Risk-based Offshore Facility Design (RB-OFD) under Arctic Operational Conditions

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ABSTRACT

Offshore facility design is a complex activity involving technical challenges from a wide range of sources, a considerable degree of risks, and substantial financial resources. Design strategies, especially in the Arctic offshore, must take account of the risk of structural failure due to ice impact and ice loading, in addition to the 'conventional' structural failure; that is, both the probability of failure and its consequences have to be considered. Further, offshore structures in Arctic have the added complication of being placed in harsh environment where winterization, ice loading, icing, hydrodynamic interaction effects, and dynamic response become major considerations in their design. Hence, when designing offshore facilities for Arctic conditions, it is imperative to identify and quantify all risks. The purpose of this paper is to suggest a simplified risk–based offshore facility design (RB–OFD) methodology, by considering the complex and fast-changing nature of the Arctic. The main goal is to highlight the fact that risk-based approach is particularly well suited to offshore project designs in the Arctic since there is less experience and data in the region. Further, a design strategy based on risk avoids the inadequacies of the traditional approach, maximizes the value of each offshore project, and increases the effectiveness of risk mitigation strategies.

KEY WORDS: Arctic; FPSO; Risk-based; Offshore facility design; Risk mitigation

INTRODUCTION

The offshore industries are drawing upon the lead set by other industries (nuclear, aircraft, etc.), in the application of risk–based approaches for design as well as in-service inspection (Serratella et al., 2007). Risk–based methodologies for design and inspection plan optimization originated in the nuclear industry in the 1970's and, over the years have migrated into other industries such as the downstream petrochemical industry in the 1980's and 1990's; these approaches are now moving into the upstream sector of the oil and gas industry. The risk-based methods include aspects of the conditions–based methods using trending techniques to estimate likelihood, but also factors in an estimation of the consequence of the structure's degradation and potential failure, enabling the program resources to be optimized and focused towards inspecting those items which have a greater overall risk weight (Serratella et al., 2007). Once those items are identified, optimum methods of design are the selected (Serratella et al., 2007).

Offshore projects, especially in the Arctic oil and gas industry, involve great technical challenges, considerable risks and massive financial resources (Ayele et al., 2016c). Moreover, as the offshore industry expands into the Arctic: remote locations, harsher environments, and deeper water, the hazards associated with these projects is expected to increase significantly compared to the well-established practices of exploration and production in other region, such as North Sea (Sember, 2004, Ayele et al., 2016a). Further, the potential for economic loss, environmental degradation, equipment damage, and work-force injuries is expected to be magnified (Ayele et al., 2013). In addition, oil and gas production project in the Arctic region could face unforeseen uncertainties and challenges. These challenges are mainly due to the new and advanced technological innovations related to the production platforms, stringent requirements to robustness against cold, little expertise on the use of international and national regulations and standards for Arctic offshore operation.

Given the inherent obstacles required to make any project successful, this industry has to serve as a proving ground for cutting edge project valuation methodologies and tools in the region (Hartke, 2012, Ayele et al., 2015). Further, as oil and gas companies operating in the Arctic offshore attempt to maximize the value of each project and optimize their portfolio of investment opportunities, it is imperative that all risks are properly identified and quantified, in order to maximize the value and increase the effectiveness of mitigation strategies (Hartke, 2012, Ayele et al., 2016c). Hence, to smooth the progress of the expansion of the offshore industry further north and, to implement new design aspects in the Arctic offshore, risk–based approach (RBA) have a key role to play. RBA in general allows for a more technical approach to the consideration of innovative designs, an appropriate methodology for assessing alternative designs to a high level of safety, and a better understanding of the hazards, mitigation measures, and risks inherent in the proposed designs (Sember, 2004). Moreover, RBA ensures the safety standards and regulation associated with design of offshore facilities by taking into consideration the peculiar Arctic challenges. In particular, minimizing the overall risk profile of the complex offshore projects under the Arctic operating environment is the main objective of risk-based approach.

In general, when offshore facility design are based on risk assessment, several factors have to be taken into consideration, such as choice of material, equipment, support strategies, physical environment, human factors, HSE (health, safety, and environment) aspects. Further, for the Arctic offshore operation, beyond the traditional risk factors, additional factors have to be taken into consideration. These peculiar risk factors are due to the stringent HSE requirements in terms of emissions to the atmosphere and discharges to the sea, and stringent design procedures with respect to risk reduction measures – prevention of risk incident, control of risk incident, and mitigation measures. To provide a basis for comparing alternative ways of achieving a certain benefit, aid safety design, and offer a fair basis for evaluating alternative design practices, a number of quantitative risk assessment models have been developed; see e.g. (Abimbola et al., 2014, Guo et al., 2005, Ayele et al., 2015, Khakzad et al., 2013, Abimbola et al., 2015, Øien, 2013). For instance, Khakzad et al. (2013) demonstrated the application of bow-tie and Bayesian network methods in conducting quantitative risk analyses during offshore facility design process. Abimbola et al. (2014) has proposed a dynamic safety assessment approach based on bow-tie analysis and a real-time barriers' failure probability assessment for offshore facility design.

However, in most of the available risk analysis literatures, risk factor is the only factor considered; and there is a lack of consideration of the impact of the operating environment on the risk profile. This is considered as a big shortcoming, particularly in the arduous Arctic operating environment (Barabadi et al., 2015). This is especially vital in the Arctic offshore operation because of its slow, non-linear, and potentially irreversible ecological and physical process (Ayele et al., 2016b). Moreover, and most of the methodologies are too cumbersome, time-consuming and generalised. Further, the unique environmental and climatic factors of the Arctic, such as large variations in temperature within a short period of time, sudden wind increase and large changes in wind direction, snow, and inadequate weather forecasting, increases the risk of system failure. The purpose of this paper is thus to proposed a simplified risk–based offshore facility design methodology, by considering the complex and fast-changing nature of the Arctic. This is to have better understanding of the hazards, mitigation measures, and risks inherent in the proposed designs.

The rest of the paper is organized as follows: In Section 2 a bird's eye view of offshore facility design concepts, procedures, standards, etc. are presented. Thereafter, the proposed risk–based offshore facility design (RB-OFD) methodology is described in Section 3. Finally, the concluding remarks is presented in Section 4. For the purpose of this paper, 'the Arctic' is taken simply to mean the Norwegian Arctic and the starting point of our discussion is the Barents Sea. Moreover, in this paper, risk is taken to mean the probability times the consequence of an adverse or hazardous event.

OFFSHORE FACILITY DESIGN: A BIRD'S EYE VIEW

Offshore facilities in general, are floating, production and mooring systems, such as FPSO (Floating Production, Storage and Offloading), FSU (floating and storage unit), FSO (Floating, Storage & Offloading), etc. Figure 1 illustrates the typical offshore productions systems and FPSO layout. The design and construction of an FPSO, for instance is divided into two parts: one for the hull system and the other for the topside system. The topside, like chemical plants, produces and off-loads crude oil and gas, and the hull, like a big tank, stores the produced oil (Hwang et al., 2009).

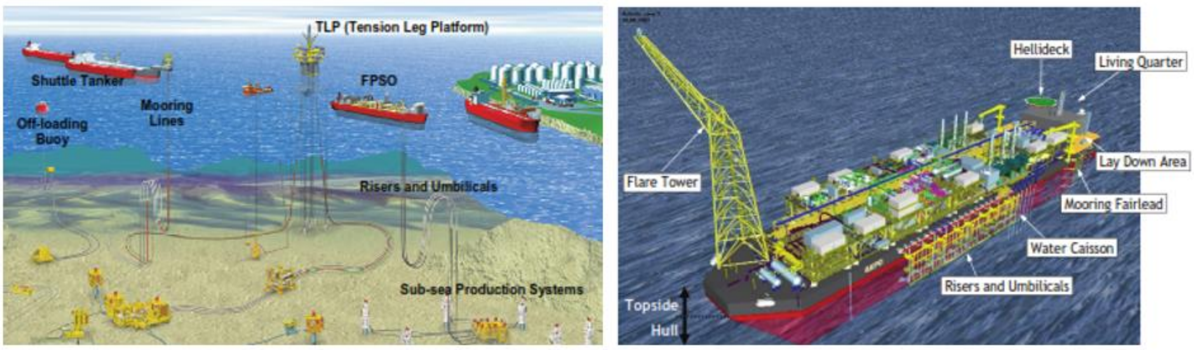

Figure 1. A) Offshore productions systems. B) A typical FPSO layout, adapted from Hwang et al. (2009).

A typical FPSO produces and processes crude oil and gas on the topside, and stores the stabilized oil in cargo tanks of the hull. The FPSO also off-loads the stabilized oil and gas to a shuttle tanker through the oil export/metering pump (Mather, 2000). However, the FPSO alone cannot produce oil and gas in the oil field. It requires many offshore production systems such as the mooring lines, riser structure, accommodation, process (oil, gas, and water) facilities, gas and water injection facilities, flaring facilities, oil storage facilities, export facilities (pumping and metering), gas export facilities, and control systems (Hwang et al., 2009). Thus, the design and construction of an FPSO includes many other offshore production systems (Shimamura, 2002).

Characteristically, when developing an oil and/or gas field, an exploration and feasibility study must first be performed. Thereafter, based on the result of the study, FEED (Front End Engineering Design) of the offshore facilities is commenced if the economic value of the field development is positive, taking the circumstances of offshore market into account(Hwang et al., 2009). Afterwards, based on the initial data of FEED, the design of the hull should be performed (Shimamura, 2002). At this time, IFR (Issued For Review) P&ID (Pipe & Instrumentation Diagram) should be prepared for submission to the client. Main activities are, specification incorporation, FEED clarification, and incorporation of lessons learned from previous project. In going from IFR P&ID to IFA (Issued For Approval) P&ID, the most important activity is the design of various systems in the hull (Hwang et al., 2009). The detailed design procedure of the offshore facilities, by taking an FPSO as an example, is depicted in Figure 2. In general, the interface data between the topside and the hull of FPSO must first be incorporated, and the utility balance, which was fixed at FEED stage, must be verified at the detailed design stage. After that, the design of the systems, including hydraulic calculations, should be performed based on the updated utility balance (Hwang et al., 2009). During this procedure, preparing equipment and instrument datasheets and overall line size calculation are very important activities in achieving a balance of all systems of the hull (Mather, 2000).

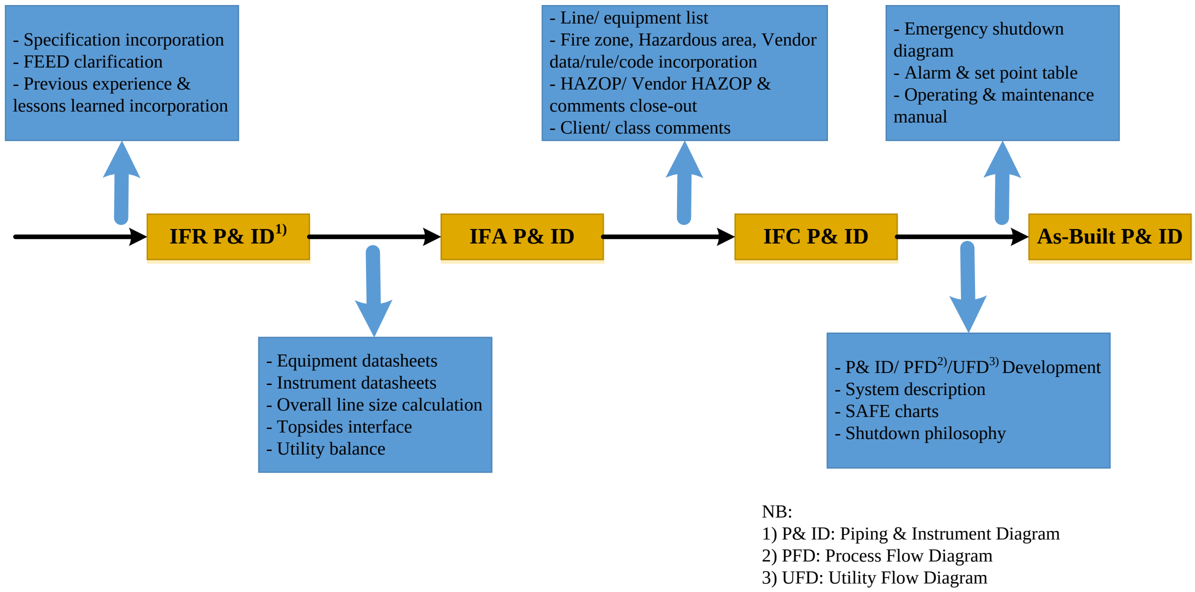

Figure 2. Detailed design procedure for P&ID of the hull of FPSO, adapted from Hwang et al. (2009)

Furthermore, in the process of constructing IFC (Issued For Construction) P&ID from IFA P&ID, the P&ID should include actual construction information. In this stage, the most important activity is the incorporation of safety factors and client/class comments. Line and equipment lists, which are very important items at the construction stage should be updated based on IFC P&ID. The design should be performed considering safety factors, such as the fire zone and hazardous area. The Hazard and Operability Analysis (HAZOP) evaluation is vital for safety in offshore design, and needs to be executed to remove potential risks during the site operation of FPSO (Hwang et al., 2009). Moreover, stakeholder's comments on consideration items of the safety, operation, and maintenance of each system should be incorporated in the IFC P&ID through technical review (Hwang et al., 2009). The interface data of each vendor and related rules/codes needs to be incorporated in IFC P&ID. In the final stage, in preparing the As-Built P&ID, the principal action is the integration of changes in the modelling or construction designs (Shimamura, 2002). Moreover, safety work and items on operation and maintenance are also important. In detail, preparing system descriptions, safety charts, shutdown philosophy, an emergency shutdown diagram, alarm, a set point table, and the operating and maintenance manual should be included at this stage (Mather, 2000).

A SIMPLIFIED RISK-BASED OFFSHORE FACILITY DESIGN (RB-OFD) METHODOLOGY

A risk-based design approach is an alternative to the prescriptive or performance-based design approaches. Under risk-based design approach, the potential hazards and consequences of undesired events related with an offshore facility design are firstly identified and, presented in a structured format. The expected frequency of each event is then determined based on historical data and expert judgment. For offshore facility design in Arctic offshore, for instance the historical data from NCS (Norwegian Continental Shelf) can be extrapolated in order to consider the ''additional'' hazards due to the Arctic operational conditions. With this information, the data can then be analysed, to identify those risks, which need to be mitigated and, to select the most appropriate risk-reduction approach. The steps involved in the risk–based offshore facility design (RB–OFD) for Arctic offshore facilities are outlined in Figure 3.

The initial step in the simplified RB-OFD methodology is to select components for further analysis. By analysing case-specific design features/components and, identifying and quantifying the unique risks involved, the industry can take appropriate measures to mitigate those risks (Sember, 2004). For instance, the range of possible design solutions pose their own peculiar demands in terms of failure modes, response to ice loading, application of winterization measures, hydrodynamic loading effects, foundation support conditions, and character of the dynamic response of not only the structure itself but also of the riser systems for oil extraction adopted by them.

Thereafter, performing evaluation of the peculiar Arctic risk influencing factors (RIFs) is the next stage. RIFs are factors that potentially affect the barriers and barrier performance (Vinnem, 2007). In the Arctic offshore, the predominant RIFs are the climatic and environmental conditions, such as snowstorms, atmospheric and sea spray icing conditions. These factors depend on various variables and they interact with each other. Their interaction is very complex and has a cumulative negative synergy effect on the offshore facilities. In combination, these factors will determine the performance of the offshore facilities or the suitability of new floating, production and mooring technologies in the region. In this stage, a considerable background knowledge and expertise is required from those involved in the engineering design and approval process, in order capture the impact of the Arctic operating environment and, to meet the defined companies and governing bodies requirements (Gareth and Luiz, 2008).

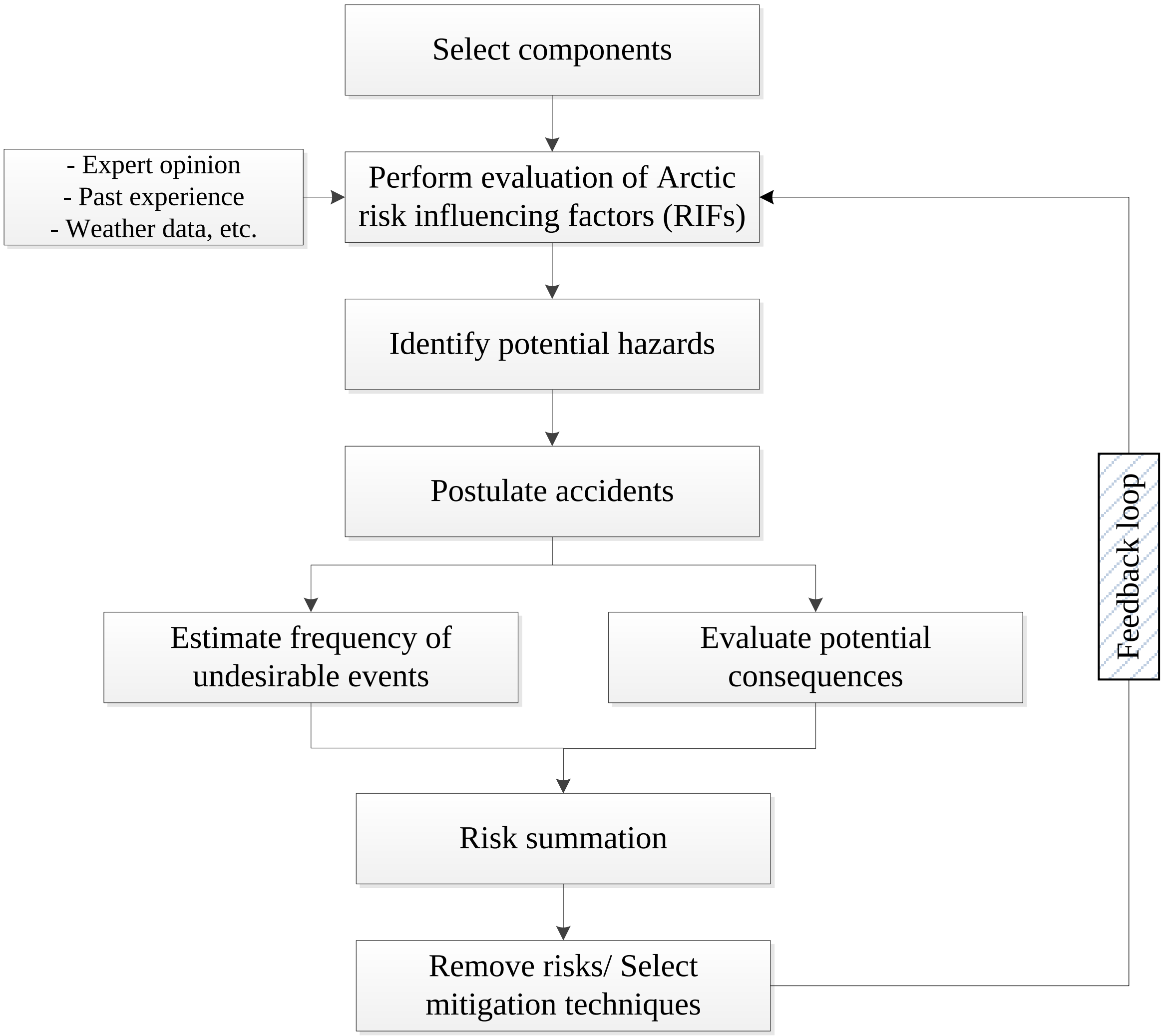

Figure 3. A simplified risk–based offshore facility design (RB–OFD) methodology for Arctic operating conditions

The next stage, requiring the identification of potential hazards of selected components and postulating accidents, while seemingly simple requires considerable professional judgment. All hazards need to be recognized during this step. This consists of those which are known, but their effects are not totally understood and those which have not yet been identified (Gareth and Luiz, 2008). In particular, for Arctic offshore facility design, risk assessment must take account of the risk of structural failure due to ice impact and ice loading, in addition to the ‘‘conventional’’ structural failure; that is, both the probability of failure and its consequences have to be considered. Further, a probabilistic consideration of ‘unforeseen’ challenges, due to the Arctic operating condition, as additional risk, should be carried out to determine the most probable levels of damage, and to check the adequacy of the design loads and resistance values.

Moreover, for Arctic offshore operations, since complete information is not available for frequency of events and potential consequences, appropriate tolerances need to be considered (Gareth and Luiz, 2008). In general, definition of scenario is a very important part of the consequence analysis, and it is related to the frequency estimates. The elements in consequence evaluation are illustrated in Figure 4. Overall, risk-based design provide a proactive systematic approach to assist the identification and categorization of the potential risks. Sound management and decision-making permits this information to be used as a tool in the design and regulatory compliance process (Gareth and Luiz, 2008).

Figure 4. Consequence Evaluation, based on Bjerketvedt et al. (1997)

After evaluating the frequency of the undesirable events as well as the consequence of a given scenario, then, the summation of the risk need to be performed. In the case of the summed risk are above the acceptance criteria, the next step will be removing the risk or putting risk mitigation measures. Acceptance criteria are criteria used as a basis for decisions about acceptable risk – a risk that is accepted in a given context based on the current standards, regulations and values of the company (Rausand, 2013). The mitigation measures will include reinforcing the already identified barriers, exploring and/or evaluating new (realistic) barriers and evaluating the hazards/ risk reduction measures. Furthermore, there should be a feedback loop where the recommendations should help to review the risk assessment and, the choice of the alternative risk reduction measures. This loop helps to detect any changes in the operating environment and their effect on the risk profile.

An illustrative example: Application of the RB–OFD methodology

The main steps of the simplified RB–OFD methodology are briefly discussed, by using FPSO as an example.

Subdivision

The entire hull of the FPSO can be split into three main zones: submerged, above water and internal. The main advantages of breakdown the hull structure in such way are (Biasotto and Rouhan, 2004):

- To logically structure the risk assessment, the consequences, barriers, inspections and repair actions are specified for each zone, and
- To adapt the sub-groups of components in accordance with the asset definition.

Risk screening

The main objective of this step is to identify those components to be included in the detailed risk analysis and, determine the suitable methodology for risk assessment for each selected component: quantitative or qualitative (Biasotto and Rouhan, 2004). In this stage, components are ranked according to their criticality; and thus the number of components selected for the quantitative analysis is reduced to the potentially most critical ones. The remaining components are analysed separately, either by qualitative analysis, semi-quantitative or using class requirements for example (Biasotto and Rouhan, 2004). Therefore, the first screening can be conducted through HAZID (hazard identification) sessions, performed by a group of different experts including the consultant and the operator (Hwang et al., 2009). In general, the work group includes risk experts, naval architects and structural engineers. The HAZID is a brainstorming exercise where each hazard or threat is identified in terms of possible causes for its occurrence, its possible effects and mitigation actions to prevent the hazard and its effects and consequences (Rausand, 2013). Each scenario is also assessed regarding the likelihood or frequency of its occurrence regarding the severity of possible effects and consequences (Biasotto and Rouhan, 2004).

Investigating the peculiar Arctic risk influencing factors

Another important challenge in the RB–OFD process is the need to employ risk management practices during the operational phase of an offshore facility. In particular, the complexities of risk management in the Arctic offshore arise from the peculiar Arctic RIFs – low sea and air temperature, sea spray and atmospheric icing, strong wind. Further, the following challenges also play an important role:

- Stringent design procedure, with respect to risk reduction measures,
- Stringent HSE requirements,
- ‘‘Untested’’ knowledge in Arctic offshore, especially Norwegian Arctic, regarding to risk management of major hazards, such as Fires, Explosions and Blow-outs,
- Winterization measures,
- Sensitive environment to disruption, on one hand, but harsh and unforgiving on the other, and
- Environmental impacts take longer to heal and cost more to remediate.

Quantitative risk assessment

Structural risks may be assessed using various models, such as quantitative degradation models and so on. This leads to compute explicitly the annual probability of failure versus time, given a quantitative probabilistic degradation model and, a set of limit state functions (Biasotto and Rouhan, 2004). For instance, for crack propagation, a fracture mechanics model can be used. Then, the consequences of events can be used to compute the total expected cost of failure. One advantage of this approach is the analysis of a high number of components with a limited amount of computational time. The main steps in quantitative risk assessment of FPSO, basically are: risk acceptance criteria, damage computations (fatigue, corrosion, etc.), and detailed risk analysis (Biasotto and Rouhan, 2004).

Qualitative risk assessment

The purpose of the qualitative assessment is to establish plans for those components where degradation models are not available or for those elements disregarded in the quantitative assessment (Biasotto and Rouhan, 2004). This is attained through the risk rating obtained after assessment of the likelihood and consequences of failure for each component. Each hazard identified is analysed in terms of its functional failure, failure mode, consequences (including the possible different scenarios), existing barriers, control methods and repair strategies (Biasotto and Rouhan, 2004). Once the possible hazards are analysed, the Risk Ranking Matrix is used to evaluate the risk of each hazard and ranks its risk level based on the Risk Acceptance Criteria for the project (Rausand, 2013). In general, the hazards identified are qualitatively classified on the basis of the likelihood and the related consequences regarding risks to personnel, to environment and to asset and production (Biasotto and Rouhan, 2004).

CONCLUSION

Offshore structures in Arctic have the added complication of being placed in harsh environment where winterization, ice loading, icing, hydrodynamic interaction effects, and dynamic response become major considerations in their design. To have a better perceptive of the hazards, mitigation measures, and risks inbuilt in planned designs of offshore facilities, this paper proposed a simplified risk-based approach to offshore facility design (RB-OFD) methodology for Arctic offshore operation. The proposed RB-OFD methodology is particularly well suited to offshore facilities in the Arctic offshore where oil and gas industry faces with unpredictable and tough challenges.

Our conclusion is that the use of risk-based approach as base of design tool of offshore facilities, by considering the peculiar Arctic challenges, is vital, for the expansion of the petroleum industry in the region. Employing the risk-based approach helps the industry to look for other design/modification alternatives with better risk reduction measures, by considering unforeseen uncertainties and challenges. However, a shortage of valid system performance data can be a challenge associated with a risk-based regulatory regime. Since such data is critical to the decision making process, the absence of valid data can be a significant restriction to this approach. Hence, the proposed approach should be updated as new data/evidence becomes available, preferably in the form of field (hard) data reflecting the actual operational experience in this Arctic region.

REFERENCES

Abimbola, M., Khan, F. & Khakzad, N. 2014. Dynamic safety risk analysis of offshore drilling. *Journal of Loss Prevention in the process industries*, 30, 74-85.

bimbola, M., Khan, F., Khakzad, N. & Butt, S. 2015. Safety and risk analysis of managed pressure drilling operation using Bayesian network. *Safety Science*, 76, 133-144.

Ayele, Y. Z., Barabadi, A. & Barabady, J. 2016a. Dynamic spare parts transportation model for Arctic production facility. *International Journal of System Assurance Engineering and Management*, 7, 84-98.

Ayele, Y. Z., Barabadi, A. & Barabady, J. 2016b. A methodology for identification of a suitable drilling waste handling system in the Arctic region. *International Journal of Environment and Waste Management*, 17, 227-250.

Ayele, Y. Z., Barabadi, A. & Droguett, E. L. 2016c. Risk-Based Cost-Effectiveness Analysis of Waste Handling Practices in the Arctic Drilling Operation. *Journal of Offshore Mechanics and Arctic Engineering*, 138, 031301.

Ayele, Y. Z., Barabadi, A. & Markeset, T. 2013. Spare Part Transportation Management in High North.

Ayele, Y. Z., Barabady, J. & Droguett, E. L. 2015. Risk assessment of Arctic drilling waste management operations based on Bayesian Networks. Safety and Reliability of Complex Engineered Systems: ESREL 2015, Zurich, Switzerland. CRC Press 1907-1915.

Barabadi, A., Gudmestad, O. T. & Barabady, J. 2015. RAMS data collection under Arctic conditions. *Reliability Engineering & System Safety*, 135, 92-99.

Biasotto, P. & Rouhan, A. Survey and Inspection management for FPSOs. Proc., 23rd International Conference on Offshore Mechanics and Arctic Engineering, 2004.

Gareth, C. B. & Luiz, P. F. 2008. Practical Role of Classification Societies in Verifying Safe Design on Offshore Oil and Gas Facilities. *In:* SHIPPING, A. B. O. (ed.). Houston, Texas, USA.
Guo, Q., Geehan, T. & Pincock, M. 2005. Managing Risks and Uncertainties in Drill Cuttings Re-Injection in Challenging Environments–Field Experience from Sakhalin Island. SPE 93781, paper presented at the SPE/EPA/DOE E&P Environmental Conference, Galveston, March 2005.
Hartke, R. 2012. *The Application of Quantitative Risk Analysis Techniques in the Oil and Gas Industry* [Online]. Oil and Gas Monitor. Available: http://www.oilgasmonitor.com/application-quantitative-risk-analysis-techniques-oil-gas-industry/1966.
Hwang, J. K., Bang, G. J., Roh, M. I. & Lee, K. Y. 2009. Detailed Design and Construction of the Hull of an FPSO (Floating, Production, Storage, and Off-loading Unit).
Khakzad, N., Khan, F. & Amyotte, P. 2013. Quantitative risk analysis of offshore drilling operations: A Bayesian approach. *Safety Science,* 57, 108-117.
Mather, A. 2000. Offshore Engineering – An Introduction. *Witherby*.
Rausand, M. 2013. *Risk assessment: theory, methods, and applications,* John Wiley & Sons.
Sember, W. J. 2004. A Risk-Based Approach to Offshore Classification.
Serratella, C. M., Wang, G. & Conachey, R. 2007. Risk-based strategies for the next generation of maintenance and inspection programs. 20-21.
Sshimamura, Y., 2002. FPSO/FSO: State of the Art, *Journal of Marine Science and Technology,* VOL. 7, NO. 2, PP. 59-70.
Vinnem, J.-E. 2007. *Offshore risk assessment: principles, modelling and applications of QRA studies,* Springer Science & Business Media.
Øien, K. 2013. Remote operation in environmentally sensitive areas: development of early warning indicators. *Journal of Risk Research,* 16, 323-336.