistical properties of spontaneous waves in a sea may be assumed to be approximately constant for short periods of one to three hours [12]. Few frequency spectra models have been proposed, which include JONASWAP, Pierson & Moskowitz, etc. [11]. These models present formulation to analyze the spectrum that characterizes the prevailing waves in an open sea, and the wave height is represented by the routinely estimated period. The significant wave height is denoted by H_s and represents the height for a sea state [12]. This analysis is dependent on the 100-year return period.

The system performance analysis is inadequate for a remote harsh environment with limited data and an unpredictable sea state. The impact of this limitation and the wave generation, especially at an extreme height, affects the offshore operation in such an environment. Research also shows that swells is predominant in remote and harsh operating environments, affecting the dynamic of the floating structures [13]. Swells are waves with gradually increasing height and period along the path; usually, the period is between ten to twenty seconds. Although the wave amplitude may be small, it can cause heavy vessel oscillations because the wave period is close to the vessel's natural period. Therefore, orienting the ship into the incoming waves (wind-induced waves or swell coming from different directions) is essential to sustain its operability. Research has shown no firm conclusion of swell spectrum modeling, although Forristall et al. [14] showed that swell spectrum has a triangular or lognormal shape. Understanding this phenomenon will help predict its impact on the floating system design and operation. Wave loads on floating offshore systems play a dominant role in the design, construction, transportation, installation, and process [15]. Wave formation by sea state is irregular, and this causes a non-linear loading impact on the floating systems.

The dynamism in sea wave formation calls for a time-history analysis of structural response during extreme loading conditions [16]. Although conventional dynamic analysis has been in use, its time-consuming disadvantages informed the development of a better methodology. Further improvement to obtain more optimum solutions and cost reduction analysis under harsh environment wave loading conditions was proposed by [15,17]. The Endurance Time Analysis (ETA) model proposed by Riahi and Estekanchi [17] shows a high degree of accuracy and efficiency for the dynamic structural modeling subjected to a natural disaster (e.g., an earthquake). For modeling irregular wave loading on the structure in a harsh environment, Diznab et al. [18] and Jahanmard et al. [19] proposed the Endurance Wave Analysis (EWA) technique for the non-linear analysis of the structure. This model shows better performance and scope of application compared to ETA.

Further research has been done to fully understand the performance at extreme high environmental loading on the vessel dynamics. Abaei et al. [16] proposed the dynamic modeling of floating structures using EWA for considering a range of storm conditions. The methodology was applied to a Floating Storage Unit (FSU), and it shows a high degree of credibility for the analysis of offshore structures in a harsh environment. They subjected the structure to three states of excitation and evaluated the structural response to the impact of the storm wave. This model predicts the operating envelope and an unsafe condition that demands an emergency response during operations. The Intensifying Constrained New Wave model (ICNWM) is also an advanced model used to conduct risk escalation assessments for offshore structures under storm impact. The model can predict the storm envelope for operational and survival limits of the offshore systems in an extreme state. Its linear form is detailed in the work of [18]:

Further analysis of extreme and rogue waves and their impacts on offshore systems in a harsh environment are recorded in the referenced literature [20,21]. Numerical investigations of extreme and rogue waves based on field data have given a clear understanding of this phenomenon's generation mechanism and dynamic properties. Detailed work done can be found in [22,23]. Mohajernassab et al. [24] presented a modified endurance wave analysis based on the "Modified Intensifying New-wave (MINW)" for a time-dependent performance prediction. The new-wave model involves a time series superposition of linear wavelets for extreme wave prediction in a random sea state. Although Denchfield et al. [25] and Enderami et al. [26] have demonstrated the application of a new-wave model for the prediction of the ship and offshore structure performance in random sea state, the modified methodology of Mohajernassab et al. [24] has provided a more accurate result in offshore safety assessment under extreme wave conditions.

Sloshing is a phenomenon that occurs due to extreme wave effects; it affects the ship's motion response and significantly influences the ship's hydrodynamic behavior. In most cases, the sloshing flow's natural frequency becomes close to the ship's motion response, creating significant discomfort and excitation of the vessel. Researchers have used various theories to model the sloshing effect on LNG carriers and FPSO operations to understand their dynamics and predict the impacts on the vessel performance for different operating modes [27–29]. Jiang et al. [27] analyzed the effect of the sloshing coupling, considering the ship motion response and the loading impact on the ship. The numerical model was examined on a three-dimensional LNG-FPSO, and it shows how the sloshing effect on the vessel can be predicted. More research is needed for an integrated risk-based framework to predict and analyze the real-time degradation effect of slamming on offshore systems in remote and harsh environments.

The green water effect is a non-linear phenomenon that is wave-based and common in harsh environments. The impact of green water is devastating, resulting in vessels capsizing and destroying of superstructure onboard the drillship. Mac Gregor et al. [30] reported damages of bow and superstructure because of green water incidents. Attention has been drawn to examine this phenomenon and properly model its effect on critical offshore infrastructures. Kleefsman et al. [31] presented a numerical prediction of green water loading together with the vessel motion and wave field. The result gave an overview of associated uncertainty. Further analysis was conducted by Zhu et al. [32] to minimize uncertainty using a numerical wave tank to simulate the wave-ship interaction and green water. They adopted the Navier-Stokes equation and continuity equation to model the fluid field. The integrated model was able to predict and analyze the impacting forces of green water on the model drillship.

For accuracy and better prediction of wave analysis and design integration in a harsh environment, some industry regulators have updated their standards to accommodate extreme and severe wave conditions with a 10,000-year return period [33]. This is to guide against endangering the structural integrity of the floating or fixed structures in a harsh environment. Despite the several applications of modern CFD to predict the length of the calm period and the time of occurrence of dangerous sea states, there still exists a critical level of uncertainty in the result of most predictions [34,35]. Continuous research is needed to understand further the impact of extreme and rogue waves on the system dynamics in the operational phase of floating offshore systems in remote and harsh environments. This understanding could be integrated into the risk assessment and structural integrity management framework.

2.1.3. Current and storm effects

In a harsh environment, the subsea systems such as the riser, mooring system, and umbilical are susceptible to currents' effects, and their responses are destructive [1]. The total extreme water level (TEWL) at a location during a stormy event determines the degree of impact on the topsides and supporting structure of the drillship. This causes a large structural effect that affects the integrity of the structure. The storm surge is a critical condition that must be estimated during tropical storms. The storm type formation and surge propagation are classified as tropical, extra-tropical, and surge-tide formation [36,37]. The surge formation is due to a large-scale increase in the sea level during any storm. Physical and environmental processes influence the magnitude and formation. In the harsh environment of the high tide range, storm-tide formation can be created, and the structure can experience a dual loading impact.

Predictive models for the surge impact analysis, especially for hurricane surges and others, are presented in the literature [37–39]. Bernier and Thompson [37] present a 2D non-linear barotropic model to predict the frequency of storm surges and extreme sea levels in the northwest Atlantic. This prediction guides deep sea operators to schedule major projects or maintenance work. The effect of future climates due to storm surge formation, joint statistics of extreme storm surge, sea severity, and the statistical model for surge characteristics conditional on the occurrence of extreme values of significant wave height are presented in the literature [40–42]. This provides the range for storm surge probability of occurrence at a given location.

Abaei et al. [16] also predicted the offshore structure's response to the storm and developed the structural safety envelope for the offshore structure's storm-induced sway and surge motion, as shown in Fig. 1. Outside the predicted safe envelope, the drillship will suffer major structural damage resulting in the vessel capsizing due to extreme wave impact. This environmental phenomenon is dynamic, so more studies on its effect on critical offshore infrastructures are needed to enhance structural resilience for operations in remote and harsh environments.

2.1.4. Ice loads effects

Ice formation is characteristic of remote and harsh (arctic) environments. This environment is harsh to the drilling operation. The iceberg and offshore structure (ship) interaction affect the system's structural integrity. The integrity degradation of the structure is common in the arctic environment and is caused by the formation of local and global actions, vibration, abrasion, seabed scouring, etc. The iceberg's loading impact depends on the ice strength, geometry of the interaction, and the speed of the ice field movement [43]. Research has shown that a ship-shape turret moored system provides better support in severe wave conditions and the dynamic condition of an ice field [8]. Offshore structures experience sharp oscillation due to very slow-moving ice, and the ice strength is dependent on the loading rate. The oscillations result in excitation of the structural elements and degradation of the structural integrity [43]. The ice loading depends on the area of impact on the structure. Takeuchi et al. [44] show that the real contact area of the offshore facility by the iceberg is related to the material strain and stress. This defines the failure pattern of the structure under the iceberg impact and its velocity. Numerical modeling of the iceberg behavior and influence on the offshore facilities is also presented [45].

The ice-structure interaction is of different types based on the iceberg's relatively low and very high velocity. Shkhinek et al. [46] group the interactions into two: (1). An initial impact corresponding to the first ice/structure contact; (2). Penetration of the structure into the ice. Ice-induced vibration may create operational challenges (the serviceability limit state) and lead to fatigue failure of structural elements. Flexible structures, such as risers, and the umbilical under ice action, suffer vibration significantly and can result in total failure. Vibration impact also depends on the iceberg's velocity and the maximum action level [47]. Increased icing occurs simultaneously with extreme wind speeds and low air and seawater temperature [48]. Although ice load scenarios are

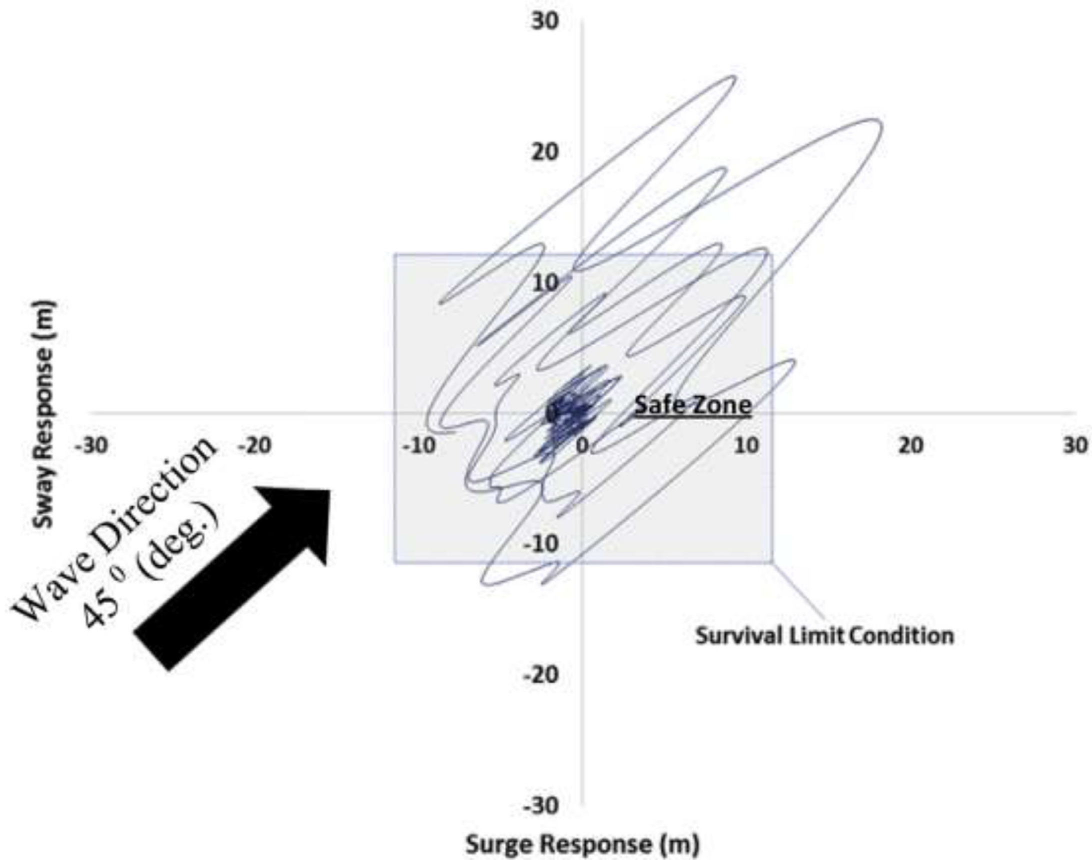

Fig. 1. Trajectories of the Sway and Surge motions during the storm [16].

site dependent, the need to understand their geometry in relation to the dynamic response of the offshore facility (FPSO), in combination with other prevailing harsh environmental factors, calls for further research.

Ice formation and accumulation increase rapidly in extreme wind, wave, and tide conditions and impose additional gravity (load) actions on the offshore structure or drillship [49]. The safety of these facilities is threatened, especially if the vessel is moored and fended. Although safety factors might have been integrated in design consideration, certain off-design environmental impacts may occur, and potential life and operational threat scenarios may occur. Further studies for a better understanding of the ice-structure interaction and prediction are necessary for operation in the remote harsh environment.

3. Floating offshore system operational challenges in remote harsh operations

Ship motion is described by six degrees of freedom (6-DOF), represented by the ship's orientation in the operating environment. These are the roll, pitch, heave, sway, surge, and yaw motions. The environmental factors' prevalence in the harsh environment critically affects the dynamic of the offshore system orientation. This combination poses serious challenges for remote offshore operations.

3.1. Roll motion effects

Roll motion is a critical dynamic of the phenomenon of critical offshore infrastructure and is overexcited by the waves. Swell waves critically affect the dynamic of the drillship during operation because they attack from a different direction. Anundsen [13] shows that the swell wave effect causes heavy rolling of offshore systems and must be considered in design load estimation to ensure the safe operation of the systems. Swells-based roll becomes more critical with a combination of head sea and beam formation and may cause significant roll acceleration that will affect the topside structure, equipment, and subsea systems.

Ross [50] presented a non-linear modeling equation for ship maneuvering analysis in waves using convolution integral formulations of the added mass. This model was able to predict the rolling characteristic of the vessel to a certain degree of accuracy. The weak and strong non-linear sea loads on the offshore system under waves' influence are identified to improve the integral convolution model. He groups the weak and robust non-linear models for hydrodynamic loads as wave-current-body interaction and slamming loads, respectively. High amplitude resulting in roll motion is strongly non-linear and exhibits a high chaotic behavior. Fig. 2 demonstrates the direction of motion of the vessel as she lists from the center of buoyancy, and Fig. 3 is a stability diagram that shows that the roll stability is dependent on the roll angle and is crucial in the design and operation of the floating offshore structure.

The dynamic stability method for a ship's roll motion under waves is built on the restoring moment is detailed in the referenced literature [51]. A more complex formation by applying the Taylor series expansion has been developed from the simple model proposed by Ibrahim and Grace [51]. Lin and Kuang [52] conducted a test for roll-motion prediction using a digital self-consistent ship experimental laboratory (DiSSEL) model. The result shows the effectiveness of roll-damping component accuracy on numerical prediction of its impact. Chakrabarti [53] formulated a model prediction for damping characteristics using the empirical formula. Several improvements to optimize the non-linear damping term in roll modeling have been made using the non-linear polynomial term and random decrement, where the wave excitation takes the Gaussian white noise process. Ibrahim and Grace [51] developed an advanced ship stability prediction model in beam sea analysis. The model revealed that the hydrodynamic roll moments on the vessel are depen-

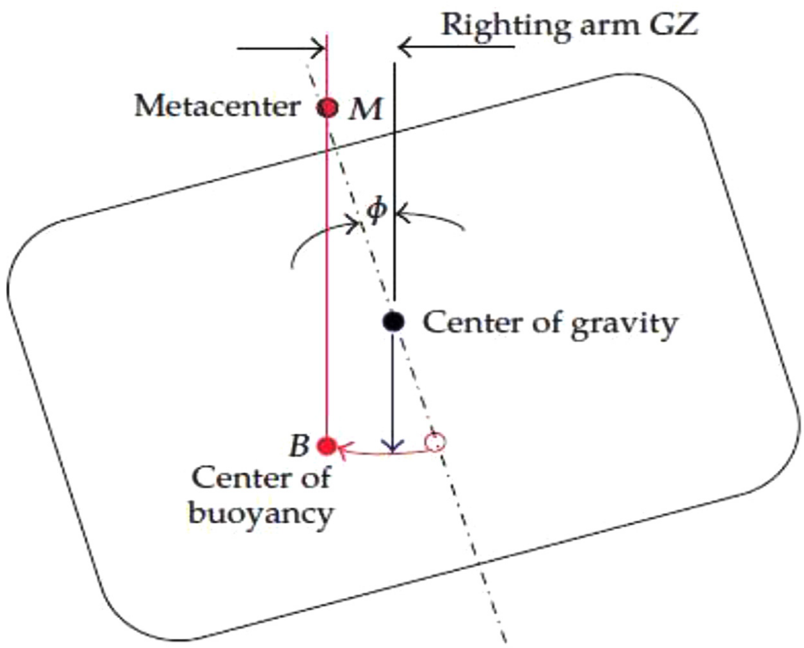

Fig. 2. The Righting Arm.

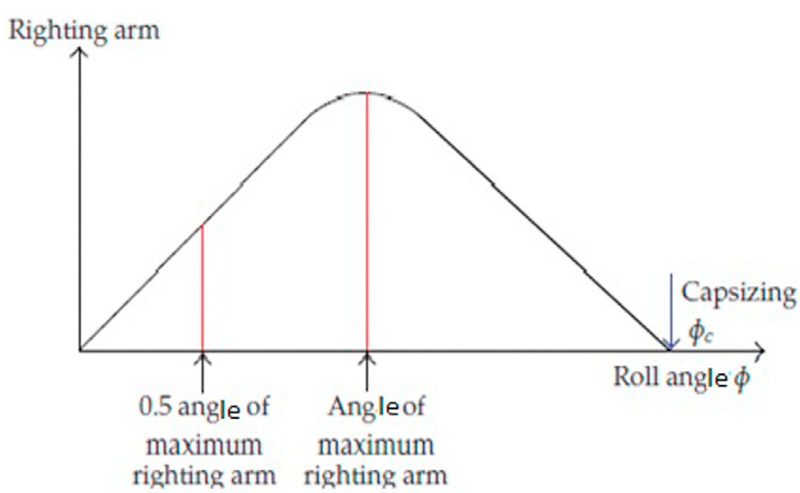

Fig. 3. Dependence of the Righting Arm on the Roll Angle [51].

dent on the relative motion of the vessel and wave. Further methods for identifying linear and non-linear damping and restoring roll parameters were described in the referenced literature [54]. The author presented a combination of random decrement techniques, linear regression, auto- and cross-correlation functions, and artificial neural-network techniques for linear and non-linear parameter identification. He notably predicts the ship rolling effect by an unknown excitation in a realistic sea.

Stochastic and probabilistic models have also been developed to predict the ship's sea wave-induced roll motion. These models can also integrate the pitch equation and represent its coefficient for the restoring moment of the roll motion analysis. Roberts [55], among other researchers, has stochastically analyzed the ship roll prediction using the stochastic averaging methods and obtained the roll angle amplitude. The probabilistic description of random seas helps to predict the upper bound operating envelope against a ship's capsizing by identifying the ship's parameter in roll motion. Different approaches have been adopted, such as path integral techniques [56], stochastic chaotic roll motion techniques [57], quasi-two-degree-of-freedom stochastic model [58], and the successive-transition method [59]. The latter is based on an analytical approximation for the transition probability density. It can account for the damping matrix in its application for a one-dimensional non-linear model.

For safe offshore system operation in random waves, Liu et al. [60] and Liu et al. [61] consider the instantaneous state of the ship and narrowband energy spectrum to solve the non-linear roll differential equation in the time domain. They further integrate the random Melnikov mean-square criterion to determine the threshold intensity for the onset of chaos. The result shows that the ship may undergo a stochastic chaotic motion when the real intensity of white noise exceeds the threshold intensity [61]. In extreme roll formation where the roll angle exceeds 5°, drilling operations are interrupted and even suspended. Yin et al. [62] predicted the ship roll motion during maneuvering using a radial basis function neural network (RBFNN) model. The model showed accuracy in online critical roll angle identification and prediction.

Fu et al. [63] predicted the ship roll motion using the extreme learning machine technique (ELM) to address the uncertainty of traditional time series models. The prediction gave a more accurate result in comparison with another model. Rahaman et al. [64] used a potential flow-based solver to predict ship response in waves. The model was demonstrated on three ship types, and it identified safer ship heading angles for operation, especially for oceangoing vessels. Different probability approaches are needed in determining the upper bound of roll motion. A better understanding of the probabilistic characteristics of the roll motion formation will help offshore system reliability prediction and ensure safe offshore operation in a remote and harsh environment.

3.2. Pitch motion effects

Pitch motion involves the ship lifting at the bow, lowering at the stern, and vice versa and is propagated along the y-axis. The angles of pitch vary with the length of the vessel. They are within the range of 5°–8°. Pitch motion is associated simultaneously with heave and roll motion occurrence. Various researchers have investigated the heave-pitch motion of platforms, both fixed and floating systems. Rho and Choi [65] analyzed the heave-pitch motion of a spar platform and showed that the non-linearity mechanism developed is due to the energy transfer phenomenon between the heave and pitch mode. Most associated instability in the spar platform pitch is caused by heave [66]. That is the coupling effect between the heave and pitch on the spar platform. The coupled non-linear mathematical model was developed by Neves et al. [67] to simulate the coupled heave-roll-pitch motion, and the model is applied to the dynamic stability of a vertical cylinder in regular waves.

Further analysis was presented by Liu et al. [68] based on Mathieu's unstable motion and coupled heave-pitch motions in regular waves. They applied the model to obtain the parameter domain of wave height and the period of unsteady motion. Zhao et al. [69] studied the heave-pitch coupling of the spar platform and revealed that the energy of the heave mode was saturated at a specific wave height, which defined the characteristics of the safe state of the platform. A 1st-order random wave loads model, Morison equation, 2nd-order, and an integrated coupled model were used for the heave-pitch analysis of the spar platforms [70–72].

Advanced non-linear vibration modes were presented by Gavassoni et al. [73] to investigate a spar platform's non-linear dynamic behavior and stability. They were able to predict the structural response under impact. Liu et al. [74] considered the 1st-order and 2nd-order random wave loads and used the frequency-domain wave load transfer functions and JONSWAP spectrum to model the platform's pitch motion. The result shows that the 2nd-order low-frequency wave loads cause an increase in the platform's pitch motion, which shows the contributory effects of wave loads on the offshore structure. This also has a contributory effect, when coupled with a heave, on the safe state of the platform.

Wang et al. [75] analyzed the pitch motion for a new sandglass-type floating body using a control law and pitch inertial effect. They proposed a new design concept that shows better pitch response in extreme sea states. The result shows that there is a decrease in the pitch motion response using sandglass-type floating system. The FPSO operation experiences larger pitch motions in long head waves than in bow waves. Though studies have described the heave-pitch coupled motion effects on offshore structures, a better understanding of the stochastic state of the sea and associated complexity in the harsh environment is critical for safe operation and needs further investigation.

3.3. Sway motion effects

Sway motion is the sideway motion of a ship in maneuvering. It is a translational type of motion influenced by internal and external forces. These forces may result from rudder-hull interaction, propulsor, wind, or sea current. The damping coefficient describes the hydrodynamic interaction involved in sway motion. In an offloading operation, where there is side-to-side interaction with tankers, the hydrodynamic interaction is stronger in the sway direction. Several models predict the sway motion interaction and effects on floating vessels. Ching-Tang and Li-Chen [76] presented a model for real-time motion analysis using the Newton-Euler formulation. This new algorithm could predict the linear interaction of the yaw and sway motions without their combination. In Gatis and Peter [77], surge, sway, and yaw dynamic responses were predicted, and the model was able to simulate complex non-linearity in different ships' applications. Fossen [78] and Chen and Ju [79] predict the sway motion using transfer function models and time-dependent differential equations. In side-side operation, sway drift forces act collinearly in opposite directions. In most cases, this occurs in head wave conditions and is the determinant parameter for the safe design and performance of the floating system.

3.4. Heave motion effects

Heave motion effects on floating vessels or platforms are crucial for the safe operation of such systems. The generation of random waves' loads on board the ship increases the vessel dynamic, as described by the six degrees of motion associated with offshore floating systems. Heave motion of a floating system or drillship is expressed in the vertical plane and vortex-induced in the horizontal plane because of wave impact. A non-linear mechanism defines Heave-resonance associated with the critical state. Tao et al. [80] revealed that the hull form geometry plays a key role in the heave-resonant reduction. A hull shape's geometry increases damping and modulates the natural heave period. This reflects the advances in the structural design of drillships for harsh environment applications.

Li and Ou [81] obtained the heave response Amplitude Operators (RAOs) of a spar platform using the combination of numerical iteration and viscous damping linearization methodology. It shows that the heave response of the system displays a high level of sensitivity to the wave period. High wave formation (increases in wave period) critically increases the heave response of the floating system. Liu et al. [82] show that the heaving amplitude increases significantly with transient wave elevation. Dynamic coupling of moon pool and platform, as presented in [82,83], shows that the heave motions of a truss spar platform were significantly affected by the motions of the water of the moon pool. Several coupling scenarios are necessary to understand the contributing effects of the heave motion configuration on the safe operation of the floating offshore systems in remote and harsh environments.

3.5. Surge motion effects

Surge motion describes the floating ship's linear longitudinal bow and stern motion and is translational. This motion is internally (rudder-hull interaction) or externally (wind or sea current) induced, and it creates hydrodynamic forces on the vessel. It is necessary to understand the phenomenon and its effect on the vessel dynamics in the course of operation. Extreme environmental conditions increase the associated loading impact of the phenomenon on floating offshore systems. Understanding this hydrodynamic force, Fonseca et al. [84] and Guedes et al. [85] proposed a diverse methodology integrating strip theory, Cummin's formulation, Froude Krylov, and hydrostatic model to estimate the vertical motions and global structural loads resulting from the surge motion effect. Determining the surge coefficient help to predict its impact on the vertical loading influence experienced under extreme wave loads. Journée [86] used a semi-empirical method to calculate the surge coefficient, which is also dependent on the vessel configuration. The associated viscous damping is dependent on the frictional resistance characteristics equation. In most cases, coupled motion integrates the surge, heave, and pitch motions to predict the effects on the floating offshore system [87]. This gives an overall coupled effect on the system performance.

3.6. Yaw motion effects

The yaw phenomenon is a mode of ship dynamic (rotation) around the vertical axis. This phenomenon becomes overexcited in a remote and harsh environment. The most associated effect of the yaw is coupled, either with roll or other associated degrees of motion. The coupled effect, especially in the yaw-roll phenomenon, is critical for offshore system safety. Quartering is one of the effects of yaw-roll coupling on ships. Quartering results in dynamic instability (broaching) in the high-speed ship and the ship capsizing. The yaw-roll coupling effect can also result in the dynamic instability of a drilling ship.

Experimental investigation and a three-dimensional model for drillship analysis under wave induced roll-yaw coupling was presented by [88,89]. Their results showed a mutual influence between parametric-roll resonance, bottom slamming, and water-on-deck in the head-sea condition of the drillship. They further defined the angle of 180° as the considering heading angle β and the bow-sea due to roll-yaw coupling at 175°. An experiment conducted by Greco et al. [90] on an FPSO model showed that the effect of water on the deck is reduced when a yaw motion is unrestricted. Although coupled with a roll motion, a high level of excitation promotes instability and affects other associated phenomena like water-on-deck, slamming, etc.

Lopez et al. [91] presented an experimental study of FPSO behavior in the Gulf of Mexico. The analysis shows the effect of yaw as represented by its response amplitudes operator in a beam sea incident wave condition. Although the purpose of the mooring system is to eliminate surge, sway, and yaw, the operation of the drillship suffers surge and yaw-related impact in most cases during tandem offloading operations. This may result in damage to hawsers and spills.

4. Offshore systems risk and safety challenges in harsh Arctic operations

In the past few decades, there has been a range of significant accidents in offshore facilities with severe consequences (fatalities, economic loss, and environmental damages). The accidents of Piper Alpha and the Gulf of Mexico, among other cases, show devastating outcomes, causing the semi-submersible platform's sinking and a helicopter accident. The operating environment plays a contributory role that affects human and system performance in a harsh environment. There are recent models for human error analysis in offshore operations [92–94] and modern safety instrumented systems on offshore facilities, yet the operation is still not safe. Inherent safety [95] has made tremendous achievements by reducing the degree of offshore accidents in terms of installation configuration, layout, and operation.

The extreme harsh environment where catastrophic hurricanes occur, like the Gulf of Mexico, requires a critical analysis of environmental loading on floating and fixed offshore structures at the operational phase. Townsend [96] reported the shipwreck incident because of extreme vessel responses experienced in a harsh environment. Decision making in a critical accident situation is difficult because of the terrain of operation. Researchers have assessed floating structure accidents using several models based on historical data [97–99], yet there is still a high rate of uncertainty in these predictions. In most cases, the unpredicted nature of natural phenomenon occurrence still limits the performance of these frameworks.

Abaei et al. [100] proposed a novel model that integrates the risk estimation and the harsh environmental factors to model onboard crew evacuation plans and a ship operating envelope in extreme storm conditions. They used a numerical model (Endurance Wave Analysis) and Bayesian network in their prediction; see methodology in Table 1. The framework provides a better operational envelope for the floating storage unit in extreme storm conditions. In Abaei et al. [100], several other contributory factors in the harsh environment were not considered. However, to sustain operations and minimize interruption during operations in the harsh environment, further research is needed to develop a design-operational framework that can increase the resilience of the offshore structures in extreme weather conditions and enhance operational sustainability.

4.1. Risk scenario analysis

Offshore support systems operation has associated hazards and risks in a harsh arctic environment that can interrupt drilling activity if not properly managed. Various configurations are available in the different oil fields, and they are expected to meet functional and safety requirements. Many factors influence the performance and safe operation of the FPSO. In most environmentally sensitive areas, waves and other environmental factors significantly affect the vessel's stability. Several risks and failure scenarios have been observed over the years in FPSO operation. Risk management (assessment, prevention, mitigation, and response measures) should be dynamic for holistically safe operation.

The offshore structure/drillship is a complex structure with the primary purpose of drilling, processing, and storing oil and gas products using onboard production processing facilities. Its complexity demands a comprehensive risk modeling framework that will integrate the process facilities (topside), ship, subsea systems, and auxiliary systems. The prevailing hazards arise from the drilling, production, processing, and offloading operations; risk and reliability analysis of the FPSO has been extensively studied over the years. MMS [101] uses a systematic operational safety technique to predict areas in the offshore system that need improvement for safer operation. As reported by Capsey et al. [102] and Amdel et al. [103], risk-based lessons learned for FPSO operation and the FPSO-shuttle tanker interaction, if not managed adequately, result in collision and spill accidents.

4.1.1. Spill (release) risk effects

Several studies on spill or release incidents with FPSO operations and other offshore platforms have been reported in most harsh arctic operations. Ward et al. [104] presented a quantitative risk assessment of subsystem failure and the resulting spill from an FPSO, fixed platform, spar, and tension-leg platform (TLP). The research revealed that though the FPSO poses environmental spill risks, the most contributory spill risk factor is the FPSO-tanker operation, accounting for 63% by volume of the total spills from FPSOs. The Mineral Management Service [101] classified FPSO risk as generic and site-specific, depending on the prevailing sea state, resources sensitivity, structural configurations, vessel shape,

Table 1
Risk assessment methodology for offshore structure under storm [100].

Step 1-Critical Variables	Step 2-Risk Model	Step 3-Decision Analysis
Hydrodynamic Analysis	Probabilistic Analysis	Decision Making
Develop a storm based on EWA	Define/categorize probability distribution of different sea states and storm	Determine the crew optimum action in different storm conditions
Floating system encounters hydrodynamic storm modeling	Find appropriate probability density function for the critical response of the floating object	Employ advanced probabilistic techniques such as BN and ID in decision making
Computational cost minimization during storm simulation	Develop a BN for failure analysis Inference diagram (ID) development	

and other factors. Hazard identification and probabilistic risk analysis methodology are presented by [105] for modeling oil spills from FPSOs in the Gulf of Mexico (GoM). The frequency and consequences modeling were evaluated using fault and event trees. They also categorized different hazard sources for offshore oil release by volume.

Regg et al. [106] summarize offtake incidents reports and spills due to loading and offloading FPSO operations in a harsh sea environment (North Sea). Metzger et al. [107] present an overview of the associated risk of FPSO performance relative to the environment. They expatiate the various failure modes in detail and suggest a robust risk management system that integrates strong FPSO design and best operational practices. Lončar et al. [108] proposed a numerical model for oil spill risk analysis in the northern Adriatic. The model was applied to a hypothetical case study to predict the dispersive transport phenomenon of oil sea pollution. Li et al. [109] presented a fuzzy comprehensive evaluation mode for oil spill risk analysis. They applied the model to a port-based tank and were able to establish a risk level and management procedure.

Blvd [110] and Anderson et al. [111] presented an updated spill from different platforms (floating and fixed) and identified causal factors for equipment failure, human error, weather/natural disaster, and other external factors. Couples of causal factors can initiate offshore system-related releases. These associated spill risks in floating offshore systems and auxiliaries' systems within the remote and harsh environment are rooted in riser leaks, topside process releases, cargo tank leaks, swivel leaks, cargo pipe leaks, and structural failure in extreme weather. Several leak (gas, liquid, or two-phase release) scenarios are associated with drillship (FPSO) operation for 15 years, and the classification of major, significant, and minor based conditions are detailed in [112]. In most cases, a large spill or release size is frequently caused by natural disasters and harsh weather conditions in floating offshore system related release scenarios.

4.1.2. Collision and offloading risk effects

Collision scenarios and related marine risk consequences from FPSO operations are presented in [113]. The common risk scenario that occurs between an FPSO and an off-take shuttle tanker is a collision. Vinnem et al. [114] use risk influencing factors to model the collision frequency of shuttle tankers and FPSOs during offloading operations. They identify that human and organizational factors are key elements for such an operation. The risk influencing factors (RIF), as presented by Vinnem et al. [114], are static states that represent an average level of some prevailing conditions during operation. They are grouped into (1). Operational RIFs describe the shuttle tanker's safe and efficient loading operation and FPSO offloading operations, (2). Organizational (Managerial) RIFs describe the control and management framework of the operation, and (3). Regulatory RIFs describe requirements and guidelines for operational monitoring and compliance. Similarly, Wang et al. [115] show that collision in ships generally is affected by a number of factors that must be integrated for a holistic collision modeling, especially in structural response assessment. Different scenarios associated with the FPSO-shuttle tanker collision incident are shown in Vinnem [116], which he refers to as the risk influence diagram.

The combination of human (operational) and technical failure gives a more significant contribution of about 40% of total collision risk. Moan et al. [117] present a collision risk analysis of an FPSO-shuttle tanker in structural failure, sinking, or capsizing. They use the accidental limit state (ALS), which gives a prescriptive or semi-prescriptive analysis of the accident scenario. The ALS approach uses external and internal mechanics processes. The safety assessment of the FPSO considering the failure modes with respect to stability, structural strength, and positioning could predict the survival limit in accident conditions through ultimate fatigue strength or ALS. This gives a design check on the structure to resist abnormal effects (fire, explosion collision) and its response to resist specified environmental conditions without extensive failure (total collapse), especially when there is a high annual sea state probability of exceedance.

A new 2D and 3D formulation have been presented in the literature. Liu and Amdahl [118] present an energy dissipation model that utilizes the strain energy concept. Their formulation focuses on the external mechanics and impact analysis and is also applied to ship-iceberg collision modeling. The ship-iceberg collision assessment is done considering a non-vertical contact surface of the ship, and the mass of the iceberg is modeled empirically. Different impact angles are modeled and predicted the energy dissipated due to the iceberg collision scenario.

Chen [119] describes the tanker drive-off initiation during tandem offloading as a complex human-machine interaction (HMI). Tandem offloading is a complex and complicated marine operation and demands a highly safe procedure. To better understand the accident scenario associated with tandem offloading in a harsh environment, Chen [119] categorized its finding from the human-caused mode of the incident and near misses as initiating action, response action, and latent action. He developed a human error-based probabilistic model for a shuttle tanker. Excessive surging and yawing motions from environmental constraints affect the offloading operations. In excessive yaw motion, heading deviation from the tanker vessel could result in position reference signal loss between the FPSO and the shuttle tanker [119]. In such a situation, the dynamic positioning inappropriateness and other technical failures result in drive-off collision accidents [120]. Rodriguez et al. [121] presented a cause-consequence model that identifies a physical condition that describes hazardous events in offloading operations. The hazardous events identified are classified based on their stage of occurrence. They adopt a qualitative assessment, establish the possibility, and set mitigation for the hazard event occurrence.

Recent approaches for risk analysis in the three operational phases of FPSO offloading are presented in the literature [122–126]. The models cover areas of quantitative risk analysis, qualitative risk analysis, and dynamic models. Vinnem et al. [127] present an updated report on the last decade's risk analysis and present online decision support models for FPSO-shuttle tanker collision risk reduction. This is expected to integrate and handle data uncertainty and measure, simulate and generate probabilistic risk information. This integrated framework provides decision making aid in safety-critical deep offshore and harsh environment operations. Although the model presents a prospective application, uncertainty, the human factor and extreme environmental scenario still pose interruption and economic risk in offshore operations.

4.1.3. Topside systems risk effects

The drillship configurations are structured into different units with specific functions and operations. Risers connected to the FPSO transmit production fluids from the subsea oil reservoirs, and the fluids are separated using topside facilities (Fig. 4). The topside facilities include oil treatment (filtering, oil separation, oil storage), gas treatment (gas compression, dehydration, well injection, equipment fuelling), and water treatment (filtration and processing, sea discharge, well injection). Other auxiliary systems include electrical power systems, flaring systems, firefighting equipment, the inert gas system, freshwater systems/accommodation support and fuel, lubrication, greasing systems, etc. The operation of these facilities has associated hazards and risks that affect the entire vessel and interrupt the drilling operation if not adequately managed. System failures, leaks, overflow, and release are common topside risk scenarios that are also critical to the safe operation of the drillship. Generally, risk analysis is grouped into qualitative, quantitative, and dynamic risk analysis frameworks.

Several qualitative tools have been adopted for offshore process risk assessment, such as hazard identification (HAZID), hazard and operability (HAZOP), what-if-analysis, structured what-if-technique (SWIFT), cause and effect diagrams, checklist, strength, weakness, opportunities and threats (SWOT), failure mode and effects analysis (FMEA) [129]. These techniques, in general, are checklists used to identify and examine potential hazards and risks as well as their causes and associated consequences. These provide information for design, maintainability, safety, reliability, probability, and availability analysis for engineering systems.

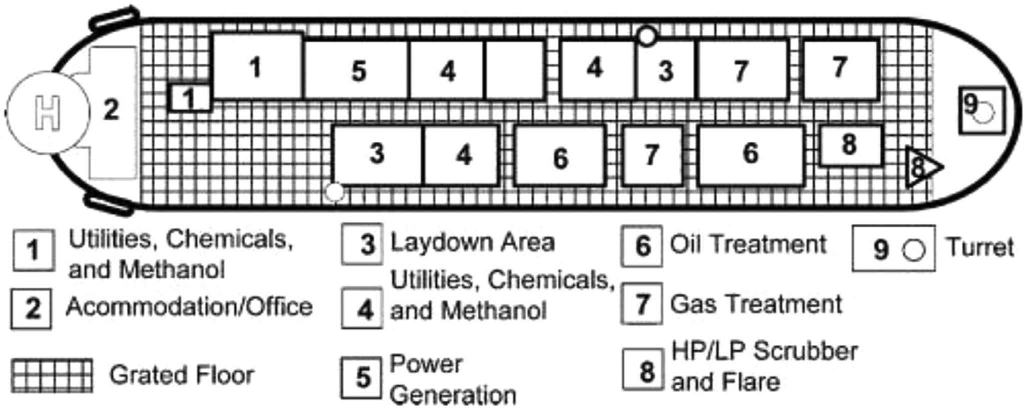

Fig. 4. Typical FPSO Modules Layout [128].

Several terms are adopted to describe the individual approaches based on the areas of applications.

Quantitative risk models for the offshore industry have tremendously improved over the years. The quantitative models integrate risk identification, ranking, prioritization, consequences, and corrective (precautionary) measures. An overview of the process risk and accident models can be found in [130]. They presented a distinguished comparison of the various models and the most promising offshore accident modeling technique. They presented a framework for comparison of the quantitative risk analysis and the dynamic risk analysis (DRA) strategies.

The capacity of the DRA to include an updated probability of failure of safety systems make it most promising for a dynamic risk scenario. The Bayesian network (BN) is one of the DRA tools that has been extensively used in risk and safety engineering because of its capability to assess scenarios involving dependability, probability prediction, and conditional probability formation [131–134]. Advanced configuration through hybridization of BN has been proposed as seen in the Dynamic Bayesian Network (DBN) [135] for military application, Bow-tie BN framework [136] for offshore application, the Fuzzy BN approach and the Hybrid BN approach [94, 137,138,139] for marine system application. Other DRA frameworks, configurations, and applications in the offshore and process industry, such as the SHIPP models, are detailed in [130–144].

Accident scenarios have associated consequences in offshore process operations. For process operation, common consequences can be classified as an explosion, fire, and toxic release [145] and for marine (offshore) operation, like collision, foundering, grounding, stranding, capsizing (loss), fire, and explosion [146]. Several consequences modeling techniques have been proposed over the years for offshore process-related operations, ranging from source modeling to impact modeling [147,148].

Several topside fire models have also been developed. Some are cited in [149], where a quantitative risk assessment of gas explosion was carried out on the topside of an offshore platform using a flame acceleration simulator. They were able to assess the hydrocarbon leak risk and various fire consequences due to an accident scenario. Suardin et al. [128] presented a model for comparative analysis of fire and explosion on FPSO topside operations. The model gave an overview and showed consequences assessment capability with expert systems to identify areas for control recovery measures. Dan et al. [150] present a quantitative consequences-based risk analysis of the LNG Liquefaction process (DMR cycle) on an FPSO using PHAST. The model was applied to an optimization DMR cycle process of an LNG FPSO, possible leaks scenarios were identified, and subsequent fire and explosion scenarios were modeled. The authors were able to establish that for the topside operation, jet fire, explosion, and flash fire are the possible accidents in releases due to possible leaks.

Jin and Jang [151] presented a probabilistic-based fire risk analysis model for the topside of an FPSO. The proposed model was developed to solve the common challenges of applying accidental design loads [112] to fire-based structural consequence analysis. The model was demonstrated on the FPSO separation modules and was able to present a cumulative failure frequency of the topside structure, and was useful in determining the minimum passive fire protection application area. Jin et al. [152] proposed a quantitative-probabilistic fire risk assessment model that integrates possible scenarios of hazard identification and their probabilities with CFD-based simulation. For a release scenario, the model was demonstrated the safety of the topside structure (living quarters) on a semi-drilling rig system. The model predicted the damages and temperature distribution and contours because of the release scenario.

Baalisampang et al. [153] present a CFD model for fire modeling of floating LNG process facilities. The model was demonstrated on the topside facilities for an LNG spill due to leakage or tank overfilling. The result shows that the consequences are fatal for humans, causing catastrophic failure on structures and equipment damage. High severity of impact was observed in the mixed refrigerant module of the liquefaction process plant. An integrated, highly sensitive, and proactive risk model that will measure and comply with resilience system design is needed to promote performance optimization of these systems and minimize frequent interruption in remote and harsh offshore operations.

4.1.4. Drilling risk effects

The drilling operation process is prone to high risk in remote and harsh environments. The most critical drilling risky scenario is a blowout. Geuns [154] identified blowout as a critical accident scenario in an extreme (arctic) environment. Several concepts for blowout occurrence in offshore operations have been presented [154–158]. Abimbola et al. [159] presented blowout risk analysis for drilling operations using bow-tie analysis. Abimbola and Khan [160] and Bergan [158] explained various risk consequences of blowout occurrence. In the remote and harsh environment, the drilling operation is prone to frequent well-control subsystems' failures that may result in release, fire, explosion, and blowout. Recent models use various techniques to predict and mitigate system failures in a harsh environment. The dynamics of the remote and harsh environment require continuous research to understand better the best safely prediction in offshore drilling operations in this terrain.

4.2. Reliability and integrity challenges

The remote and harsh environment has been described as characterized by extreme ice features, wind, waves, and storms. These environments have posed a dangerous threat due to extreme and complex structural degradation that is unpredictable because of the dynamic nature of its elements. The reliability and integrity of structures and equipment operating in this terrain are critically threatened, and the need to understand these risk factors for oil and gas exploration is necessary. The impacts of these environmental factors cause failures of the offshore systems and lead to financial losses through frequent interruption, system shutdown, and maintenance. As discussed earlier under risk analysis in an offshore environment, the qualitative tools mentioned are applicable for such systems' reliability analysis (RAs).

Several analytical probabilistic models, such as FORM, SORM, and reliability-based design optimization (RBDO), have been applied to model different assets' reliability in the oil and gas industry [161]. The merits of this reliability technique over a range of floating structures with several failure modes are outlined in [162]. Although insufficient data, missing data, and insufficient data are still significant issues in comprehensive reliability analysis of critical offshore infrastructure in the remote and harsh environment, expert systems' integration can help in data assessment and accuracy [129]. Therefore, a dynamic and holistic approach with expert domain application needs critical attention to solve the present challenges in harsh environment operations. Abaei et al. [94] used BN for moored floating system reliability and integrated the hydrodynamic response into the modeling structure. The model shows promise in risk mitigation prediction for offshore systems.

Integrity challenges in this environment, such as degradation resulting from corrosion and cracks, are still a critical concern for the operator in the industry. Thodi et al. [163,164] presented a risked-based integrity model to predict environmentally induced defects in the process and offshore structure. The authors used a sampling-based Metropolis-Hastings (M-H) algorithm and demonstrated the framework for asset degradation mechanisms in process plants. This framework makes a useful prediction, considering the uncertainty for corrosion and crack profile over time, and assesses cost-based implications of the system's degradation in the harsh environment. Winterization is a crucial phenomenon associated with harsh environment operations where low-temperature matters, and continuous research is needed for better prediction.

4.2.1. Hull structural failures

Extreme wave formation with critical wave height and period are experienced in a harsh environment. These wave-impact related loads (slamming) cause stress impact on offshore structures and can result in deformation of the structural components. In such systems' design and operation phase, a better understanding of the environmental load's impact is critical. The development in the shipping industry has also promoted advanced methodology to predict structural response to slamming impacts. This impact sets the ship hull into a vibratory response. Slamming related impacts are presented in [165]. Ramos and Soares [166] predicted the stresses induced on ships' forms due to wave impact. They used finite element methods to model the response by modal superposition. They were able to predict the associated slam-based vertical bending moment across the vessel's length and the place of maximum effect.

The ship hull's strength, loading, and bending effect is holistic, and in practice, the mean longitudinal bending effect is highest near the midship. So, in most analyses, the vessel is treated as a single beam and the strength is analyzed longitudinally using the Euler-Bernoulli model. Sagging and hogging are prevailing conditions that could be critically analyzed when the hull plating is slamming. However, Wang et al. [167] revealed that the vessel experiences more significant slam induced relative vertical motions at the fore than near midship in the head sea. Wang et al. [168] further analyzed the hydroelastic responses of horizontal elastic hull plates and discovered that the slam-induced impact could also affect the bottom form of the ship.

In the harsh arctic environment, the ship hull suffers ice load either from collision or accumulation on floating structures. The collision of the iceberg with offshore structures is an alarming experience and needs to be evaluated. Haris and Amdahl [169] presented the analysis of the ice-ship collision effect at midship (hull). The mid-region of the ship's structural integrity is very important for the safety of life and goods, especially if a fracture occurs after the collision. To understand the ice-hull collision impact, structural behavior, and critical scenarios [170,171], presented different loadings on the critical part of the ship, such as the fore mid-ship and aft end. The ship's hull form is made of steel and the mechanical characteristic of steel after collision changes in a low-temperature environment [172]. Based on the energy conservation approach, Bae et al. [173] proposed a numerical simulation model for hull-ice collision modeling. More research is needed to better understand the structural susceptibility to harsh environments. This environment critically affects the reliability and integrity of the structures and causes catastrophic failures.

4.2.2. Riser system failures

In most subsea systems, corrosion fatigue is a critical factor that affects performance and causes such systems' failure. Mainly in the riser system, a couple of serious shortcomings were caused by corrosion of the armor wires in the top section near the splash zone or above sea level [174], common in remote and harsh environments. The most consequential failure factor is a damaged outer sheath due to a breach. The performance analysis of the riser system, especially in the harsh environment that demands new technology, new material, and new design, introduces a new failure scenario that is not common to any other terrain [175].

The global analysis for riser performance is used for sensitivity and calibration checks related to flexible subsea systems [176]. It collates the external environment conditions for fatigue loading. This external environmental impact increases and exhibits the worst unpredicted scenario in remote and harsh environments. Although design considerations may have inculcated safety factors, this system will suffer a setback and fail at certain abnormal sea states. The interconnectivity with the pipeline may also be set in pipe-related tension and bending, which may reduce the angular motions relative to an interface of bending curvature or moment [174]. The local fatigue analysis converts the global loading at selected hotspots to stress in the armor wires and can affect the integrity of the riser.

4.2.3. Mooring line failures

The mooring system provides stability for the vessels in deep water operation. There are different types of mooring systems that are commonly used, such as catenary, semi-taut and taut. In the harsh environment, the mooring systems experience unstable behavior due to the extreme wave effect on the drillship and the ship dynamics [177]. Several models have been used to analyze moored system stability in rough weather conditions. For flexible and deep-water operation, the single point mooring system is used for permanently mooring in a critical, harsh environment.

The mooring systems exhibit instability and fishtailing motion types in such an environment. Lee and Choi [178] and Aghamohammadi and Thompson [179] discussed the fishtailing motion of the mooring system under impact and revealed that the motion arises from the asymmetry in the restoring force matrix. The asymmetry may be caused by mooring stiffness and fluid loading interaction. Also, there is high nonlinearity in turret mooring, which causes instability or chaotic responses in operations. For viscous flow-related terms, the yaw motion moment on the mooring system can be modeled using the relation proposed by [178].

Mooring line dynamics become complicated in rough weather conditions and are mostly analyzed relative to the drillship response in such a sea state. Large amplitude wave frequency motions and viscous flow-related hydrodynamic effects contribute to the mooring dynamic and instability, and the reliability of the mooring systems will be affected over time. The research of [179,180], shows that in large amplitude unstable sea states, the mooring system was unable to keep the drillship on the station; the state of instability increases with time-dependent varying loads. Therefore, Paton et al. [177] evaluated the unstable behavior of mooring lines based on time-varying loads and suggested that this should be accounted for in the stability modeling of mooring systems for harsh environment operation.

Mousavi [181] uses Monte Carlo simulation to predict the failure probability of mooring systems. In his analysis, the mooring system sub-components failure is time-dependent (that is, one failure at a time), which defines their sub-component functionality. Mousavi et al. [182] further use a progressive reliability method to quantify the reliability of a mooring system under sea loading impact and compare it with that of the Monte Carlo simulation. The model was able to predict the failure probability of the system and its sub-components., especially for a serviceable mooring type. The report of [183] shows the failure trend of mooring systems of mobile offshore drilling systems in the harsh environment. The cases presented were in the harsh North Sea environment. The result revealed a tendency for a high failure rate of mooring systems in such an environment. The need to understand and develop integrated models that can predict such a system's safety in extreme sea states requires further work.

4.2.4. Umbilical system failures

The umbilical is part of subsea systems that are grouped under flexible pipes. It provides power and control (electricity, hydraulic power, chemical injection) to the subsea oil and gas equipment [12]. The performance of the umbilical is condition-based. Therefore, the remote and harsh environment presents an abnormal scenario because of environmental and accidental loads. The umbilical system is prone to vortex-induced vibration in the steady current condition and worsens in harsh environment operation [12,184]. This scenario increases the failure mode of the umbilical system.

Global loading analysis is used to predict the dynamic and non-linear effects of the environmental impact on the umbilical. The study indicates the displacement and stress results (axial force, bending, and torsional moment) along the umbilical's length. It is necessary to integrate fatigue life determination into the stress models for holistic analysis, especially in a harsh environment where loading impact is sometimes unpredictable. Also, under extreme wave conditions, vessel motion causes the umbilical to move in different directions and the touchdown zone to vary in time. Fatigue damage sets in due to the seafloor restraints and can result in total failure.

4.2.5. Human failures

The drilling operation in remote and harsh environments significantly increases occupational risk. According to [185,186], slips, trips, and falls from heights are common events that result in injuries in harsh environment operations. The operating environment is characterized by strong wind and ice loads which affect vessel motion and create a deteriorating working condition. Safety and production performance are essential aspects of offshore drilling investment, which are associated with many uncertainties in remote and harsh environments due to prevailing human failures.

The Arctic environmental condition is characterized by extreme cold, darkness, and isolation, creating difficult working conditions for crew operations [3]. The operational and logistics challenges include limited oilfield support infrastructure, operation complexity, sparse offset data, strong ocean currents, and a lack of real operational data for risk analysis [187,188]. Recent studies by Deacon et al. [189] show a significant difference between relative human error probabilities in cold and normal conditions and the importance of the effect of cold temperature on human performance. There are associated health-related challenges in the remote environment that critically affect personal performance. Some are highlighted in the literature. Occupational safety mainly relates to personal safety, and the focus is on the prevention and mitigation of hazards that could result in health issues (e.g., slips, trips, and falls).

Winterization is a phenomenon that characterizes the harsh arctic environment, which greatly affects human performance if not adequate. Yang et al. [190] proposed a risk-based winterization technique to predict an onboard crew ship's operational envelope. In remote harsh environments, the relationship between these two areas of safety is stronger than that in normal climatic conditions, and one may lead to the other. Further work was presented by Ratnayake [191] on winterization integrity management. The author used a fuzzy-based approach to minimize the variability of the associated winterization risk in offshore operations. Research awareness of winterization integrity-based management is evolving, and more dynamic models that can integrate a robust critical element require further work.

4.3. Logistics challenges

Logistics and the supply chain are vital parts of an offshore drilling operation. Transport of drilling facilities, installation, construction, and production involve a series of logistic services. The offshore operation involves heavy lifting operations, such as positioning rig structures, subsea installations, and offloading, which are greatly affected in remote and harsh environments. Although the remote and harsh environment operation is still underdeveloped and there are limited infrastructures that can enhance stress-free oil and gas operation, there is no developed network connection in terms of communication and seaports' infrastructure [188]. Communication and response infrastructures are critical for safe offshore operations in remote and harsh environments [192]. There are restrictive laws and environmental sensitivity in remote and harsh arctic environments. Due to the lack of highly effective emergency infrastructure, limited oil spill contingency measures pose a threat to oil and gas development in this region [9,193]. Weather infrastructure that enhances weather predictions is rare in most this region. Especially for adequate weather prediction, we need robust weather infrastructure that is technologically sophisticated to account for every hidden detail of the weather at all sea states. Indeed, the available technology cannot accurately predict the size, location, and strength of polar low pressure when it is building up [194]. The region in question is complex and problematic, affecting logistics and supply chain planning.

The costs of the drilling, operation, and logistics in a harsh environment are expressed in non-linearity with the operation; cost increases exponentially, and the investment risk also increases significantly. The challenges faced are significant and complex: from the rig to the deepest section of the well. Long distances to the market and suppliers introduce significant transport logistics and cost problems. In this situation, service and spare parts delivery takes more time, affecting the prompt repair of the breakdown facility. The long distance to the market, combined with the climate condition and lack of suitable infrastructure, can lead to unacceptable downtime in the production process and return on investment [3]. The harsh environment creates the need for special logistic and maintenance strategies that can overcome the problems. The Arctic (harsh) environment is characterized by freezing temperatures. Research showed that an annual minimum temperature of −39 °C to −20 °C can be experienced in the northern part of the Barents Sea [195]. Offshore operations at such temperatures will be affected, and marine icing will affect the offshore facility. Dominant causative factors are high air humidity, cold rain, accumulation of dense fog, sea spray, and cold temperatures [196,197]. Fog formation affects the visibility, which restricts ship and helicopter support service for some periods of the year. This results in logistics challenges that will affect the offshore drilling operations and increase the running cost of the project's production phase.

Remoteness and lack of highly sensitive infrastructures affect emergency oil-spill and logistics responses [198]. No real-time model has been developed to predict the logistics profile and economic risk due to interruption and the environmental constraints in a remote and harsh environment. However, capacity optimization of the FPSO/drillship is an evolving concept that most of the oil and gas companies are exploring as one of the options. The larger drillship will provide more storage

Table 2
State of knowledge of challenges in remote and harsh Arctic environment offshore operations.

Challenges	Sub-categorization	Current state	Importance to offshore operation in remote & harsh environment	Recommendation
Environmental	Wind loads	Models exist for wind load prediction but are site specific	Most important for offshore reliability	Continuous research for a generalized model for an improved wind loads prediction
	Waves loads	Limited models exist for extreme scenario	Critical for safe operation	Robust generic models for real-time higher significant wave height and wavelength ratio(λ/L) are required to improve the current models
	Ice loads	Limited models exist for moored structure prediction	Most important for remote arctic environment	More studies are required to understand ice geometry and impact characteristics better
	Current and storm	Limited models exist for structural response in storm	Most necessary for offshore system stability prediction	Continuous research is needed to improve the current models
Offshore system dynamics	Roll motion effects	Current models exist for structural dynamic response with uncertainty	Most critical in offshore system structural dynamic response	Continuous research to improve existing models and minimize uncertainty
	Pitch motion effects	New model proposed for design optimization and position	Important for position reference in operations	Improvement required for a generalized application
	Heave motion effects	Limited models exist for harsh operation prediction	Critical in dynamic response that defines operational stability	Continuous research to better understand the complexity of most critical scenarios
	Yaw, sway, surge effects	Limited models exist that predict effect minimization	Most important in the tandem offloading operation	More study required to improve the current models
Offshore system risk/safety	Spill risk	No holistic model exists for remote harsh environment	Most important for environmental policy compliance	The development of a robust terrain specific algorithm is necessary
	Collision risk	Accident limit state and collision models exist	Critical in offloading and logistic operation	More study is required for the development of an integrated dynamic model
	Topside/production risk	Current qualitative, dynamic, and consequences models exist	Critical in the support and subsystems operations	Continuous research to understand critical causative factors and improve the current model's framework
	Drilling/blowout risk	Current models exist	Most critical in safe drilling operation	Continuous research is needed to meet the dynamic terrain
	Operational reliability/integrity risk	Limited models exist but not adequate	Critical for safe and sustainable operation in the remote harsh environment	More studies are required to better understand the dynamic in reliability and integrity management in remote harsh environment
	Economic risk	No holistic model exists for remote harsh environment operational interruption prediction	Critical for investment and operational sustainability decision making	The development of a robust dynamic terrain specific model is necessary
Logistics	Shipping	No model for routing and supply chain prediction in remote harsh environment	Most critical for sustainable operation (repairs, spare parts, maintenance, etc.) and emergency response	More studies are required to develop a holistic logistic flow model for the remote arctic operations
	Air(helicopter)	Limited framework for air logistic support prediction	Most critical for sustainable operation (personnel, supply, etc.) and emergency response	The development of an integrated dynamic model is necessary

compartments for goods and support materials needed for the period of operation. The concepts have their associated cost and limited application in case of critical facilities' failures.

5. Knowledge gaps and research opportunities

The characterization of remote and harsh environments is complex and evolving, limiting offshore infrastructure performance and making failure predictions difficult. Though several models have been proposed for application in offshore systems risk and safety modeling during drilling operations in remote harsh environments, most of the models are site specific with a high level of uncertainty. Their inability to accurately predict multicriteria influences in each time domain is still a challenge. Although the dynamic structural models for moored-offshore systems provide accurate reliability, the system under critical impact still needs further research. The reviewed operational risk models are not dynamically structured to capture influential factors' interdependency (see Table 2). There is a need to develop an intertwined design for safety to integrate the multiple dimensional risk factors during operations in remote arctic offshore environments.

The following provides an extended research frontier to improve operational sustainability in remote and harsh offshore operations:

- Development and adoption of data digitalization and IoT for marine system design and operations
- Development of resilience infrastructure for optimum survivability in harsh arctic environments
- Development of optimization tools through data mining and smart system for risk management
- Advanced design and material characterization via machine learning algorithms for remote arctic operations

6. Conclusions

This paper presents the state-of-the-art of offshore system operational challenges in remote and harsh environments. An assessment to understand the state of operations and system dynamics in remote and harsh environment operations has been presented. The review shows that the remote and harsh operating environment faces serious challenges, and technological development is still evolving to minimize operational interruption. From the study, the initial challenges are grouped thus:(1) Environmental factors, (2) offshore structural dynamics, (3) operational risk and safety, (4) logistics challenges. The environmental constraints are waves, wind, currents, storms, and ice phenomena that interrupt operation. The environmental constraints affect the offshore systems' dynamics and stability, causing risky operations. The operation in remote and harsh environments is strongly dependent on the environmental constraint and offshore systems responses. This dependability affects the work and logistical services, causing an interruption. In terms of operation and economic resources, risk measurement is also critical in remote and harsh environments. The drilling, production, and logistics operations are time-bound because of the terrain. This affects the investment recovery plan. Summarized areas of concern, such as structural design and response prediction of a modern drillship and semi-submersible platforms, are presented.

Logistics and supply chain planning and prediction are still a challenge because of the lack of accurate data and meteorological uncertainties. An innovative model development that can integrate logistics risk prediction in the remote harsh environment is necessary. Several other risks and consequences models for operational analysis in a remote harsh environment are unable to capture the likely interdependencies and instability in influential parameters. For economic risk prediction due to interruption, a dynamic risk framework that is time and space-dependent is needed for a holistic analysis of drilling operations in the remote harsh arctic environment. Table 2 in section 5 summarizes the challenges of remote harsh environment operation, recent research contributions and recommendations for future work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] P. Wang, X. Tian, T. Peng, Y. Luo, A review of the state-of-the-art developments in the field monitoring of offshore structures, Ocean Eng. 147 (October 2017) 148–164 2018, doi:10.1016/j.oceaneng.2017.10.014.

[2] Y. Du, W. Wu, Y. Wang, and Q. Yue, Prototype data analysis on Lh11-1 semisubmersible platform in South China Sea OMAE2014-24610, pp. 1–8, 2014.

[3] A. Barabadi, M. Naseri, R.M.C. Ratnayake, Design for arctic conditions: safety and performance issues, in: Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE2013-10287, 2013, pp. 1–10.

[4] F. Khan, G. Reniers, V. Cozzani, Special Issue: safety and integrity in harsh environments, Saf. Sci. 95 (2017) 148–149, doi:10.1016/j.ssci.2017.03.008.

[5] A. Wassink, Development of solutions for Arctic offshore drilling, *SPE Arct. Extrem. Environ. Conf. Exhib. Moscow, Russ.* 15–17 Oct. 2013 (2013) 1–12 October, doi:10.2118/166848-MS.

[6] J.R. Hasle, U. Kjellén, O. Haugerud, Decision on oil and gas exploration in an Arctic area: case study from the Norwegian Barents Sea, Saf. Sci. 47 (6) (2009) 832–842, doi:10.1016/j.ssci.2008.10.019.

[7] J. Krüger, Operations and maintenance of oil and gas platforms under Arctic conditions, Master Thesis University of Stavanger, Norway, 2013.

[8] S. Løset, Science and technology for exploitation of oil and gas - an environmental challenge, Eur. Netw. Conf. Res. North (1995) 12–16 December.

[9] T. Szelangiewicz, B. Wisniewski, K. Zelazny, The influence of wind, wave and loading condition on total resistance and speed of the vessel, Polish Marit. Res. 21 (3) (2014) 61–67, doi:10.2478/pomr-2014-0031.

[10] R. Zangeneh, K.P. Thiagarajan, and M. Cameron, OMAE2017-62134, pp. 1–7, 2017.

[11] N.D.P. Barltrop and A.J. Adams, Dynamics of fixed marine structures, vol. 1, p. 764 pp, 1991, doi:10.1016/B978-0-7506-1046-9.50011-0.

[12] S. Yasseri and B. Wang, Extreme response of dynamic umbilicals in random sea extreme response of dynamic umbilicals in random sea, no. June 2014, 2015.

[13] T. Anundsen, "Operability comparison of three ultra-deepwater and harsh environment drilling vessels," p. 106, 2008, [Online]. Available: https://brage.bibsys.no/xmlui/bitstream/handle/11250/182649/Anundsen%2CThorgeir.pdf?sequence=1.

[14] G.Z. Forristall, K. Ewans, M. Olagnon, and M. Prevosto, The West Africa Swell Project (WASP), 2013.

[15] M. Zeinoddini, H.Matin Nikoo, H. Estekanchi, Endurance Wave Analysis (EWA) and its application for assessment of offshore structures under extreme waves, Appl. Ocean Res. 37 (2012) 98–110, doi:10.1016/j.apor.2012.04.003.

[16] M.M. Abaei, E. Arzaghi, R. Abbassi, V. Garaniya, S. Chai, A novel approach to safety analysis of floating structures experiencing storm, Ocean Eng. 150 (2017) 397–403 November 2017, doi:10.1016/j.oceaneng.2017.12.011.

[17] H. Riahi, H.T. Estekanchi, Seismic assessment of steel frames with the endurance time method, J. Constr. Steel Res 66 (6) (2010) 780–792.

[18] M.A.D. Diznab, S. Mohajernassab, M.S. Seif, M.R. Tabeshpour, H. Mehdigholi, Assessment of offshore structures under extreme wave conditions by modified endurance wave analysis, Mar. Struct. 39 (2014) 50–59.

[19] V. Jahanmard, M.A.D. Diznab, H. Mehdigholi, M.R. Tabeshpour, S.M. Seif, Performance-based assessment of steel jacket platforms by wave endurance time method, Ships Offshore Struct. (2015) 1–11.

[20] ISSC 2015, ISSC 2015 Committee I.1 Environment Report, 2015.

[21] ISSC, ISSC 2012 Committee I.1 Environment Report, 2012.

[22] A. Osborne, Classification of rogue wave solutions of the nonlinear Schroedinger equation, EGU Gen. Assem. Geophys. Res. 2 (2013) NH5Vie.

[23] C. Onorato, M. Osborne, A. Serio, M. Cavaleri, L. Brandini, C. Stansberg, Extreme waves, modulational instability and second order theory: wave flume experiments on irregular waves, Eur. J. Mech. B Fluids 25 (2022) 86–601.

[24] S. Mohajernassab, M.A.D. Diznab, H. Mehdigholi, M.S. Seif, M.R. Tabeshpour, Modification of endurance wave analysis based on New-wave theory, Ships Offshore Struct. 12 (3) (2017) 330–340, doi:10.1080/17445302.2016.1149319.

[25] S.S. Denchfield, D.A. Hudson, P. Temarel, W. Bateman, and S.E. Hirdaris, Evaluation of rogue wave induced loads using 2D hydro-elasticity analysis, 2009.

[26] S. Enderami, M. Zeinoddini, N. Shabakhty, and H. Ameryoun, Dynamic non-linear analysis of offshore jacket type platforms under extreme wave loads, 2010.

[27] S.C. Jiang, B. Teng, W. Bai, Y. Gou, Numerical simulation of coupling effect between ship motion and liquid sloshing under wave action, Ocean Eng. 108 (2015) 104–154, doi:10.1016/j.oceaneng.2015.07.044.

[28] Y. Gou, Y. Kim, T.Y. Kim, A numerical study on coupling between ship motions and sloshing in frequency and time domain, in: Proceedings of the 21st ISOPE Conference, Maui, Hawaii, USA, 2011, pp. 158–164. June 19-24.

[29] Y.S. Nam, B.W. Kim, Y. Kim, D.W. Kim, Experimental and numerical studies on ship motion responses coupled with sloshing in waves, J. Ship. Res. 53 (2) (2009) 68–82.

[30] J.R. Mac Gregor, F. Black, B. Wright, D, Design and construction of FPSO vessel for the Schiehallion field, Trans. R. Inst. Nav. Archit. Lond. 141 (1999) 270–304.

[31] K.M.T. Kleefsman, G. Fekken, A.E.P. Veldman, B. Iwanowski, B. Buchner, A volume-of-fluid based simulation method for wave impact problems, J. Comput. Phys. 206 (2005) 263–393.

[32] R.C. Zhu, G.P. Miao, Z.W. Lin, Numerical research on {FPSOs} with green water occurrence, J. Sh. Res. 53 (1) (2009) 7–18.

[33] NORSOK, "Standard N-003: action and action effects," 2007.

[34] E.M. Bitner-Gregersen, et al., Sea state conditions for marine structures' analysis and model tests, Ocean Eng. 119 (2016) 309–322 June, doi:10.1016/j.oceaneng.2016.03.024.

[35] J. Hennig et al., OMAE2015-41167, pp. 1–15, 2015.

[36] H.F. Needham, B.D. Keim, D. Sathiaraj, A review of tropical cyclone-generated storm surges: global data sources, observations, and impacts, Rev. Geophys. 53 (2015) 545–591.

[37] N.B. Bernier, K.R. Thompson, Predicting the frequency of storm surges and extreme sea levels in the northwest Atlantic, J. Geophys. Res. Ocean. 111 (10) (2006) 1–15, doi:10.1029/2005JC003168.

[38] C.P. Jelesnianski, J. Chen, W.A. Shaffer, SLOSH: sea, lake, and overland surges from hurricanes, Natl. Ocean. Atmos. Adm. U. S. Dep. Commer. URL. 48 (1992) *http//www.nhc. noaa.gov/surge/slosh.*.

[39] M. Reistad, Ø. Breivik, H. Haakenstad, O.J. Aarnes, B.R. Furevik, J.R. Bidlot, A high-resolution hindcast of wind and waves for the North Sea, the Norwegian Sea, and the Barents Sea, J. Geophys. Res. Ocean. 116 (5) (2011) 1–18, doi:10.1029/2010JC006402.

[40] F. Mazas, L. Hamm, An event-based approach for extreme joint probabilities of waves and sea levels, Coast. Eng. 122 (2017) 44–59 January, doi:10.1016/j.coastaleng.2017.02.003.
[41] E. Ross, S. Sam, D. Randell, G. Feld, P. Jonathan, Estimating surge in extreme North Sea storms, Ocean Eng. 154 (2018) 430–444 March, doi:10.1016/j.oceaneng.2018.01.078.
[42] E. Vanem, Joint statistical models for significant wave height and wave period in a changing climate, Mar. Struct. 49 (2016) 180–205, doi:10.1016/j.marstruc.2016.06.001.
[43] S. Løset, K.N. Shkhinek, O.T. Gudmestad, K.V. Høyland, Actions from Ice on Arctic offshore and Coastal Structures, 2006.
[44] M. Takeuchi, T. Kavamura, T. Sakai, M. Nakazava, N. Terashima, A. Kamio, Z. Matsushita, H. Kurokawa, H. Akagawa, S, Saeki, Ice load equation by medium scale indentation test data, in: Proceedings of the 18th ISOPE Conference, II, 2001, pp. 713–720. *Stawanger, Norway, June 17–22, 2001*Vol.
[45] K. Skorobogatov, A. and Shkhinek, “Numerical simulation of ice/structure interaction,” 2005.
[46] F. Shkhinek, K.N. Bolshev, A, A, C.S. Maluytin, V., modelling of level ice action on floating anchored structures concepts for the Shockman field, in: Proceedings of the IAHR Ice Symposium., II, 2004, pp. 84–94. Vol.
[47] M. Arif, F. Khan, S. Ahmed, S. Imtiaz, Rare event risk analysis – application to iceberg collision, J. Loss Prev. Process Ind. 66 (2020) 104199 February, doi:10.1016/j.jlp.2020.104199.
[48] J.R. Tawekal, “Master ’ S Thesis ‘ice loads; platform design; standards; stavanger,’” no. March 2015, doi: 10.1177/0739456X9401300405.
[49] L. Liu, S. Ji, Ice load on floating structure simulated with dilated polyhedral discrete element method in broken ice field, Appl. Ocean Res. 75 (2018) 53–65, doi:10.1016/j.apor.2018.02.022.
[50] A. Ross, Nonlinear maneuvering models for ships: a lagrangian approach No Title, 2008.
[51] R.A. Ibrahim, I.M. Grace, Modeling of ship roll dynamics and its coupling with heave and pitch, Math. Probl. Eng. 2010 (2010) 13–18, doi:10.1155/2010/934714.
[52] W. Lin, Q. R, Kuang, Modeling nonlinear roll damping with a self-consistent, strongly nonlinear ship motion model, J. Mar. Sci. Technol. 13 (2) (2008) 127–137.
[53] S. Chakrabarti, Empirical calculation of roll damping for ships and barges, Ocean Eng. 28 (7) (2001) 915–932.
[54] A.B. Mahfouz, Identification of the nonlinear ship rolling motion equation using the measured response at sea, Ocean Eng. 31 (2004) 2139–2156 17–18.
[55] J.B. Roberts, Effect of parametric excitation on ship rolling motion in random waves, J. Sh. Res. 26 (4) (1982) 246–253.
[56] J. Kwon, S. Kim, D, Chung, Application of path integral solution to ship rolling motion, in: Proceedings of the 3rd International Offshore and Polar Engineering Conference (ISOPE ’93), 1993, pp. 657–660. *Singapore*.
[57] H. Lin, S.C.S. Yim, Chaotic roll motion and capsize of ships under periodic excitation with random noise, Appl. Ocean Res. 17 (3) (1995) 185–204.
[58] E.T. Yim, S.C. Nakhata, T, Huang, Coupled nonlinear barge motions—Part II: deterministic models stochastic models and stability analysis,” in Coupled nonlinear barge motions—Part II: deterministic models stochastic models and stability analysis, in: Proceedings of the *23rd ASME International Conference on Offshore Mechanics and Arctic Engineering*, 2004, pp. 293–302. *(OMAE ’04) Vancouver Canada*.
[59] A. Mamontov, E, Naess, An analytical-numerical method for fast evaluation of probability densities for transient solutions of nonlinear Ito’s stochastic differential equations, Int. J. Eng. Sci. 47 (1) (2009) 116–130.
[60] J.Y. Liu, L.Q. Tang, Y.G. Zheng, H.-Y, Gu, Analysis method of capsizing probability in time domain for ships in random beam waves, J. Tianjin Univ. Sci. Technol. 39 (2) (2006) 165–169.
[61] H.X. Liu, L.Q. Tang, Y.G, Li, Stochastic chaotic motion of ships in beam seas, J. Mar. Sci. Technol. 15 (12) (2007) 123–128.
[62] J.C. Yin, Z.J. Zou, F. Xu, On-line prediction of ship roll motion during maneuvering using sequential learning RBF neural networks, Ocean Eng 61 (2013) 139–147 October 2017, doi:10.1016/j.oceaneng.2013.01.005.
[63] H. Fu, Y. Wang, H. Zhang, Ship rolling motion prediction based on extreme learning machine, in: 2015 34th Chinese Control Conference, 2015, pp. 3468–3472, doi:10.1109/ChiCC.2015.7260174.
[64] M.M. Rahaman, H. Islam, H. Akimoto, M.R. Islam, Motion predictions of ships in actual operating conditions using potential flow based solver, J. Nav. Archit. Mar. Eng. 14 (1) (2017) 65–76, doi:10.3329/jname.v14i1.28674.
[65] J.B. Rho, H.S. Choi, Vertical motion characteristics of truss spars in waves, in: The Fourteenth International Offshore and Polar Engineering Conference, 2004, pp. 662–665. *Toulon, France*.
[66] Y.P. Hong, D.Y. Lee, Y.H. Choi, S.K. Hong, S.E. Kim, An experimental study on the extreme motion responses of a spar platform in the heave resonant waves, in: The Fifteenth International Offshore and Polar Engineering Conference Seoul, 2005, pp. 225–232. *Korea*.
[67] M.A.S Neves, S.H. Sphaier, B.M. Mattoso, C.A. Rodríguez, T.F.G Vileti V L, On the occurrence of Mathieu instabilities of vertical cylinders, in: *The 27th International Conference on Offshore Mechanics and Arctic Engineering*, Estoril, Portugal, 2008, pp. 619–627.
[68] L. Liu, Y. Tang, W. Wang, Unstability of coupled heave-pitch motions for spar platform, J. Sh. Mech. 13 (4) (2009) 551–556.
[69] J. Zhao, L. Tang, Y. Tang, W. Wang, Internal resonant responses of heave-pitch coupled motions of classic spar platform, J. Tianjin Univ. 42 (3) (2009) 201–207.
[70] L.H. Shen, W. Tang Y, Time domain analysis of heave motion for truss spar in random seas, Ocean Eng. 30 (1) (2012) 60–65.
[71] O... Montasir, V... Kurian, Effect of slowly varying drift forces on the motion characteristics of truss spar platforms, Ocean Eng. 38 (2011) 1417–1429.
[72] S.A. Islam, M. Jameel, S. Ahmad, Z.M. Jumaat, Nonlinear response of coupled integrated spar platform under severe sea states, in: *The 31st International Conference on OceaC*, Offshore and Arctic Engineering, Rio de Janeiro, Brazil, 2012, pp. 559–567, doi:10.1115/OMAE2012-83862. DOI.
[73] E. Gavassoni, P.B. Gonçalves, D.M. Roehl, Nonlinear vibration modes and instability of a conceptual model of a spar platform, Nonlinear Dyn. 76 (1) (2014) 809–826.
[74] S. Liu, Y. Tang, W. Li, Nonlinear random motion analysis of coupled heave-pitch motions of a spar platform considering 1st-order and 2nd-order wave loads, J. Mar. Sci. Appl. 15 (2) (2016) 166–174, doi:10.1007/s11804-016-1349-7.
[75] L. Wang, W. Wang, Y. Du, H. Gao, Y. Huang, Pitch motion problem induced by dynamic positioning system for new sandglass-type floating body, J. Mar. Sci. Technol. 22 (1) (2017) 162–175, doi:10.1007/s00773-016-0403-0.
[76] C. Ching-Tang, F. Li-Chen, VR-based motion simulator for dynamics ship on six degree-of-freedom platform, Roma, Italy 2007. *ICRA International Conference*, 2007 SBN: 1-4244-0601-3.
[77] B, Gatis, F. Peter, Fast-time ship simulator, Saf. Sea (2007) 2007.
[78] T.I. Fossen, Guidance and Control of Ocean Vehicles. England, Jhon Wiley, 1996.
[79] C.T. Chen, F. Ju, Fundamental properties of linear ship steering dynamic models, J. Mar. Sci. Technol. 7 (1997).
[80] L.B. Tao, K.Y. Lim, K. Thiagarajan, Heave response of classic spar with variable geometry, J. Offshore Mech. Arct. Eng. 126 (1) (2004) 90–95.
[81] B. Li, J. Ou, Heave response analysis of truss spar in frequency domain, Ocean Eng. 27 (1) (2009) 8–15.
[82] L. Liu, A. Incecik, Y. Zhang, Y. Tang, Analysis of heave motions of a truss spar platform with semi-closed moon pool, Ocean Eng. 92 (2014) 162–174, doi:10.1016/j.oceaneng.2014.09.048.
[83] L.Q. Liu, H. Zhou, Y.G. Tang, Coupling response of heave and moon pool water motion of a truss Spar platform in random waves, China Ocean Eng. 29 (2) (2015) 169–182, doi:10.1007/s13344-015-0013-3.
[84] N. Fonseca, R. Pascoal, C. Guedes-Soares, G.F. Clauss, C.E. Schmittner, Numerical and experimental analysis of extreme wave induced vertical bend- ing moments on a FPSO, Appl. Ocean Res. 32 (2010) 374–390.
[85] C.G. Soares, N. Fonseca, R. Pascoal, Abnormal wave induced load effects in ship structures, J. Sh. Res. 52 (1) (2008) 30–44.
[86] J.M.J. Journée, “Technical Report No.1216. Delft University of Technology, Ship,”, Hydromech. Lab. (1999).
[87] S. Rajendran, N. Fonseca, C.Guedes Soares, Effect of surge motion on the vertical responses of ships in waves, Ocean Eng. 96 (2015) 125–138, doi:10.1016/j.oceaneng.2014.12.034.
[88] M. Greco, C. Lugni, O.M. Faltinsen, “Can the water on deck influence the parametric roll of a FPSO? A numerical and experimental investigation,”, Eur. J. Mech. B Fluids 47 (2014) 188–201 vol.
[89] M. Greco and C. Lugni, “Numerical and experimental study of parametric roll with water on deck,” 2012.
[90] M. Greco, C. Lugni, O.M. Faltinsen, Influence of motion coupling and nonlinear effects on parametric roll for a floating production storage and offloading platform, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 373 (2033) (2015), doi:10.1098/rsta.2014.0110.
[91] J.T. Lopez, L. Tao, L. Xiao, Z. Hu, Experimental study on the hydrodynamic behaviour of an FPSO in a deepwater region of the Gulf of Mexico, Ocean Eng. 129 (2017) 549–566 August 2015, doi:10.1016/j.oceaneng.2016.10.036.
[92] D.G. DiMattia, P... Amyotte, F. Khan, Determination of human error probabilities for offshore platform musters, in: International conference on Bhopal and its effects on process safety IIT-Kanpur India, 18, 2005, pp. 488–501.
[93] R. Islam, F. Khan, R. Abbassi, V. Garaniya, Human error probability assessment during maintenance activities of marine systems, Saf. Health Work 9 (1) (2018) 42–52, doi:10.1016/j.shaw.2017.06.008.
[94] M.M. Abaei, R. Abbassi, V. Garaniya, S. Chai, F. Khan, Reliability assessment of marine floating structures using Bayesian network, Appl. Ocean Res. 76 (2018) 51–60 April, doi:10.1016/j.apor.2018.04.004.
[95] F. Khan, S.A. Abassi, Assessment of risks posed by chemical industries - application of a new computer automated tool MAXCRED-III, J. Loss Prev. Process Ind. 12 (1999) 455–469.
[96] R.M. Townsend, The European Migrant Crisir (Lulu.com), 2015.
[97] A. Papanikolaou, et al., GOALDS - goal based damage stability, Proc. 11th Int. Sh. Stab. Work. (2010) 46–57 2010.
[98] J. Montewka, S. Ehlers, F. Goerlandt, T. Hinz, K. Tabri, P. Kujala, A framework for risk assessment for maritime transportation systems - a case study for open sea collisions involving RoPax vessels, Reliab. Eng. Syst. Saf. 124 (2014) 142–157, doi:10.1016/j.ress.2013.11.014.
[99] A.D. Papanikolaou, G. Bulian, C. Mains, GOALDS – goal based damaged stability : collision and grounding damages, 12th Int. Sh. Stab. Work. (2012) 37–44.
[100] M.M. Abaei, E. Arzaghi, R. Abbassi, V. Garaniya, S. Chai, F. Khan, A robust risk assessment methodology for safety analysis of marine structures under storm conditions, Ocean Eng. 156 (2018) 167–178 May, doi:10.1016/j.oceaneng.2018.02.016.
[101] MMS, Proposed use of floating production, storage and offloading systems on the Gulf of Mexico outer Continental Shelf: western and Central Planning Area. Final Environment Impact Statement, OCS EIS/EA MMS 2000-090. Contract No 1435-01-99-CT-30962. Mineral Man, New Orleans, Louisiana (2001) *(January 2001)*.
[102] M. Capsey, D. Lewelyn, and E. Dyrkoren, “A Summary report on FPSO lessons learned from 5 Norwegian FPSO. Offshore management centre, Robert Gorden University Abeerdeen UK,” 2002.
[103] R. Amdel, H. Kleppesto, and J. Krokeide, “A Summary Report on FPSO-shuttle tanker interface. Lesson learned from 4 shuttle tanker operation and 2 Norwegian FPSO/FSUs Operator. OLF FPSO/Shuttle tanker Project. Stavanger Norway,” 2004.

[104] E.G. Ward, R. Gilbert, A. Wolford, Comparative risk analysis for deepwater production system, Final Rep. Offshore Technol. Res. Center (2001) College Station, Texas (January 2001),".
[105] DNVFinal Report, MMS Contract, 2001.
[106] J.B. Regg, A. Staci, B.J. Hauser, J. Hennessey, Bernard J. Kruse, J. Lowenhaupt, B. Smith , A. White, Deepwater development: a reference document for the deepwater environment assessment gulf of Mexico OCS, 2000.
[107] B.H. Metzger, D. Salmond, A. Tilstone, FPSO environmental risk management, Soc. Pet. Eng. - SPE Int. Conf. Heal. Saf. Environ. Oil Gas Explor. Prod. 3 (2010) 1613–1629 April2010.
[108] G. Lončar, N. Leder, M. Paladin, Numerical modelling of an oil spill in the northern Adriatic, Oceanologia 54 (2) (2012) 143–173, doi:10.5697/oc.54-2.143.
[109] Y. Li, W. Wang, B. Liu, X. Zhou, Research on oil spill risk of port tank zone based on fuzzy comprehensive evaluation, Aquat. Procedia 3 (2015) 216–223, doi:10.1016/j.aqpro.2015.02.214.
[110] W. Blvd, 2016 update of occurrence rates for offshore oil spills, 2016.
[111] C.M. Anderson, M. Mayes, and R. Labelle, "Update of occurrence rates for offshore oil spills," p. 87, 2012.
[112] J.K. Paik, J. Czujko, Assessment of hydrocarbon explosion and fire risks in offshore installations: recent advances and future trends, IES J. Part A Civ. Struct. Eng. 4 (3) (2011) 167–179, doi:10.1080/19373260.2011.593345.
[113] A.W. Sipkema, Single vs double sides for FPSO Hulls- a decision model-paper SPE 86669, SPE International Conference on Health, Safety and Enviornment in Oil and Gas Exploision and Production, 2004 Calgary 29-31 March Doi, doi:10.2118/86669.
[114] J.E. Vinnem, P. Hokstad, T. Dammen, H. Saele, H. Chen, S. Haver, O. Kieran, H. Kleppestoe, J.J. Thomas, L.L. Toennessen, Operational safety analysis of FPSO - shuttle Tanker collision risk reveals areas of improvement, Proc. Offshore Technol. Conf. (2003), doi:10.4043/15317-MS.
[115] G. Wang, J. Spencer, Y. Chen, Assessment of a ship ' s performance in accidents, Mar. Struct. 15 (2002) 313–333, doi:10.1016/S0951-8339(02)00017-5.
[116] J.E. Vinnem, "Operational safety of FPSOs shuttle tanker collision risk summary report," 2003, [Online]. Available: http://www.hse.gov.uk/research/rrpdf/rr113.pdf.
[117] T. Moan, J. Amdahl, X. Wang, J. Spencer, Risk assessment of FPSOs with emphasis on collision, Annu. Meet. Soc. Nav. 110 (2002) 24–27 September [Online]. Available http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Risk+Assessment+of+FPSOs+with+Emphasis+on+Collision#0.
[118] Z. Liu, J. Amdahl, A new formulation of the impact mechanics of ship collisions and its application to a ship-iceberg collision, Mar. Struct. 23 (3) (2010) 360–384, doi:10.1016/j.marstruc.2010.05.003.
[119] H. Chen, PhD Thesis, 2003.
[120] Statoil., Granskningsrapport fra berøring. Document No. 00A05×0209, 2000., 2000.
[121] C.E.P. Rodriguez, G.F.M. de Souza, M.R. Martins, Risk-based analysis of offloading operations with Fpso production units, 20th Int. Congr. *Mech. Eng.* (2009) noJanuary[Online]. Available http://www.abcm.org.br/anais/cobem/2009/pdf/COB09-2003.pdf.
[122] J.E. Vinnem, J.P. Liyanmage, Human-technical interface of collision risk under dynamic conditions: an exploratory learning case from the North Sea, Int. J. Technol. Hum. Interact. 4 (1) (2008) 35–48.
[123] N. Leveson, Engineering a Safer World. Systems Thinking Applied to Safety, The MIT Press, Cambridge, USA, 2011.
[124] B. Foss, Process control in conventional oil and gas fields challenges and opportunities, Control Eng. Pract. 20 (10) (2012) 1058–1064.
[125] J.E. Vinnem, Offshore Risk Assessment (QRA), Springer, London Uk, 2013.
[126] M.E.K. Lundborg, Human technical factors in FPSO-shuttle tanker interactions and their influence on the collision risk during operations in the North Sea, no. June 2014.
[127] J.E. Vinnem, I.B. Utne, I. Schjølberg, On the need for online decision support in FPSO - shuttle tanker collision risk reduction, Ocean Eng. 101 (7491) (2015) 109–117, doi:10.1016/j.oceaneng.2015.04.008.
[128] J.A. Suardin, A. Jeff McPhate, A. Sipkema, M. Childs, M.S. Mannan, Fire and explosion assessment on oil and gas floating production storage offloading (FPSO): an effective screening and comparison tool, Process Saf. Environ. Prot. 87 (3) (2009) 147–160, doi:10.1016/j.psep.2008.12.002.
[129] M. Leimeister, A. Kolios, A review of reliability-based methods for risk analysis and their application in the offshore wind industry, Renew. Sustain. Energy Rev. 91 (2018) 1065–1076 November 2017, doi:10.1016/j.rser.2018.04.004.
[130] A. Al-shanini, A. Ahmad, F. Khan, Accident modelling and analysis in process industries, J. Loss Prev. Process Ind. 32 (2014) 319–334, doi:10.1016/j.jlp.2014.09.016.
[131] G. Bearfield, W. Marsh, Generalising event trees using bayesian networks with a case study of train derailment, Comput. Saf. Reliab. Secur. (2005) 52–66.
[132] K. Przytula, D. Thompson, Construction of Bayesian networks for diagnostics., 2000.
[133] P. Weber, G. Medina-Oliva, C. Simon, B. Lung, Overview on Bayesian networks applications for dependability, risks analysis and maintenance areas, Eng. Appl. Artif. Intell. 25 (4) (2012) 671–682.
[134] S. Adumene, F. Khan, S. Adedigba, S. Zendehboudi, Offshore system safety and reliability considering microbial influenced multiple failure modes and their interdependencies, Reliab. Eng. Syst. Saf. 215 (2021) 107862 November, doi:10.1016/j.ress.2021.107862.
[135] Z. Zhou, X. Zeng, H. Li, S. Lui, C. Ma, Application of Bayesian networks in dynamic event tree analysis, J. Converg. Inf. Technol. 6 (7) (2011) p. doi, doi:10.4156/jcit.vol6.issue7.42.
[136] N. Khakzad, F. Khan, P. Amyotte, Quantitative risk analysis of offshore drilling operations: a Bayesian approach, Saf. Sci. 57 (2013) 108–117 August 2016, doi:10.1016/j.ssci.2013.01.022.
[137] S. Ung, Development of a weighted probabilistic risk assessment method for offshore engineering systems using fuzzy rule-based Bayesian reasoning approach, Ocean Eng. 147 (2017) 268–276 October 2017, doi:10.1016/j.oceaneng.2017.10.044.
[138] S. Adumene, F. Khan, S. Adedigba, S. Zendehboudi, H. Shiri, Dynamic risk analysis of marine and offshore systems suffering microbial induced stochastic degradation, Reliab. Eng. Syst. Saf. 207 (2021) 107388 March 2021, doi:10.1016/j.ress.2020.107388.
[139] S. Adumene, F. Khan, S. Adedigba, Operational safety assessment of offshore pipeline with multiple MIC defects, Comput. Chem. Eng. 138 (2020), doi:10.1016/j.compchemeng.2020.106819.
[140] S.A. Adedigba, F. Khan, M. Yang, Dynamic safety analysis of process systems using nonlinear and non-sequential accident model, Chem. Eng. Res. Des. 111 (2016) 169–183, doi:10.1016/j.cherd.2016.04.013.
[141] S.A. Adedigba, F. Khan, M. Yang, Process accident model considering dependency among contributory factors, Process Saf. Environ. Prot. 102 (2016) 633–647, doi:10.1016/j.psep.2016.05.004.
[142] M. Yang, F.I. Khan, L. Lye, Precursor-based hierarchical Bayesian approach for rare event frequency estimation: a case of oil spill accidents, Process Saf. Environ. Prot. 91 (5) (2013) 333–342.
[143] Q. Tan, G. Chen, L. Zhang, J. Fu, Z. Li, Dynamic accident modeling for high sulfur natural gas gathering station, Process Saf. Environ. Prot. (2013) http://dx.doi.org/10.1016/j.psep.2013.03.004..
[144] S. Rathnayaka, F. Khan, P. Amyotte, Accident modeling approach for safety assessment in an LNG processing facility, J. Loss Prev. Process Ind. 25 (2) (2012) 414–423 http://dx.doi.org/10.1016/j.jlp.2011.09.0.
[145] T. Abbasi, H. Pasman, S. Abbasi, A scheme for the classification of explosions in the chemical process industry, J. Hazard. Mater. 174 (1) (2010) 270–280.
[146] T. Baalisampang, R. Abbassi, V. Garaniya, F. Khan, M. Dadashzadeh, Review and analysis of fire and explosion accidents in maritime transportation, Ocean Eng. 158 (2018) 350–366 April, doi:10.1016/j.oceaneng.2018.04.022.
[147] A. Summers, W. Vogtmann, S. Smolen, Consistent consequence severity estimation, Process Saf. Prog. 31 (1) (2012) 9–16.
[148] H.W. Witlox, M. Harper, Modeling of time-varying dispersion for releases including potential rainout, Process Saf. Prog., 2013, doi:10.1002/prs.11652.
[149] M. Weber, Some safety aspects on the design of Sparger systems for the, Process Saf. Prog. 25 (4) (2006) 326–330, doi:10.1002/prs.
[150] S. Dan, C.J. Lee, J. Park, D. Shin, E.S. Yoon, Quantitative risk analysis of fire and explosion on the top-side LNG-liquefaction process of LNG-FPSO, Process Saf. Environ. Prot. 92 (5) (2014) 430–441, doi:10.1016/j.psep.2014.04.011.
[151] Y. Jin, B.S. Jang, Probabilistic fire risk analysis and structural safety assessment of FPSO topside module, Ocean Eng. 104 (2015) 725–737, doi:10.1016/j.oceaneng.2015.04.019.
[152] Y.L. Jin, B.S. Jang, J.Du Kim, Fire risk analysis procedure based on temperature approximation for determination of failed area of offshore structure: living quarters on semi-drilling rig, Ocean Eng. 126 (2016) 29–46, doi:10.1016/j.oceaneng.2016.07.010.
[153] T. Baalisampang, R. Abbassi, V. Garaniya, F. Khan, M. Dadashzadeh, Fire impact assessment in FLNG processing facilities using Computational Fluid Dynamics (CFD), Fire Saf. J. 92 (2017) 42–52 October 2016, doi:10.1016/j.firesaf.2017.05.012.
[154] L. Van Geuns, The challenges of arctic oil exploration and production, 2012. [Online]. Available: http://braemartechnical.com/files/Lecture-80_The-Challenges-of-Arctic-Oil-Exploration-and-Production_13th-March_Grant-Smtih-CEO-Braemar-Adjusting_Please-contact-the-office-for-a-copy-of-this-presentation.pdf.
[155] N. Energy, "Advanced risk and impact models for offshore systems advanced risk and impact models," no. April 200, 2010.
[156] J.-.E. Vinnem, Offshore risk assessment *vol* 1., vol. 1. 2014.
[157] S.K. Hansen, Modelling failure mechanisms in subsea equipment, no. June 2016.
[158] H. Bergan, Risk analysis of well control operations considering arctic environmental conditions, no. June 2015.
[159] M. Abimbola, F. Khan, N. Khakzad, Dynamic safety risk analysis of offshore drilling, J. Loss Prev. Process Ind. 30 (1) (2014) 74–85, doi:10.1016/j.jlp.2014.05.002.
[160] M. Abimbola, F. Khan, Dynamic blowout risk analysis using loss functions, Risk Anal. 38 (2) (2018) 255–271, doi:10.1111/risa.12879.
[161] Z. Lu, J. Song, S. Song, Z. Yue, J. Wang, Reliability sensitivity by method of moments, Appl. Math. Model. 34 (10) (2010) 2860–2871, doi:10.1016/j.apm.2009.12.020.
[162] C. Rendón-Conde, E. Heredia-Zavoni, Reliability assessment of mooring lines for floating structures considering statistical parameter uncertainties, Appl. Ocean Res. 52 (2015) 295–308, doi:10.1016/j.apor.2015.06.011.
[163] P.N. Thodi, F.I. Khan, M.R. Haddara, The development of posterior probability models in risk-based integrity modeling, Risk Anal. 30 (3) (2010) 400–420, doi:10.1111/j.1539-6924.2009.01352.x.
[164] P. Thodi, F. Khan, M. Haddara, Risk based integrity modeling of offshore process components suffering stochastic degradation, J. Qual. Maint. Eng. 19 (2) (2013) 157–180, doi:10.1108/13552511311315968.
[165] T.E. Schellin, O. el Moctar, Numerical prediction of impact-related wave loads on ships, J. Offshore Mech. Arct. Eng. 129 (1) (2007) 39, doi:10.1115/1.2429695.
[166] J. Ramos, C.G. Soares, Vibratory response of ship hulls to wave impact loads, Int. Shipbuild. Prog. 45 (441) (1998) 71–87, doi:10.3233/ISP-1998-4544104.

[167] S. Wang, D. Karmakar, C. Guedes-Soares, Hydroelastic impact due to longitudinal compression on transient vibration of a horizontal elastic plate, in: C. Guedes Soares, T.A Santos (Eds.), MaritimeTechnologyandEngineering, Taylor&FrancisGroup, London, 2015, pp. 1073–1079.
[168] S. Wang, D. Karmakar, C.Guedes Soares, Hydroelastic impact of a horizontal floating plate with forward speed, J. Fluids Struct. 60 (2016) 97–113, doi:10.1016/j.jfluidstructs.2015.11.005.
[169] S. Haris, J. Amdahl, Analysis of ship-ship collision damage accounting for bow and side deformation interaction, Mar. Struct. 32 (2013) 18–48, doi:10.1016/j.marstruc.2013.02.002.
[170] D.M. Bae, A.R. Prabowo, B. Cao, A.F. Zakki, G.D. Haryadi, Study on collision between two ships using selected parameters in collision simulation, J. Mar. Sci. Appl. 15 (2016) 63–72.
[171] A.R. Prabowo, D.M. Bae, J.M. Sohn, A.F. Zakki, Evaluating the parameter influence in the event of a ship collision based on the finite element method approach, Int. J. Technol. 7 (4) (2016) 592–602, doi:10.14716/ijtech.v7i4.2104.
[172] D.-K. Min, C.-S. Shim, D.-W. Shin, and S.-R. Cho, On the mechanical properties at low temperatures for steels of ice-class, vol. 48, no. 2, pp. 171–177, 2011.
[173] D.M. Bae, A.R. Prabowo, B. Cao, J.M. Sohn, A.F. Zakki, Q. Wang, Numerical simulation for the collision between side structure and level ice in event of side impact scenario, Lat. Am. J. Solids Struct. 13 (16) (2016) 2691–2704, doi:10.1590/1679-78252975.
[174] F. Nugteren, Flexible riser fatigue analysis Frederike Nugteren, Reposit. Tudelft.Nl (2015) [Online]. Available http://repository.tudelft.nl/assets/uuid:80488024-c2be-4601-832f-050811e5736a/Frederike_Nugteren_-_Final_Report_Graduation_12.05_2.pdf.
[175] J.M. Sheehan, F.W. Grealish, A.M. Harte, R.J. Smith, Characterizing the wave environment in the fatigue analysis of flexible risers, J. Offshore Mech. Arct. Eng. 128 (2) (2006) 108, doi:10.1115/1.2185129.
[176] J.P. Zhan, Review and verification of marine riser analysis programs, Glob. Response Anal. (2010) 107.
[177] C.G. Paton, C.J. Carra, P. Sincock, A. Consulting, OTC 18039 investigation of sway /yaw motions of deepwater FPSOs, Current (2006) 1–8.
[178] D.H. Lee and H. Choi, A nonlinear stability analysis of random offloading system, 2003.
[179] F. Aghamohammadi, J.M.T. Thompson, An experimental study of a large amplitude fish-tailing instability of a tanker at a single point mooring, Appl. Ocean Res. 12 (1) (1990) 25–32.
[180] M.M. Bernitsas and J.P.J. Matsuura, Revealing nonlinear dynamics phenomena in mooring due to slowly-varying drift, 2005.
[181] M.E. Mousavi, PhD Dissertation, Texas A&M University, 2013.
[182] M.E. Mousavi, P. Gardoni, M. Maadooliat, Progressive reliability method and its application to offshore mooring systems, Eng. Struct. 56 (2013) 2131–2138, doi:10.1016/j.engstruct.2013.08.016.
[183] W. Brindley and A.P. Comley, OMAE2014-23395, pp. 1–9, 2014.
[184] G.P. Drumond, I.P. Pasqualino, B.C. Pinheiro, S.F. Estefen, Pipelines, risers and umbilicals failures: a literature review, Ocean Eng. 148 (2018) 412–425 November 2017, doi:10.1016/j.oceaneng.2017.11.035.
[185] Bomel Ltd, Improving health and safety in construction Phase 1: data collection, review and structuring, Construction (2001) 246.
[186] G. Song, F. Khan, H. Wang, S. Leighton, Z. Yuan, H. Liu, Dynamic occupational risk model for offshore operations in harsh environments, Reliab. Eng. Syst. Saf. 150 (2016) 58–64 November 2017, doi:10.1016/j.ress.2016.01.021.
[187] J. Priestley, A. Peters, Managing a remote, complex, deepwater wildcat, Hart's E P (2012) no. SEPTEMBER.
[188] S. Adumene, et al., Dynamic logistics disruption risk model for offshore supply vessel operations in Arctic waters, Marit. Transp. Res. 2 (2021) 100039 November, doi:10.1016/j.martra.2021.100039.
[189] T. Deacon, P.R. Amyotte, F.I. Khan, S. MacKinnon, A framework for human error analysis of offshore evacuations, Saf. Sci. 51 (1) (2013) 319–327, doi:10.1016/j.ssci.2012.07.005.
[190] M. Yang, F. Khan, D. Oldford, L. Lye, H. Sulistiyono, Risk-based winterization on a North Atlantic-based ferry design, vol. 31, no. 2, pp. 1–11, 2015, doi: 10.5957/JSPD.32.2.140008.
[191] R.M.C. Ratnayake, Minimization of variability in risk-based winterization analysis: asset integrity assurance in arctic environments, vol. 27, no. 3, pp. 245–251, 2017.
[192] M.S. Rahman, F. Khan, A. Shaikh, S. Ahmed, S. Imtiaz, Development of risk model for marine logistics support to offshore oil and gas operations in remote and harsh environments, Ocean Eng. 174 (2019) 125–134 May 2018, doi:10.1016/j.oceaneng.2019.01.037.
[193] M.S. Rahman, F. Khan, A. Shaikh, S. Ahmed, S. Imtiaz, A conditional dependence-based marine logistics support risk model, Reliab. Eng. Syst. Saf. 193 (2020) 106623 July 2019, doi:10.1016/j.ress.2019.106623.
[194] O.T. Gudmestad et al., "Basic Marine and offshore petroleum engineering and development of facilities with emphasis on the Arctic offshore.," 1999, [Online]. Available: ISBN%0A0100-1.
[195] ISO, International standard. ISO 19906: petroleum and natural gas industries-Arctic offshore structures. Geneva:ISO 2010, vol. 2010, 2010.
[196] A. Larsen, T. Markeset, Mapping of operation, maintenance and support design factors in arctic environments, Taylor Fr. Group, London (2007).
[197] NORSOK, NORSOK: N-003 actions and action effects, Nor. Oil Ind. Assoc. Fed. Nor. Manuf. Ind. (2007) no. September.
[198] M.S. Rahman, B. Colbourne, F. Khan, Conceptual development of an offshore resource centre in support of remote harsh environment operations, Ocean Eng. 203 (2020) 107236 March, doi:10.1016/j.oceaneng.2020.107236.