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Multicriteria risk assessment framework for components' risk ranking: Case study of a complex oil and gas support structure

Uzoma Okoro | **Athanasios Kolios**

Offshore Energy Engineering Centre, School of Water, Energy and Environment, Cranfield University, Cranfield, UK

Correspondence
Athanasios Kolios, Department of Naval Architecture, Offshore and Marine Engineering, University of Strathclyde, Glasgow G4 0LZ, UK.
Email: athanasios.kolios@strath.ac.uk

Abstract

This paper develops and applies a methodology for multicriteria risk assessment aiming to overcome the limitations of the conventional failure mode and effect analysis where risk evaluation is performed at the higher level consideration of occurrence, severity, and detection. Breaking down these higher level criteria into a set of parameters and variables makes it possible to analyse in greater detail the physical, environmental, and process conditions of the components in response to the activities of factors of biological, chemical, and mechanical stresses. By adopting a framework comprising multicriteria decision analysis, Delphi method, nominal group technique, and technique for order of preference by similarity to ideal solution, the fidelity, transparency, and repeatability of the assessment are ensured. The highlight of the paper is the demonstration of the capability of the model for time dependent assessment, which allows the comparison between different states of the asset's conditions through alteration in the risk profiles. The analysis conducted shows the efficient applicability of the method for the reference case study of an offshore oil and gas support structure, proving its relevance for systems of similar class.

KEYWORDS

failure mode effect analysis, multicriteria risk assessment, risk assessment criteria, TOPSIS method

1 | INTRODUCTION

In the foreseeable future, global demand for energy will continue to be on the rise: Oil and gas will continue to dominate as the main sources, as predicted by the U.S. Energy Information Administration (2016). The offshore oil and gas industry is evolving—a characteristic that has been aggravated by fluctuations in oil price, increased awareness of environmental pollution, tighter safety regulations (on personnel and the environment), and rising market instability. Offshore operators are now exploring various options to remain competitive in the market where efficiency and cost-effectiveness are sought in exploration, drilling, and production globally. There is renowned interest in marginal fields and a need for the extension of service lives of offshore facilities in stations. Exploration and production activities have, in recent times, moved to deep and ultradeep water fields, with the aim of increased production. Vessels not initially meant for the purpose of drilling and production are being converted for the said purpose; laid-up offshore drilling and production rigs are being reintroduced into service at short notice, expanding the operational capacity of existing units (David, 2012). These facts have increased the complexity of design and operation of structures/systems and safety management processes.

As it is impossible to eliminate risks in totality, risk managers are left with the only option of striking proper balance between exploring these opportunities on the one hand and avoiding accidents and catastrophes on the other (Aven, Vinnem, & Wiencke, 2007). System safety can only be ensured by knowing, understanding, and choosing the risks to except, and there is growing expectation that systematic risk management is the key to achieving this. An effective risk management framework is instrumental to the extension and efficiency of operations, increasing production, and lowering the overall cost of production, considering that capital expenditure is distributed over a larger production output. In this context, risk is defined as "the effect of uncertainties on the objectives" (International Standard

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Organisation, 2009), where effect refers to a deviation from the expected. Risk assessment provides a structured process that identifies how objectives may be affected and estimates the level of risk commensurate with the consequences of the effect on the objectives and the probability of such effect. Risk assessment is used to support decision making to manage the risk. Risk management involves the aspects of risk assessment and decision making. A comprehensive review of risk-based methods can be found in Ioannou, Angus, and Brennan (2017).

Generally, cost-effective safety processes, such as inspection, maintenance, and repair for offshore energy structures, are extremely expensive compared with those of onshore production facilities. An effective maintenance plan targets components with the most urgent failure modes or mechanisms (Linares, 2002; Sakai, 2010), while deploying the limited resources. Such decisions are supported by risk analysis, wherein sources of uncertainty that matter to the integrity of offshore oil and gas production structures and systems are considered systematically in decision making.

Measures of safety insurance in offshore structures include, in part, keeping risk under an acceptable level—specified for the component/substructure—by adopting adequate design criteria and quality assurance and control in the design, fabrication, and operation phases. For instance, the desirable level of safety/risk achievable through structural design is contained in the design criteria formulated in terms of the limits states: ultimate limit state, fatigue limit state, and serviceability and accidental limit states (International Standard Organisation, 2013). The design of offshore structures forces a compromise between safety and construction cost: To cut on cost, hazardous equipment, and vessels, multiple wellheads, separating offices and accommodations, are often built too near each other for safety with the use of a number and types of necessary barriers—determined through extensive risk-based studies—to reduce the risk of major accidents to a level in compliance with the prevailing regulatory authority. Successful risk management requires reflective monitoring of the condition/status of the equipment/structure, the effects of the human behaviour, and the effectiveness of safe operating procedures. All these factors will have been considered before an operating licence is issued. Throughout their service life, assets should be maintained against inevitable deterioration phenomena - for example fatigue and corrossion- through inspection, repair and maintenance as well as quality assurance and control of the engineering processes (Moan, 2005). Without Inspection, Repair, Maintenance (IRM), the assumed performance of the structures and the process safety barriers cannot be said to have met the standard to which it was designed. Therefore, differing inspection and maintenance has the inevitable consequence of elevating the major accident hazards (MAH) residual risk.

The questions operators must answer are—by how much and whether this risk is tolerable? (Neill, 2016).

The information involved in such decision comes from multiple sources and varies all the time. In general, quality of the result of a risk assessment model depends, to a large extent, on the accuracy and the volume of data considered in the analysis. However, managing reasonably large volume of data still constitutes a challenge to majority of available risk assessment methodologies. There is always a trade-off between comprehensiveness of input data and quality of the model result. Large data inputs are difficult to handle (Muhlbauer, 2004) whereas scanty data inputs are not representative enough or renders some risk factors and/or their interactions obscure.

Many methodologies have been proposed and applied to obtain measures of risk level inherent in a structure/component as it relates to prevalent operating process conditions and the performance of inspection, maintenance, repair, and test. Monte-Carlo-based risk assessment has been applied in managing large computing resources involving numerous random variables characterised by complications and high cost such as ship collision damage models. Sun, Zhang, Ma, and Zhang (2017) applied a hybrid method comprising artificial neural network and Monte Carlo system to assess quantitatively the event of a ship collision damage. Although in a related application targeting risk due to dropped object in ship, a combination of artificial neural network and genetic algorithm is trained based on the collision data and used as an alternative for the computational finite element modelling performed within Monte Carlo system methodology. However, Monte-Carlo-based risk assessment does not have enough flexibility for a full blown quantitative analysis to be realized: Some system variables, combinations of which can cause accident, can be rendered obscure.

Ren, Jenkinson, and Wang (2009) used a fuzzy Bayesian network-based model to investigate causal relationship among risk factors and possibility of accident resulting in the offshore operations thereby reducing the obscurity effect. Also, in a related research by Bolsover (2015), Bayesian network method is employed to monitor risk in real time and so enable safer decision making.

Another known risk assessment tool widely applicable for offshore energy structures and systems is the failure mode and effect analysis (FMEA). FMEA has been applied as an essential decision support tool in risk and maintenance management involving prioritization of failure modes based on estimated risk levels (Braaksma, 2012;. Wang, Cheng, Hu, & Wu, 2012; Yang, Huang, He, Zhu, & Wen, 2011). Arabian-Hoseynabadi, Oraee, and Tavner (2010) applied FMEA to study the reliability of an offshore wind turbine, and the result of the model showed convincingly similarities with field failure rate data for assemblies. However, the FMEA model for risk priority number suffers certain limitations due to its simplicity (Chang & Cheng, 2010). It does not take into account prevalent inspection data—that is, data of current inspection activities containing current state of information—in the selection of index number for occurrence, effect severity, and detection (O, S, and D; Tsinker, 2004). Another observation counting against FMEA is that the elicitation of indices for the risk factors O, S, and D do not follow, in most cases, any logical or systematic procedure, rather it is done out of intuitive tacit knowledge of the risk analyst. For this reason, it is often referred to as a “high level” consideration of risk. Risk priority number (RPN) is derived from only three factors mainly in the terms of safety and no consideration of interaction between these factors. No consideration of indirect relationships between the components. As a consequence, such risk conclusion is hardly transferrable, nonrepeatable, and inconsistent: that is, decision makers will often elicit scores that will contradict themselves (Dodgson, Spackman, Pearman, & Phillips, 2009).

From the review of the available risk assessment methodologies in offshore risk assessment, the existing risk assessment models lack the capacity to handle risk assessment of larger and more technically complex structures and systems of recent times. They (a) lack a systematic way of considering large volumes of data at various levels of details and (b) lack a way to consider interrelationships between the various failure modes and the system variables.

Okoro, Kolios, and Cui (2016) proposed and implemented an enhanced, condition-based multicriteria risk assessment framework that (a) identifies variations in the conditions and environment of the components of an offshore structure or system, (b) identifies failure modes and mechanisms to which the components can be exposed as a result of these variations, (c) analyses the implicit relationship/interaction between these variations and the O, S, and D of the failure modes/mechanisms, and (d) takes a guided decision on prioritization. In so doing, the framework identifies unforeseen failure and integrity challenges that site personnel may not have previously encountered and that, in many cases, can cause unexpected obstruction to the flow of production, resulting in costly emergency repairs to get the asset back on line.

This paper demonstrates the development and application of an enhanced condition-based multicriteria risk assessment framework for the assessment of an offshore jacket support structure. Reference is made to publicly available literature to identify components of the support structure unit and their failure modes and mechanisms. Evaluation is conducted by a team of field experts to replicate the experience of a real case study. Compared with traditional risk analysis approaches, the proposed model aims to overcome limitations listed earlier, allowing for a more granular assessment of the risk profile of an asset, reducing the degree of bias that is often introduced when dealing with experts' opinions and increasing repeatability of the assessment. Further, it allows for the condition-based assessment of components and systems incorporating inspection/monitoring information that become available during operation of an asset.

2 | SYSTEM BREAKDOWN OF A JACKET SUPPORT STRUCTURE

2.1 | Parts and functions

Fixed platforms are described as the class of offshore oil and gas structures that are erected on steel legs and anchored directly into the seabed (Graff, 1981). They support a deck, with space for drilling rigs, production facilities, and crew quarters. Such platforms are, by their immobility, designed for very long-term use: A typical offshore structure is designed for a service life of about 30 years (Moan, 2008). The jacket substructure and the foundation together form what is referred to as the jacket support structure. This section reviews the components of an offshore oil and gas jacket support structure, identifying typical failure modes and mechanisms of the structure.

The support structure unit, as the name implies, supports the deck structure, which is also known as the top side. It consists of the transition piece, steel tubular legs and horizontal braces, conductor guide frame, conductors, riser and riser-clamp, piles, pile sleeve, skirt pile and sleeve cluster, and mudmat (Graff, 1981). Steel tubular chords are strengthened by welding internal ring stiffeners and joined to form a jacket leg. A leg, on average, contains about four chords. Similarly, steel tube members—but of smaller diameter relative to the chords—called braces interconnect with the legs (diagonal-in-vertical plane, horizontally and diagonal-in-horizontal plane) to form a single rigid structural unit or a space frame called the jacket. The jacket provides support and protection to well conductors. These are a series of vertical tubes of about 0.76 to 0.91 m diameter used to drill the well; the riser is another vertical tube but of smaller diameter (compared with the conductors; 0.36 to 0.41 m) used for (a) pumping seawater to the decks, (b) heat exchange, (c) connecting pipelines to other platforms or to the shore, and many other processing functions (Graff, 1981). The jacket provides a guide to the foundation piles and other appurtenances, such as the boat landings, mooring bitts, barge bumpers, corrosion protection system (anode), navigation aids, and jacket walkway. Most parts of the jacket operate permanently below the water line. Piles are driven through their legs to secure them to the seabed and into the ocean floor. The legs serve both as bracing for the piles against lateral loads and as a template for the initial driving of the piles during installation. Legs are secured from settling (during installation) through welding to a series of rings and gussets at the top of the pile, so that the legs carry no load from the deck structure but merely hang from the top of the piles. This, in addition, provides lateral support to the piles—the main load bearing structure (i.e., carries the loads acting on the substructure). The deck legs, bearing the weight of the deck structure, connect the top of the piles—extending from above the mean low water and the template. The jacket also holds the piles' extension in position from the mud line to the deck substructure. Depending on the bearing capacity of the soil underlying the platform, skirt piles may also be required for improved stability. The pile sleeve is a circular ring of pipes welded to the bottom of each jacket's leg for the passage of additional piles. Clusters of skirt pile sleeves may be required based on the soil analysis test. During installation of the jacket, cement is poured into the gap between the piles and the pile sleeves, acting as an efficient grout and effectively securing the whole structure to the seabed. Below the pile clusters are the mud flaps, which rest on the bottom of the mud. A descriptive illustration of a typical jacket substructure is shown in Figure 1.

2.2 | Information/data requirement and collection

Jacket support structures operate in underwater locations and the structural integrity of installations in such an environment should be assessed taking into account threats from mechanical, chemical, and biological stresses both from own weight and environment forces. Wherever they are deployed, offshore installations operate within a certain risk envelope, as stipulated by regulations. In U.K. waters, installations must satisfy the Offshore Installations (Construction and Survey) Regulations 1974 under Section 3 of the Mineral Workings (Offshore Installations) Oct. 1971 (Health and Safety Executive, 2015). These stipulate the relevant technical requirements and specify that each offshore installation must possess a certificate issued by a certifying authority stating that it is fit for use in U.K. waters. The “Certificate of Fitness” is issued based on the outcome of an independent assessment of the design, method of construction and operations manual, and on associated surveys carried out by surveyors appointed

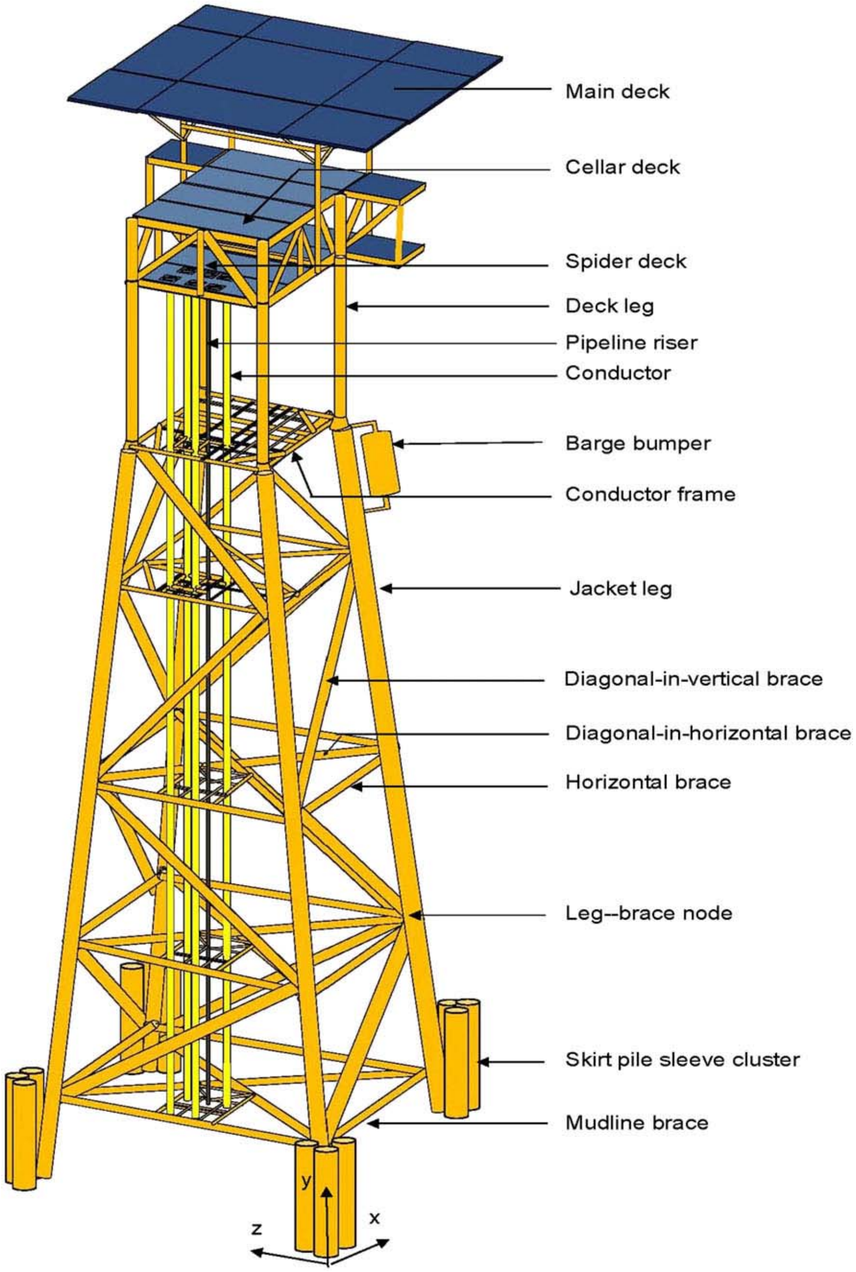

FIGURE 1 Main components of a typical jacket structure

by the certifying authority. The basis, on which a certificate is issued, is outlined in the “Guidance on the Design and Construction of Offshore Installations” (Department of Energy). An example of such a regulation is the design and construction regulation that is active for operations in U.K. waters. The design and construction regulation mandates that the integrity of the structure shall be maintained at all times, within acceptable levels (Health and Safety Executive, 1996). Maintaining the integrity of the structure within the band of safety amid offshore uncertainties and budget constraints is a daunting task for every maintenance manager. This usually begins with data collection.

Data for the risk assessment of offshore structures can be sourced from the records of past performance and maritime systems and experiences with similar facilities, etc. The most reliable sources of data, however, are inspection data (both past and present). Known failure hotspots include, but are not limited to, primary framing—for example, leg/pile connections, pipeline risers support, J-tubes and support, conductor guide framing, riser guards, boat landings and fenders, secondary framing and appurtenances, underwater cathodic protection system, and corrosion coating of components in the splash zone (British Standard, 2007; Health and Safety Executive, 2009; Shell, 2001). Additional information may be sought from—as built drawings of the structure: new information on environmental data; permanent actions and variable actions; previous and future planned functional requirements; design and fabrication specifications; original corrosion management philosophy; original design assumptions; design, fabrication, transportation, and installation reports, which should include information about material properties (e.g., material strength, elongation properties and material toughness test values or concrete strength development), weld procedure specifications and qualifications and weld repairs during fabrication, nondestructive testing (extent and criteria used), pile driving record (action effect during pile driving and number of blows); weight report that is updated during service life; in-service inspection history, including information on marine growth, corrosion, cracks, dents and deflections, scour, damages due to frost, impact, erosion/abrasion, chloride intrusion, leakages, sulphate attacks; information on in-place behaviour including dynamic response (measurements and observations); information and forecast for seabed subsidence; information on modifications, repair and strengthening to the structure during service; soil conditions, pore pressures and consolidation; and experience from similar structures. It is reiterated that of utmost importance at this stage of information/data gathering is the accuracy of the information used to perform a risk level estimation (David, 2012). Where this information is lacking or insufficient, it is recommended that assumption to be on the "safe side" be made which, of course, must be documented in the database.

2.3 | Inspection of components of offshore jacket support structures

Inspection and monitoring reports are the two most reliable sources of input data for a condition-based risk assessment. Data from recent inspections reduce any uncertainty about the nature of damage to and conditions of components of the offshore support structure. General visual inspection—also called a damage survey—is carried out on parts of the platform to detect anomalies in the form of physical damage. Cathodic protection inspection takes readings from selected critical locations. Cathodic protection inspection and general visual inspection of the anodes provide information on the state of depletion and general well-being, respectively. In a scour inspection, records of the incidence of suspended members are taken. Debris inspection details records of anomalies in accumulated debris. Marine growth inspection collects readings of the marine growth for anomaly analysis, which can be carried out using a graded probe. The probe, when stabbed into the platform components of interest, gives Marine growth (MG) reading from which estimates can be made of the thickness, coverage, type, and pattern of marine growth from water line to mud line. A typical classification for anode depletion and well-being is shown in Table 1.

TABLE 1 Classification of depletion of anode

Percentage (%) depletion	Classification	Grade
<25	Slightly depleted	1
25–50	Moderately depleted	2
50–75	Heavily depleted	3
75–100	Totally depleted	4
Disconnected	Totally buried	5

Flooded-member-detection inspection is carried out to check for the presence of water in the watertight compartments of the subsurface members. Alternating current field measurement inspection is done for crack detection and sizing—especially those hidden under paints and other forms of coating—for anomaly analysis. For anomalies related to internal corrosion rates or internal flaws, ultrasonic testing readings of thickness are taken instead. Conductor inspection is carried out for anomalies detection associated with rate of corrosion (internal and external); similar readings should be taken for protection tubes (also referred to as J-tubes). Other forms of inspection include boat landing inspection, clamp inspection, and riser face measurements taken at probe elevation. Listed in Table 2 are some examples of nondestructive techniques and their applications.

3 | AN ENHANCED CONDITION-BASED MULTICRITERIA RISK ASSESSMENT FRAMEWORK

3.1 | Description of framework

The philosophy of the enhanced condition-based multicriteria risk assessment is based on the definition of risk as contained in ISO 31000 (2009): "the effect of uncertainties on the objectives." Objective, as used in this context, is interpreted as the prevention of various failure modes and mechanisms by which the components of structures and systems can lose their integrity status or fail to fulfil their intended function. Operating the structure/system under such conditions can cause unexpected failure, disrupt the production process, lead to unplanned maintenance, and in severe cases cause major accident hazards (National Aeronautics and Space Administration, 2013; Officer of the watch, 2013; Paté-Cornell, 1993; US Government, 2011). These failure mechanisms are influenced by the physical, environmental, and service conditions of the components. Some examples of these conditions are H_2S content in the cargo, water cut, ageing,

TABLE 2 Examples of nondestructive techniques and applications for condition survey

Condition defect	Inspection method
Surface crack/flaws	Close visual inspection and magnetic particle Inspection
Subsurface (shallow) cracks/flaws without coating	Magnetic particle and ultrasonic testing
Thickness detection	Radiography and ultrasonic
Cracks for depth, size, length, and orientation without removing coating	Shear wave inspection
Internal flaw/crack detection	Radiography
Dents, buckles, or distortions. Significant coating failure, severe corrosion, condition of corrosion protection (wastage of coating and sacrificial anode)	General visual inspection
Cracks, crack-like defects, local corrosion, or pitting	Close visual inspection
Locate and size surface crack without removing coating	Alternative current field measurement
Measurement of depth of pitting	Pitting gauging
Thickness measurement without removing coating from where excessive corrosion is suspected	Ultrasonic testing
Detect water ingress in watertight member	Flooded member detection

capacity of the cathodic protection systems, to mention a few. In the developed model, these are referred to as parameters; this model considers uncertainties from the point of view of the parameters and works out their influence on the objectives, that is, failure and failure prevention. For organisational purposes, these parameters are grouped herein under variables. The enhanced risk assessment refers to the three dimensions of the risk assessment model: failure modes and mechanisms, variables, and parameters. Some examples of variables of external corrosion are given as—exposure, mitigation, and resistance. The generic list of the failure modes and mechanisms, variables, and parameters is given in Table 3. A “fundament unit” of the analysis model contains/refers to a failure mode/mechanism *fi*, variables *x*, parameters *p*, and preference values *v*, as shown in Figure 2. A complete assessment record will contain all the failure modes and mechanisms alike.

Generally, behavioural science problems involving prioritization is modelled by evaluating the performance of the alternatives/options across strings of evaluation measures/criteria. These evaluation measures/criteria are formulated to reflect individual measurable indicators of performance relative to the goal of the analysis, whereas the groups of criteria/cluster/the value tree reflect subobjective to the single main objective that underlies the behavioural science problems. Such models must deal with some issues that affects accuracy of the analysis outcome. First, it must deal with the issue of inequality in importance of the evaluation measures/criteria with respect to the goal of the analysis (Choo, Schoner, & Wedley, 1999; Dodgson et al., 2009; Jia, Fischer, & Dyer, 1998). Second, it must deal with issue related to the preference scale for the evaluation measures/criteria. It is often the case that each evaluation measure/criterion have unique scale for representing strengths of preference for the alternatives and that these scales have different units, as such cannot be implicitly compared with others.

In the context of this work, weights are used to resolve both issues; to discriminate among the various perceptions of importance of the partial objectives represented by the evaluation measures/criteria (Keeney & Raiffa, 1993; Stewart & Belton, 2002) and to determine trade-offs between the number of units of one criterion, the Decision makers (DMs) are willing to give up in order to improve the performance of another criterion by a unit category (Diakoulaki & Grafakos, 2004). Such weighting scheme is referred to as compensatory weighting. Some examples of compensatory weighting schemes are trade-off method (Keeney & Raiffa, 1993), swing methods (Edwards & von Winterfeldt, 1986), resistance to change (Rogers & Bruen, 1998), Macbeth (Bana, Costa, & Vansnick, 1994), COJOINT/HOLISTIC approach, to mention but a few. Some of these schemes have been elaborately discussed (see Hobbs, 1980, 1986; Weber & Borcherding, 1993, as well as in Diakoulaki & Grafakos, 2004; Dodgson et al., 2009; Stewart & Belton, 2002, for details).

In addition to the challenges posed by inequality in criteria importance and units of the preference scales mentioned above, weighting scheme also needs to deal with different forms of biases. (Montibeller & von Winterfeldt, 2015) identified and discussed in detail the cognitive and motivational biases affecting elicitation of attribute weights in decision and risk analysis. Each scheme can assign different sets of weights to the parameter set. This raises the question of which scheme should be selected in preference to the other for a given multicriteria decision analysis (MCDA) problem? Diakoulaki and Grafakos (2004) discussed qualities of a weighting scheme that makes them a good choice for a given prioritization problem to include simplicity and transparency, degree of inconsistencies, articulation of preferences, ability to handle wide range of number of criteria, and sensitivity to impact change. Stewart and Belton (2002) showed that weights of criteria are intimately connected to the measurement scale used. This essence is captured in the SWING weighting scheme. This is also in agreement with the comparison study carried out by Diakoulaki and Grafakos (2004). However, when the evaluators are pooled from a set of competent subject matter experts, it is possible to get reasonably accurate weighting using faster weighting schemes like point allocation method.

Many authors advocate that the weights can only be interpreted in the context of the MCDA technique adopted in solving the multicriteria problem (Choo et al., 1999). Hence, to avoid the use of wrong weighting scheme for a selected MCDA technique when finding a solution to the multicriteria decision problem, the risk assessor needs as much knowledge of the different MCDA methods and their unique aggregation algorithms as the different weighting schemes. To this effect, many MCDA methods for prioritization of alternatives (Bell, Hobbs, Elliott, Ellis, & Robinson, 2001; Garvey, 2009; J. J. Wang, Jing, Zhang, & Zhao, 2009; Weber & Borcherding, 1993; Zardari, Ahmed, Shirazi, & Yusop, 2015) are reviewed. Though the ideas developed in this framework are recommended for application to structures in the offshore environment, the basic principles are applicable for other complex infrastructures.

3.2 | Framework implementation

The implementation of the enhanced multicriteria risk assessment is covered in three stages: (a) preassessment/database development stage, (b) assessment/framework implementation stage, and (c) postassessment/multicriteria risk analysis stage. These stages are depicted in Figure 3 and discussed in the sections that follow.

3.2.1 | Preassessment/database development stage

This stage mainly involves information gathering. Information relevant to risk assessment of the structure under consideration is identified and gathered in the database. Typical information for the database includes failure modes and mechanisms and their respective parameters. These parameters classify the different condition-states of the components under such categories as “as-built,” “aged,” “failed state,” and other levels possible. As currently practised, “as built” condition-states are set as baseline conditions for evaluation. This however is subject to the agreement between the assessors and the owner. An “as-built” condition is the condition of a new and fit-for-purpose component. This, with the agreed failed-state conditions, will serve as the baseline for condition state calibration.

3.2.2 | Assessment/framework implementation stage

This stage of the analysis compares the conditions of each identified component against the parameters, one after the other, and elicits

TABLE 3 Generic list of failure mechanisms and variables of offshore jacket structure

No (*i*)	Failure mechanism (*f*)	Variables (*x*)	Parameters (*p*)
1	External corrosion	1.1-Exposure (Occurrence variable)	1.1.1-Sediment type; 1.1.2-Organic content in sludge; 1.1.3-Organic content in sand; 1.1.4-Water depth; 1.1.5-Availability of N&P; 1.1.6-Background temperature; 1.1.7-Environment of exposure; 1.1.8-Exposure environment (for concrete); 1.1.9-Temperature of surrounding (for water); 1.1.10-Water resistivity; 1.1.11-Exposure environment chlorine concentration; 1.1.12-Electrical resistivity of concrete; 1.1.13-Splash zone corrosion rate; 1.1.14-Corrosion rate of rebar (Icorr); 1.1.15-Corrosion rate in submerged zone and tidal seawater; 1.1.16-External corrosion rate
		1.2-Resistance	1.2.1-Age of assets; 1.2.2-Compressional strength of concrete; 1.2.3-Type of coating.
		1.3-Safeguard	1.3.1-Condition of the coating on concrete; 1.3.2-Adhesion of coating on structure; 1.3.3-Uniformity of coating condition on structure, 1.3.4-Condition for the particular coating; 1.3.5-Adherence to established standard for coating repair & maintenance; 1.3.6-Redundancy; 1.3.7-Interval of inspection; 1.3.8-Quality of inspection-technology; 1.3.9-Quality of inspection-inspectors; 1.3.10-Loss of metal; 1.3.11-Assessment of structural condition based on visual inspection; 1.3.12-Percentage of assets inspected in the last 5 years; 1.3.13-Established asset's inspection frequency met; 1.3.14-Failure history
2	Internal corrosion	2.1-Exposure	2.1.1-Product corrosivity; 2.1.2-Evidence of MIC; 2.1.3- Evidence of erosion; 2.1.4-Presence of dead-leg; 2.1.5-Corrosion rate; 2.1.6-Percentage loss of metal (ILI).
		2.2-Severity	2.2.1-Effect on structure health; 2.2.3-Effect on product; 2.2.4-Personnel health and safety; 2.2.5-Effect on environment; 2.2.6-Effect on image; 2.2.7-Penalty
		2.3-Safeguard	2.3.1-Time since the last inspection; 2.3.2- Failure history; 2.3.3-System inhibition and/or biocidal; 2.3.4-Cleaning compliance programme; 2.3.5-Redundancy; 2.3.6-Emergency control; 2.3.7-Accessibility & ease of repair
3	Welding, assembly, & construction	3.1-Welding	3.1.1-Year of welding; 3.1.2-Certification of quality of the base material; 3.1.3-Weld quality
		3.2-Construction	3.2.1-Design code per industrial standard; 3.2.2-Filler material; 3.2.3-Joint type; 3.2.4-Quality of pipe; 3.2.5-Number of repairs during construction
		3.3-Detectability	3.3.1-Percentage compliance of the total number of inspections to be performed in welding; 3.3.2-Susceptibility of state welds; 3.3.3-Construction defects (dents, bends, notches, marks, folds, etc.); 3.3.4-Qualified and benchmarked repairmen processes; 3.3.5-Quality control and assurance during construction
4	Manufacturing defects	4.1-Material	4.1.1-Pipe type; 4.1.2-Material; accessories under & conformable with piping class
		4.2-Quality	4.2.1-History of manufacturing faults; 4.2.2-Material quality certification; 4.2.3-Active features such as foundation type, specification, grade, diameter information etc.
5	Fatigue	5.1-Free span	5.1.1-Evaluate undercuts per “scour analysis”; 5.1.2-Interaction of the free span
		5.2-Fatigue	5.2.1-Surge/surf; 5.2.2-Susceptibility to fatigue
		5.3-Mitigation	5.3.1-Actions
6	Overloading and impact	6.1-Operating characteristics	6.1.1-Wind condition during berthing/anchoring; 6.1.2-Condition of currents during berthing/anchoring; 6.1.3-Effect of interns' boats (for Docks, Maritime's only); 6.1.4-Variation of ship draft during docking/anchoring; 6.1.5-Percentage of light weight cargo piles (i.e., under bridges; pipe racks) visually inspected in past 5 years; 6.1.6-Percentage of heavy load piles installed; 6.1.7-Visually inspected in last 5 years; 6.1.8-Permanent loads; 6.1.9-Variable loads; 6.1.10-Deformations
		6.2-Safeguard measures	6.2.1-Time since last inspection of piles; 6.2.2-Visual inspection of the safety critical systems; 6.2.3-Repair piles affected by impacts/overload; 6.3.4-Proper functioning of drainage system of piling docks; 6.3.5-Defence system ensures absorption of impact energy from ships
7	Third party damage	7.1-Activity level	7.1.1-Activity area
		7.2-Mitigation	7.2.1-Patrol; 7.2.2-Depth covered; 7.2.3-Mechanical protection; 7.2.4-Ballast piping; 7.2.5-Parameters meet DNV OS - F101; 7.2.6-From deep below the water surface to the active third-party damage region
		7.3-Past records	7.3.1-Analysis of objects falling under Annex PoF impacts party; 7.3.2-Signpost; 7.3.3-Community Education Programme, Communications Plan; 7.3.4-Abnormalities (mechanical damage) detected and sized by ILI; 7.3.5-Annex PoF impacts on anchors
8	Incorrect operations	8.1-Safeguards	8.1.1-There are established operating procedures and system maintenance; 8.1.2-There are operators trained in using procedures; 8.1.3-History of failure caused by incorrect operations; 8.1.4-Audits; 8.1.5-Actions taken in accordance with the audit findings
9	Climate and external forces	9.1-Scour on seabed	9.1.1-Debris flows; 9.1.2-Bed depressions due to gas leaks; 9.1.3-Active faults; 9.1.4-Seismic classification based on NSR-10; 9.1.5-Record of failures due to undercuts; 9.1.6-Stability in the bottom of the sea; vertical stability criterion and two lateral stability criteria
		9.2-Environmental features	9.2.1-Soil susceptible to liquefaction of sandy strata during seismic events; 9.2.2-Earthworks (landslides, erosion); 9.2.3-Topography and bathymetry conditions; 9.3.4-Heavy rains; Tides; 9.3.5-Hurricane history

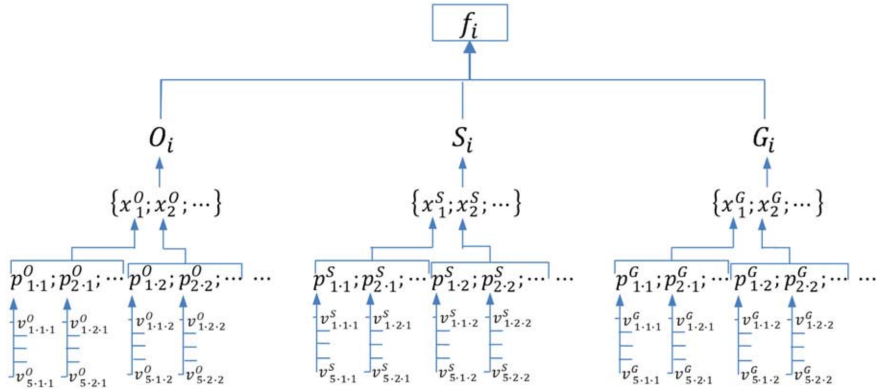

FIGURE 2 Structure of modelling generic failure modes through discretisation in variables *x* and parameters *p*

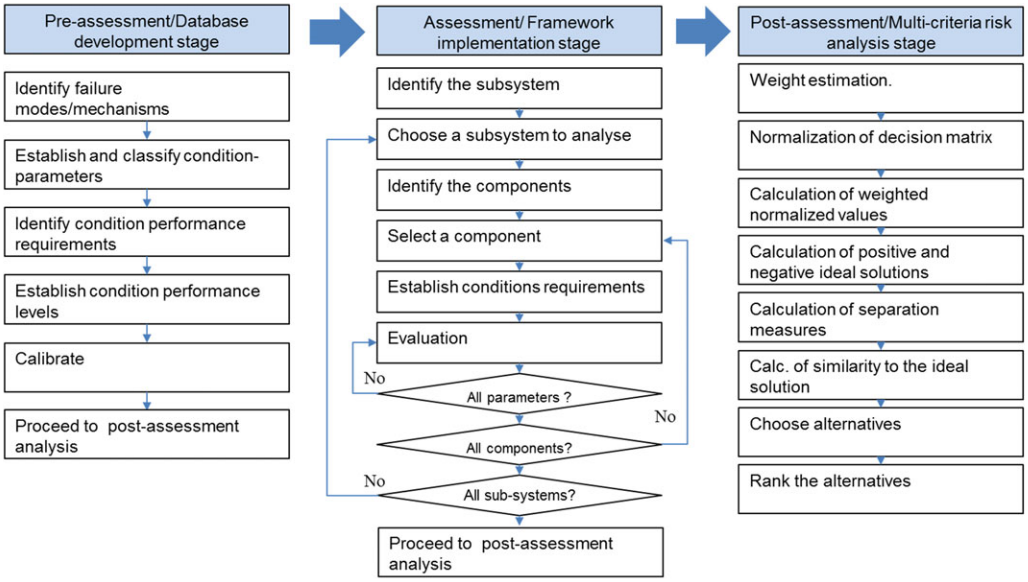

FIGURE 3 Framework for enhanced condition-based risk assessment model based on collection of performance data from identified experts, multicriteria evaluation, and ranking of risk profiles for individual components and failure modes

scores corresponding to the class that best describes those conditions. This score is referred to as the parameter-specific preference score. The condition of each component is evaluated against the baseline conditions and rated on a scale of 1 to 5. On this rating scale, 1 represents the *as-built* conditions, whereas 5 signifies the *worst* conditions of the components. In this way, the orientation of the scale is maintained across the parameters and for all variables. This also helps to ensure scoring consistency. For the scales to be compared among themselves (in so doing, the full potential of the MCDA is realized), the parameters are usually weighted. Because some parameters have greater influence on the failure modes/mechanisms than others, weighting is a way of recognizing such differences within a variable group. All the parameters under a given failure mode/mechanism do not influence the realization of the failure mode/mechanism equally: Although the presence of some parameter signify imminent danger, the presence of other parameters could be a warning sign that all is not well with the system/structure. Weighting is a way of recognizing such differences within a variable group. The weighting process is complex and always a source of uncertainty. Given the high number of parameters involved in this type of application, consideration is given to a point allocation weighting method based on the simplicity of the approach to weighting. Point allocation subjective weighting method is fast and easy to adopt and can give a relatively accurate weight when used by an experienced analyst/group of experts.

3.2.3 | Postassessment/multicriteria risk analysis stage

In this stage, the elicited scores (weights and parameter preference-scores) are aggregated using suitable aggregation algorithms to generate risk performance values (RPVs), which form the basis for components' risk ranking. Many aggregation algorithms exist; they can be distinguished as—priority-based, out-ranking, Euclidean distance-based, and mixed methods. This paper adopts technique for order of preference by similarity to ideal solution (TOPSIS), a Euclidean distance-based technique. TOPSIS is the topmost choice, given that the eventual solutions will be required to satisfy the "nearest to ideal solution (A^+)" and "farthest from anti-ideal solution (A^-)" conditions as shown in Figure 4 (Kolios, Mytilinou, Lozano-Minguez, & Salonitis, 2016; Kolios, Read, & Ioannou, 2016; Kolios, Rodriguez-Tsouroukdissian, & Salonitis, 2016; Lozano-Minguez, Kolios, & Brennan, 2011). TOPSIS is implemented for any decision matrix *V* in the following steps (Hwang & Yoon, 1981).

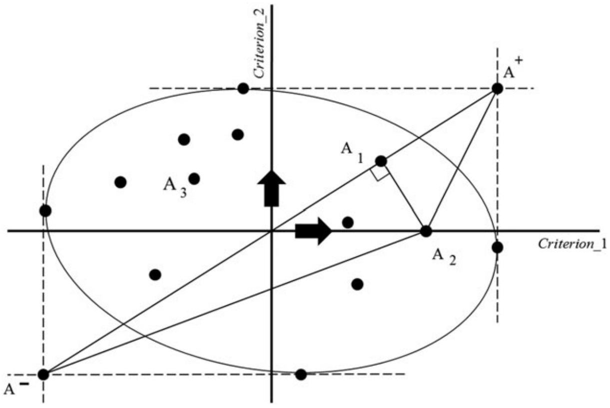

FIGURE 4 Demonstration of technique for order of preference by similarity to ideal solution Euclidean distance for the performance ranking of different alternatives in the decision-making process

- Step (I): Normalisation of decision matrix;
- Step (II): Weighted normalised values;
- Step (III): Derivation of $A^+$and A^-, the positive and negative ideal solutions;
- Step (IV): Calculation of separation measures, that is, n-dim. Euclidean distance metric;
- Step (V): Calculate similarities to the positive-ideal solution, as follows;
- Step (VI): Choose the alternatives in the decision matrix with the maximum $C_i^+$and rank these alternatives from most- to least-preferred per C_i^+in descending order.

The outcome from implementation of TOPSIS, as the output of the risk assessment model, will be a vector of RPVs with each value corresponding to an aggregate of a component's parameter-specific risk scores. These are presented as clustered bars that can compare values across the components. The enhanced condition-based multicriteria risk assessment proposes two considerations for aggregation of the weight and performance scores: local and global aggregation. In local aggregation, weights and scores aggregation is localized to the failure mode/mechanism under consideration. The aggregates are referred to as failure mode-specific RPVs denoted as $pv_q^i(q = 1, 2, \cdots, m; \forall i = 1, 2, \cdots, n)$, where q represents the components and i represents the failure mode/mechanism. Local aggregation is important for identifying the localized weak links, that is, the most susceptible component for each failure mode/mechanism. On the other hand, the global aggregation includes weights and scores of parameters that cut across all failure modes/mechanisms. The aggregates so formed are called overall RPVs and are denoted as $pv_q : (q = 1, 2, \cdots, m)$. This result finds application in system level maintenance planning; notable use is in identifying the weak links at a system level.

3.3 | Review of failure modes/mechanisms of jacket support structure components

Failure of components of jacket support structures refers to the various forms in which the component may exist and be considered/judged (by a competent authority) as unfit to perform the function for which it is intended. Here, failure does not only mean a total collapse of structure/component(s) but also a level of performance/condition that is unacceptable. Some examples of such conditions include, but are not restricted to, permanent tilt, excessive deflection (as found in riser failure) to mention just a couple. Generally, jacket structures can fail from the purely progressive deterioration of the structure or a combination of local weakening and overloading—as in delayed/gradual failure—or immediately/spontaneously, that is, failure without warning, from action of extreme accidental and/or environmental loading (Barton & Descamps, 2001).

Tubular members refer to components, such as cords, braces, and legs. A notable failure-prone spot for such rounded members is the vicinity of welded joints (the heat affected zones). Defects such as out-of-roundness and crookedness (of piles and legs) have remote cause in manufacturing defect while local buckling and/or collapse can occur (in legs and braces) under overloading and impact conditions. Overloading is attributed to either secondary action, such as corrosion, erosion, thinning of members, or due to marine growth; otherwise, it is primarily caused by accidental loading—collision, impact from boats, slamming actions of waves, dropped objects, human error during design/fabrication, etc. It also results in buckling (local and global), tearing, and punching shear. The conductor framing performs the important role of holding the risers and conductor in position. The first elevation of the conductor bracing below the water line—typically between −25′ and 40′ feet—is usually the elevation most susceptible to damage by overload due to the slamming waves. Overloading is one of the major causes of failure in risers, legs, and piles by virtue of their location. Risk assessment for such slender and lengthy structures is difficult in that they pass through different environmental zones—submerged, underwater and tidal, and splash zone. Bai and Bai (2014), ESDEP (2010), and Muhlbauer (2004) propose a procedure for risk assessments that first segments them along environmental boundaries after which each is then treated as a separate component. Risers are generally clamped to the jacket structure and are always in tension due to their own weight, as such making them prone to buckling failure mode. Underwater components, on the other hand, are protected from corrosion by cathodic protection. Cathodic protection works by casting sacrificial anodes, usually zinc/aluminium bars, about a steel tube and welding them on to the structures. Approximately 5% of the weight of the jacket is applied as the anode. Steel works in the splash zone—characterised by the high rate of corrosion—have a sacrificial wall thickness of about 12 mm to the members for its protection.

Table 4 presents other failure modes/mechanisms of offshore jacket support structures as found in many literature sources. On many occasions, important company-based information has been refined to make them generic.

3.4 | Implementation of risk assessment model

This section reports the step-by-step implementation of the proposed risk assessment model for the case study of an oil and gas jacket support structure.

TABLE 4 Functional description of components of offshore jacket support structure

No	Component	Offshore application	Observed anomaly	Failure mechanisms
1	Transition piece	Supports transition of deck leg to substructure.	Cracks, blisters, and collapse due to overloading.	FTG; MAD (Health and Safety Executive, 2009) (Graff, 1981)
2	Leg	Supports the rest of the structure. It is a main load transfer structure.	Out of roundness/crookedness, accumulation of marine growth, thinning due to external and internal corrosion, and abnormal scour survey reading on leg.	MAD; O&I (Shell, 2001) (Sheppard, Puskar, & Waldhart, 2010)
3	Leg joint and joint can, other joints	Joint cans increase the load bearing capacity and ductility of the jacket. Grouting improves reliability under compressive loads; Connects—brace to brace, brace to leg, brace-leg-brace (K-node), leg-to-pile etc.	Punch-through failure due to punching shear, buckling of tubular joints, and joint tear. Joint crack, collapse of joint, and joint overloading;	O&I; CEF; IOP; INC; ETC (Sheppard et al., 2010). FTG (Puskar, Ku, & Sheppard, 2004; Shell, 2001); O&I; MAD; WAC
4	Pile	Primary load support component of the jacket leg.	Out of roundness and straightness, crookedness, buckling, and collapse.	MAD; O&I; (Tsinker, 2004); ETC
5	Member[a]	Loads path: Provides structural integrity. Resists wrenching motion of the installed jacket-pile system, supports the corrosion anode and well conductors, and holds the leg chords in rigid condition.	Out of roundness, buckling, marine growth, joint crack, well-being, damage members, erosion, and flooded member.	O&I; ETC; INC; FTG; WAC (El-Reedy, 2012; Graff, 1981; Moan, 2007)
7	Pipeline riser	Vertical pipelines running from the well-head to the topsides for transporting oil and gas.	Local weakening—low thickness reading (as in Ekofisk A), rupture from coating condition (as in Mumbai High North Riser Rupture), metallic debris, and marine growth.	FTG; ETC; INC; O&I; (El-Reedy, 2012)
8	Pipeline riser support/ clamp	They are used to support vertical runs of piping at selected levels.	Crack, low CP reading, crushing collapse due to slamming.	FTG; ETC; INC; O&I
9	Riser guard	Protect risers from boat or vessel collision or any accident that may occur.	Crack, general integrity, marine growth, and buckling.	FTG (Shell, 2001); O&I
10	J-tube	Houses the umbilical or flexible flow line from the bottom part of the platform up to the topside, and vice versa.	Collapse, severed body, and bending.	O&I
11	J-tube support	Supports the J-tubes at all levels of the platform.	Crack and low CP reading.	FTG; ETC
12	Conductor	Hollow tubes embedded into the seabed and runs through to the topside and through which drilling is performed.	Low CP reading, collapse, burst, buckling, and rupture.	ETC; INC; coating conditions (Shell, 2001); O&I
13	Conductor guide	Support the conductor tubes at each level.	Thinning, crack, and collapse (Shell, 2001).	MAD; WAC; FTG; O&I
14	Conductor guide frame	Restrain and guide the conductors at each level.	Corrosion, fatigue crack, collapse form overloading—due to wave slamming and fatigue damage (Shell, 2001).	FTG; ETC; INC; MAD; O&I
15	Cluster of skirt pile sleeve	Increase the capacity of the structure to overcome overturning moment. Grouted to develop required resistance. Provides enough bond strength to equal the ultimate capacity the pile can develop in the soil.	Crack and blister.	FTG; MAD
16	Boat landing and fender system	Absorbs the impact of the boat or vessel to the offshore structure. Required for berthing of supply vessels.	Dent, excessive corrosion, brittle fracture detachment, and anomalous marine growth.	O&I; ETC; INC
17	Mudmat	Provides stability and additional support (adequate bearing area) at the bottom of the jacket so that it will remain upright and stable while the first piles are being driven during installation of jacket/drilling. Provides resistance to overturning.[b]	Overturning and instability/sliding, corrosion, scouring, erosion, and subsidence.	FTG; CEF
18	Cathodic protection using sacrificial anodes	This is a galvanic (sacrificial) component, coupled directly to the structure to be protected. Replenishes depleted parts lost to corrosion.	Degree of depletion above 50%, damaged or detachment of CP, changes in voltage and current densities, content of metallic debris, and anomalous marine growth readings.	Fatigue and excessive corrosion
19	Foundation soil/seabed	Resists extremely large overturning moments and large environmental horizontal forces—to support the weight of the jacket and stabilizes the structure.	Subsidence of the platform, toppling, sliding, rock back-forth, and scour.	External forces and climatic force

Note. CP: cathodic protection; CEF: climate and external forces; ETC: external corrosion; FTG: fatigue; ICO: incorrect operation; INC: internal corrosion; MAD: manufacturing defect; O&I: overloading and impact; TPD: third party damage; WAC: welding, assembly, and construction.

[a] Member is a generic name for horizontal, vertical, or diagonal components of the jacket.

[b] Topmost soil layer encountered during jacket installation is fluidized in nature and causes instability.

3.4.1 | Database preparation

The implementation of the framework begins by scrutinizing the database information. During this important step, information contained in the database is reviewed and filtered resulting in a structure-specific database. Review and filtering out can be carried out simultaneously and often focus on failure mode and mechanisms, variables and parameters, and condition attributes. Data preparation may also involve establishing components' condition baselines and calibration. This aspect relies on standards and other relevant regulatory documents. Further, it should be noted that both qualitative and quantitative data are relevant for the analysis, with preference to the latter where possible, depending on the availability and quality of data at the time of the analysis.

3.4.2 | Experts' selection

The evaluation process requires input from a group of subject area experts. Such a panel of experts should collectively represent a reasonably balanced range of respected oil and gas expertise and opinion (Bertolini, Bevilacqua, Ciarapica, & Giacchetta, 2009). In this case, selection was done based on years of experience in operation and maintenance of offshore assets and related matters, with special recognition given to experience in similar projects. In this research, this criterion is met by the choice of experts with more than 10 years working experience in operation and maintenance and/or related projects in the oil and gas sector. The peer nomination process (Roman et al., 2008) was adopted in the selection of experts from a network of offshore practitioners. The process resulted in the selection of four experts out of an initial seven: Two declined participation based on inconvenience and one was unable to participate in the meeting due to technical problems. The question of "how many participants are ideal for a qualitative research?" has been a subject much talked about within qualitative research communities. Unfortunately, researchers do not feel comfortable giving a straightforward answer on this topic (Galvin, 2015); it is most common among researchers to give an "it depends" answer. Baker and Edwards (2012) give further insight into the epistemological, methodological, and practical issues these researchers insinuate by use of the term "it depends."

In a related research, Robinson (2014) listed the four actions consistent with the results of experts' judgements, that is, coherent, transparent, impactful, and trustworthy as

1. the inclusion and exclusion criteria should be clearly defined for potential participants;
2. deciding upon a sample size;
3. sampling strategy should be selected; and
4. sample sourcing.

The inclusion and exclusion criteria define the sample universe. Decision on the sample size should consider the epistemological and practical concerns as well. Some examples of sampling strategy include random sampling, convenience sampling, stratified sampling, cell sampling, quota sampling, or single-case selection strategy. Sampling sourcing includes matters of advertising, incentivising, avoidance of bias, and ethical concerns pertaining to informed consent. As is common within offshore practice, there is always a limited number of experts who possess the required expertise and relevance to provide input to the risk assessment. This makes the number available for this qualitative evaluation representative. A description of the experts considered is included in Table 5.

3.4.3 | Evaluation and score elicitation

Due to the differences in the geographical location of these participants, the evaluation and elicitation process combined two different but complimentary qualitative research techniques: Delphi group and nominal group technique (NGT).

Delphi group method

This method has clear advantages where participants are geographically distant and cannot meet physically and disadvantages in that the participants do not have the opportunity for verbal clarification or social interaction. In the Delphi technique, the participating experts are sent a briefing note on the subject matter requiring them to provide their inputs. The briefing note contains the assets and models information relevant for risk assessment. It describes the components of the jacket support structure with respect to conditions parameters and generic failure modes and mechanisms. It also contains instructions on how to implement the proposed model. The briefing note may be accompanied by documents regarding the condition survey and structural analyses (David, 2012), and the standards and recommended practices from where this information have been obtained. In the case study being reported, all these documents were sent to each of the experts. The participating experts studied the briefing notes in detail and responded by eliciting scores, according to their perception of the performance of the condition of the components, and compared these against the respective standards/baseline conditions. Responses were collated and assessed by the facilitator who reviewed the participants' responses and clarified any questions.

TABLE 5 List of experts and their portfolios

Code name	Track record
Participant A	Holds a PhD in subsea risk assessment with more than 20 years of experience in offshore project coordination and subsea engineering. He currently works for an assets operator.
Participant B	A senior pipeline engineer within an assets operator. He has over 10 years of experience, including hands-on participation in subsea pipeline laying projects.
Participant C	A mechanical engineer with over 10 years of experience in conceptual, FEED, and detailed engineering designs of onshore/offshore facilities. He holds an MSc in offshore and subsea engineering.
Participant D	An engineer with expertise in static mechanical equipment and deep-water projects within an exploration and production company.

Preelicitation workshop

This was held via video conferencing, to fine-tune modalities for the online group meeting. In the trial meeting, the software was test-run, and all technical issues were addressed. After that, the project was formally introduced, and the method of score elicitation, the modified NGT, was elucidated. Questions were answered and all grey areas cleared.

NGT

The purpose of NGT is to achieve group consensus and action planning on a chosen area of interest (Ven & Delbecq, 1971). The areas of interest in this context are those parameter-specific values where experts have conflicts of perception. NGT encourages equal participation from all members, and results in prioritized group consent at the end of the session. The choice of NGT over other methods, such as focus and brainstorming groups, is to avoid the impending danger of having fewer high quality suggestions (Delbecq & VandeVen, 1971; Gallagher, Hares, Spencer, Bradshaw, & Webb, 1993). During the meeting with the participants, the NGT technique is applied as shown in Figure 5.

The steps require identification of components having highly contrasting scores for all parameters of all failure mechanisms. The experts are then given the opportunity to shade more light on the reasons behind their choice of scores. The exercise concludes with the facilitator (or group of facilitators) taking decision on the final score based on the level of conviction and/or availability and quality of evidence. The statistical aspect, identifying the conflicting scores and the decision making, can be left out during the meetings and done later, to avoid unnecessary delay.

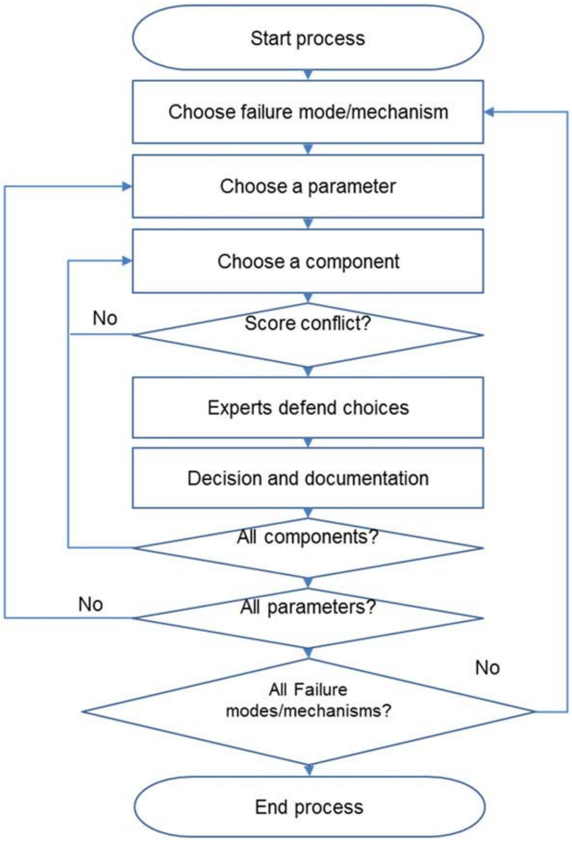

FIGURE 5 Flowchart for the practical implementation of nominal group technique in the context of risk analysis

4 | RESULTS AND DISCUSSION

This section presents the results of full-scale application of the enhanced condition-based multicriteria risk assessment framework to an offshore oil and gas production jacket support structure. A total of 23 components were identified and evaluated against 119 parameters. These parameters represent various scenarios of the condition of these components in service and that influence the risks of their respective failure modes and mechanisms. Care was taken in the selection of the parameters to ensure no mutual interdependence of preferences during evaluation stage. This also included “double-counting.” Evaluation and scoring were done by the group of experts who specialize in maintenance and safety of offshore oil and gas assets and related activities. Group consensus on the scores was reached by combined method of Delphi group technique and NGT as described in Section 3. A bar chart plot of the global aggregation approach is shown in Figure 6. The length of each bar is proportional to the RPV of each of the component.

One of the uses of the global aggregation results is in identifying the weak link. This is the component with the highest RPV. It can be seen from the bar chart of Figure 6 that the weak link for the jacket support structure is the weld/joint, which has the highest sum of risk indices across the failure modes/mechanisms. Another way to interpret the result is by classification into “priority risk class.” The components are grouped into priority classes based on their risk performance. Figure 6 shows division into four (4) priority risk classes: Class 1 defines RPV range between 0.6 and 0.8; Class 2 defines RPV range between 0.4 and 0.6; Class 3 defines RPV range between 0.2 and 0.4; and Class 4 defines RPV range between 0 and 0.2. It can also be seen that Class 1 contains components such as J-tube, pipeline riser, leg-to-pile connection, and weld and jacket leg joints. This class is characterised by high risk priority indices and so should be treated with the highest priority. For this reason, they are called the high priority treatment class. In contrast, Class 3 is a class of components with low risk performance indices. As such, they are recommended to be treated as low priority cases. For this reason, they are often referred to as the low priority treatment group. “To give priority,” as used here refers to actions such as allocating large maintenance budgets. Classification can also be applied to the appraisal of maintenance routines. For example, if by implementing maintenance interventions, the RPV of a component initially in Class 1, that is, a high priority treatment class, falls to Class 2, that will imply that the plans are effective. In contrast, an increase in the RPV value will indicate ineffectiveness on the part of the intervention process being implemented or the maintenance personnel handling the work. Agreement on the class boundaries is reached in specially organized workshops involving interested parties, composed of the risk assessment engineer and the management.

A very important concept often employed in maintenance management is the Pareto principle: the 80–20 rule. The principle was

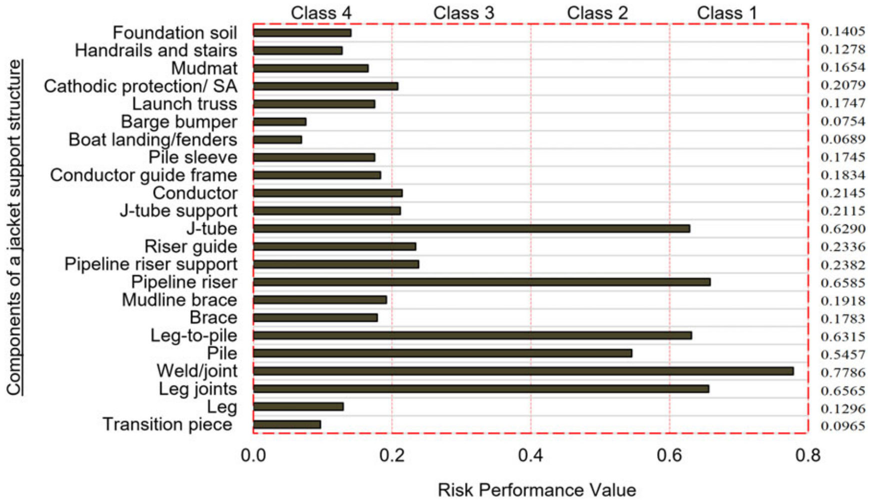

FIGURE 6 Risk performance values of components, ranked in four different priority treatment classes, that is, Class 1 is characterised by high risk priority indices and so should be treated with the highest priority—high priority treatment class whereas Class 3 is a class of components with low risk performance indices—low priority treatment group

introduced by Vilfredo Pareto (1848–1923) who observed a pattern of disproportionate wealth distribution among Italians, wherein 20% of the population controlled 80% of the wealth. The general philosophy behind the concept is that in most real-life scenarios, a vital few are always responsible for the main effects/results. In the context of maintenance management, Pareto chart—bar graphs—arranges information in such a way that priorities for intervention towards integrity sustenance/improvement can be established easily (Gulati & Smith, 2012). For example, in offshore maintenance management, where it applies, the Pareto principle implies that only 20% of the components—also called the vital few—accounts for 80% of the risk. The Pareto principle can be used to develop an effective and strategic management schedule that identifies the vital few and focuses resources on resolving them. In Figure 7, result of the global aggregation is depicted as Pareto diagram. The 100% mark on the cumulative risk percent scale corresponds to the sum of RPVs for the components. In the form as Pareto diagram, the components are arranged in the decreasing order of the RPV where in it becomes much easier to prioritize the components by ranking them and also visualize the differences between the rankings (McDermott, Mikulak, & Beauregard, 2011). Furthermore, the components can be expressed with respect to their cumulative risks. As can be seen from Figure 7, which presents in descending order of the RPVs allowing visualization of the cumulative risk profile, 60% of the total RPVs is contributed by all the components to the left of the "pile" (pile RPV inclusive).

The results of local aggregation $pv_q^i: q = 1, 2, \cdots, m;\ \forall i = 1, 2, \cdots, n$ are presented graphically, as shown in Figures 8 and 9. Figure 8 is called a 100% stacked bar: It compares the percentages of each $pv_q^i: (i = 1, 2, \cdots, n)$ to a total across categories (risk sums $\Re$-$\mathcal{S}$ see) using horizontal bars. The relationship between failure mode-specific RPVs $pv_q^i: i = 1$ or 2 or, $\cdots$, or m and the risk sum over q given by $\Re\mathcal{S} = \sum_{i=1}^{n} pv_q^i: 1 = 1,\ 2,\ \cdots,\ n$ is given in (1).

$$pv_q^i = \frac{y_q^i}{100} \times \Re\mathcal{S}_q, \tag{1}$$

where y_q^i is the length of each section of the bar.

On the other hand, Figure 9 is the plot of RPVs of different components, highlighting the most critical failure modes for each component. It compares the activities of the failure modes in each component, that is, $pv_q^i: (i = 1, 2, \cdots, n);\ \forall q = 1,\ 2,\ \cdots,\ m$. From the form shown in Figure 9, it is easy to analyse the condition of each

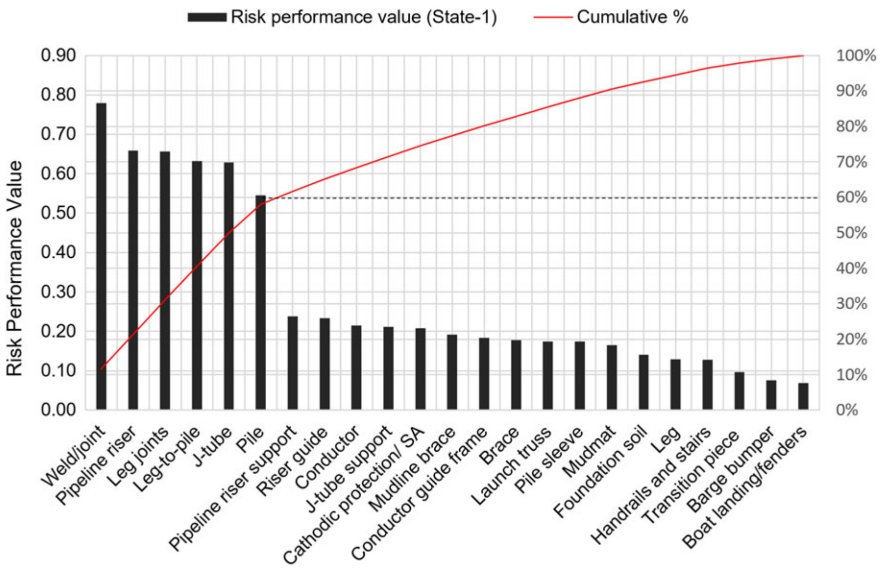

FIGURE 7 Pareto diagram of the rankings of components. The cumulative graph distinguishes the few components (first 6) that are considered most critical as the result of the analysis

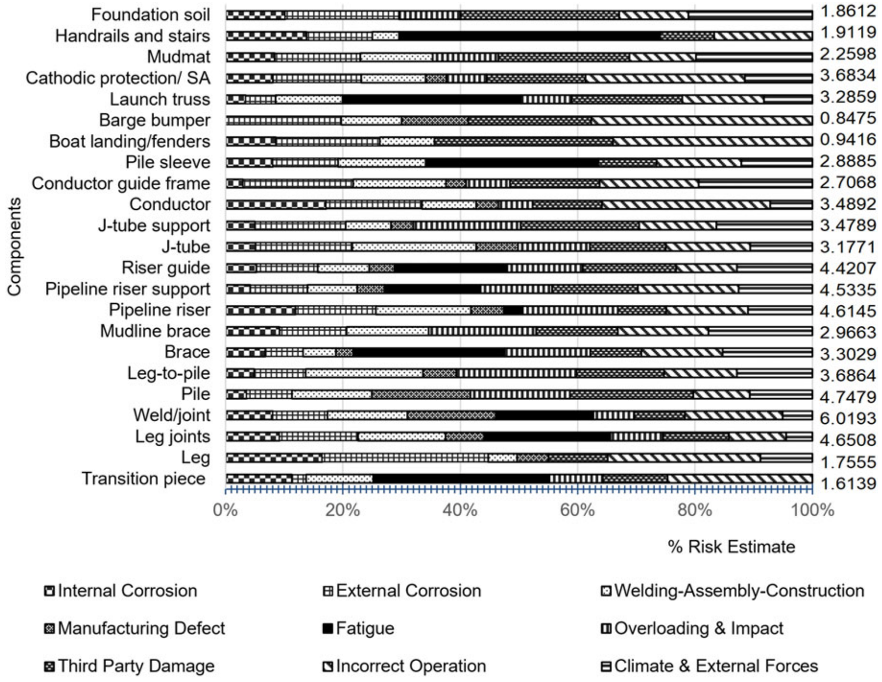

FIGURE 8 Bar chart of normalized values for the criticality of different failure modes of each component. The value in the right part of the graph denotes the aggregated score of each component (denoting critical components)

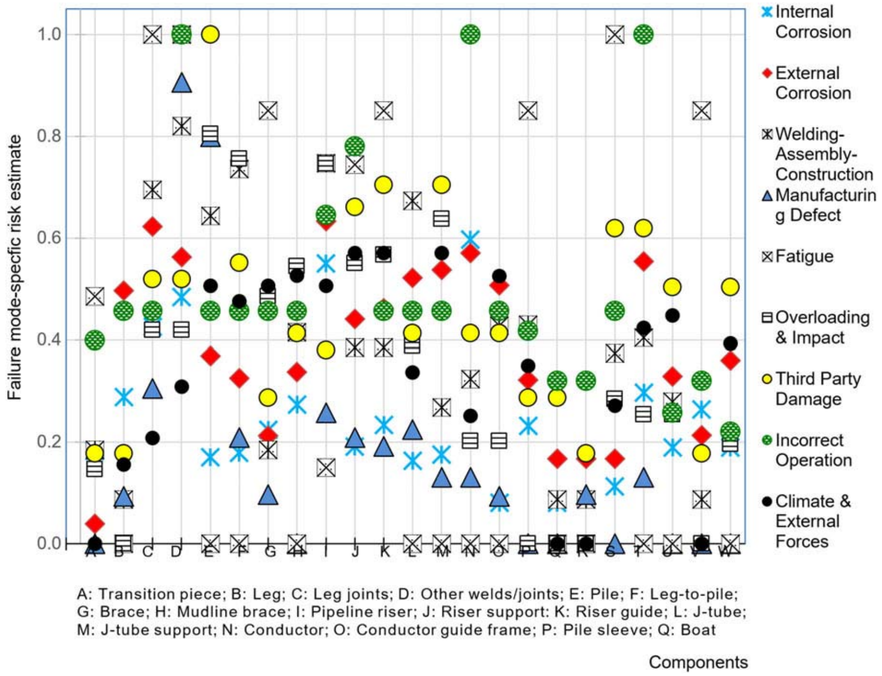

FIGURE 9 Scores of risk performance values of different components, highlighting the most critical failure modes for each component of the support structure

component based on the type of failure mode/mechanism and the respective relative activity levels. This analysis is a guide to deciding "where and what to mitigate."

For example, in Figure 8, "weld/joint" that presents the highest risk estimate across components (score of 6.0193), incorrect operation as a failure mode appears to contribute most, followed by manufacturing defect and weld-assembly-construction. The same information can be retrieved from Figure 9, where for the same component (D: weld joint), the actual values of failure mode specific risk estimates can be retrieved.

Finally, the special ability of the enhanced condition-based multicriteria risk assessment framework, that is, ability to track the changes in the conditions of the components and monitor the corresponding variations in risk profile, is presented. This ability is demonstrated as sensitivity analysis. Sensitivity analysis is used to analyse how the ranks of components change when the conditions of key components are varied. Five key components of the offshore jacket support structure, namely, leg, pile, brace, pipeline riser, and conductor, are selected for this study. In the analysis, conditions of the components are varied one at a time while keeping those of other components constant at the reference state and taking note of the ranking order that results. This is repeated with the rest of the key components. By "reference state," reference is made to the conditions of the components at the initial inspection and prior to (controlled)

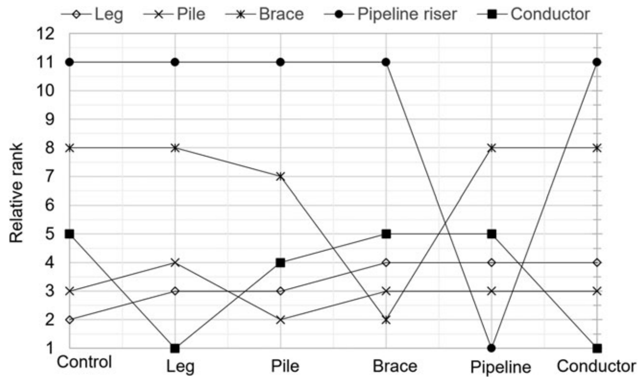

FIGURE 10 Sensitivity of the ranking order to changes in condition of components illustrating the ability of the enhanced condition-based multicriteria risk assessment framework to track the changes in the conditions of the components and monitor the corresponding variations in risk profile

variations in their conditions. In a practical sense, these controlled changes could model plant scenarios' conditions and performances, such as sea state, knowledge and experience of personnel, operational status, and effectiveness of or a change in the maintenance of processes/plan. These conditions impact differently on the risk content of components. Managers and operators of complex offshore structures and systems, as part of their daily work, must deal with these changes and make complex decisions against the background potential for a major accident. The result shows that the method/tool can monitor significant features of the risks of failure modes/mechanisms on a component basis thus adding to increases its value as tool for operational decision making. The result of this analysis is presented in Figure 10. The vertical axis of the plot presents the relative ranks axis whereas the horizontal axis is the critical components axis. The plots show the rank of the components when the condition of the key components is varied. In other words, the plots above "control," are the ranking order of the components prior to changes in the key components; above "leg" are the ranking order when the condition of the leg is altered, and so on.

From Figure 10, the changes that occurred in the condition of the component, "leg," reduced the risk content such that it moved from the second position it occupied previously (under "control") in the rank, to the third position it occupies under leg. For the rest of the critical components selected for this study, the changes that occurred in them caused an increase in their risk contents and as such a movement in the ranking to a level higher than their reference levels.

It should be noted here that the results presented above are relevant to the hypothetical case study that was analysed, with the aim of illustrating how the framework is applied to a generic set; hence, results should not be generalized unless a detailed, case-specific assessment takes place. An important aspect of the development of a framework, such as the one suggested here, is that of numerical validation, which can be realized comparing the outcome of its application with prior results from inspection and maintenance. Considering that this is a generic case study, this approach is not directly possible; hence, face validation was adopted with the results presented to the experts and asking for their views on the accuracy of the model. Outcome of this process reached consensus from all four experts about the accuracy of ranking (local and global aggregation) denoting that the framework derived realistic conclusions. Further, validation of the framework on a real case study can be found in Kolios, Umofia, and Shafiee (2017) and Okoro et al. (2016).

5 | CONCLUSIONS

This paper reports the development and application of a risk assessment methodology for complex systems. This enhanced condition-based multicriteria risk assessment method is implemented in failure modes and mechanisms identification, risk analysis, and evaluation of an offshore jacket support structure. The paper highlights the use of variables and parameters to add details to the analysis of risk of generic offshore failures modes and mechanisms. These normally disparate data, covering the broader spectrum of components' conditions, are then brought together to support risk-based prioritization. To implement the method successfully, the structure should first be broken down into constituent component levels. The authors suggest a method for reaching consensus in condition-based risk analysis by multiple experts who combine Delphi and NGTs. The work further shows that the framework has sufficient ability to track the variation in the risk-based ranks as a result of changing conditions of an offshore production structure at the components level. The assessment framework is developed for application in offshore energy structures and systems; however, the results of the case study further prove its suitability for use as an assessment tool across applications and industries other than the offshore energy infrastructure.

Though a considerable number of variables and parameters affecting the integrity of offshore structures and systems were integrated in this work, the context of each future application should be considered in order to ensure accuracy of the analysis. Therefore, the process of hazard identification and criteria refinement are and should remain a continuous process. In addition, the size and technical complexity of new generation (modern) offshore systems and structure in a constantly varying condition of operations, coupled with increasing awareness of health, safety, and environment implications of most offshore activities, amid tighter regulations mean that large volume of accurate data, greater speed of assessment/analysis, and flexibility/dynamism of inspection will be required of a suitable risk assessment methodology. These demands point to the necessity of automating the process of risk assessment incorporating real time data collection to the decision-making process through internet of things applications and advanced analytics that can provide accurate insights to the state of an asset giving guidance for efficient operational management.

ORCID

Athanasios Kolios http://orcid.org/0000-0001-6711-641X

REFERENCES

Arabian-Hoseynabadi, H., Oraee, H., & Tavner, P. J. (2010). Failure modes and effects analysis for wind turbines. *International Journal of Electrical Power & Energy Systems*, *32*(7) Elsevier Ltd), 817–824.

Aven, T., Vinnem, J. E., & Wiencke, H. S. (2007). A decision framework for risk management, with application to the offshore oil and gas industry. *Reliability Engineering & System Safety*, *92*(4), 433–448.

Bai, Y., & Bai, Q. (2014). *Subsea pipeline integrity and risk management*. Houston: Gulf Professional Publishing.

Baker SE, & Edwards R. (2012). How many qualitative interviews is enough?, National Centre for Research Methods Review Paper, pp. 1–42.

Bana, E., Costa, C. A., & Vansnick, J.-C. (1994). MACBETH—An interactive path towards the construction of cardinal value functions. *International Transactions in Operational Research*, *1*(4), 489–500.

Barton, A. D., & Descamps, B. (2001). Risk-based inspection planning applied to 14 steel jacket structures. *International Journal of Offshore and Polar Engineering*, *11*(1), 64–71.

Bell, M. L., Hobbs, B. F., Elliott, E. M., Ellis, H., & Robinson, Z. (2001). An evaluation of multi-criteria methods in integrated assessment of climate policy. *Journal of Multi-Criteria Decision Analysis*, *10*, 229–256.

Bertolini, M., Bevilacqua, M., Ciarapica, F. E., & Giacchetta, G. (2009). Development of risk-based inspection and maintenance procedures for an oil refinery. *Journal of Loss Prevention in the Process Industries*, *22*(2), 244–253.

Bolsover, A. (2015). Real-time risk assessment and decision support. *Process Safety Progress*, *34*(2), 183–190.

Braaksma, J. (2012). *Asset information for FMEA-based maintenance*. Groningen: University of Groningen.

British Standard. (2007). Petroleum and natural gas industries -fixed steel offshore structures *Standard publication*. BS EN ISO 19902:2007+ A1:2013. BSI Standards Publication, London, UK.

Chang, K.-H., & Cheng, C.-H. (2010). A risk assessment methodology using intuitionistic fuzzy set in FMEA. *International Journal of Systems Science*, *41*(12), 1457–1471.

Choo, E. U., Schoner, B., & Wedley, W. C. (1999). Interpretation of criteria weights in multicriteria decision making. *Computers and Industrial Engineering*, *37*(3), 527–541.

David, H. (2012). *Methodology and challenges of life extension of offshore assets*. Houston, Texas USA: ABSG Consulting, Inc.

Delbecq, A. L., & VandeVen, A. H. (1971). A group process model for problem identification and program planning. *Journal of Applied Behavior Science*, *7*(4), 466–492.

Diakoulaki D, & Grafakos S. (2004). *ExternE-Pol -Externalities of energy: extension of accounting framework and policy applications*. Final Report on Work Package 4: Multicriteria analysis, Athens, Greece: National University Athens.

Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). *Multi-criteria analysis: A manual*. London, UK: Department for Communities and Local Government.

Edwards, W., & von Winterfeldt, D. (1986). *Decision analysis and behavioral research*. Cambridge, UK: Cambridge University Press.

El-Reedy, M. (2012). *Offshore structures design, construction and maintenance*. Boston: Gulf Professional Publishing.

European Steel Design Education Programme. (2010). Corrosion in offshore and sheet pilling *Protection: Corrosion*. ESDEP WG 4A: 5. ESDEP

Gallagher, M., Hares, T., Spencer, J., Bradshaw, C., & Webb, I. (1993). The nominal group technique: A research tool for general practice?. *Family Practice*, *10*(1), 76–81.

Galvin, P. R. (2015). How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge?. *Journal of Building Engineering*, *1*, 2–12.

Garvey, P. R. (2009). *Analytical methods for risk management*. Bedford, Massachusetts, USA: CRC Press.

Graff, W. J. (1981). *Introduction to offshore structures: Design, fabrication, installation*. Houston, USA: Gulf Publishers.

Gulati, R. and Smith, R., (2012) *Maintenance and reliability best practices*. (2nd ed.). Carleo, J. Weinstein, R. and Remore, S. (eds.) New York: Industrial Press, Inc.

Health and Safety Executive. (1996). *The offshore installations and wells (design and construction, etc.) regulations 1996*. SI 1996/913. UK.

Health and Safety Executive (2009). *Structural integrity monitoring—Review and appraisal of current technologies for offshore applications*. UK: HSE.

Health and Safety Executive. (2015). *The offshore installations (offshore safety directive) (safety case etc.) regulations 2015*. *Health and Safety Environment Protection*. 2015 No. 398. HSE, UK.

Hobbs, B. F. (1980). A comparison of weighting methods in power plant siting. *Decision Sciences*, *11*(4), 725–737.

Hobbs, B. F. (1986). What can we learn from experiments in multiobjective decision analysis? *IEEE Transactions on Systems, Man, and Cybernetics*, *16*(3), 384–394.

Hwang, C. L., & Yoon, K. (1981). Multiple attribute decision making. 1981. *Lecture Notes in Economics and Mathematical Systems*.

International Standard Organisation (2009). *Risk management—Principles and guidelines*. London, UK: BSI Stanard Publication.

International Standard Organisation. (2013). Petroleum and natural gas industries — Specific requirements for offshore structures part 3: Topsides structure *British Standard Publication*. BS EN ISO 19900. BSI Standards Publication, London, UK.

Ioannou, A., Angus, A., & Brennan, F. (2017). Risk-based methods for sustainable energy system planning: A review. *Renewable and Sustainable Energy Reviews*, *74*, 602–615.

Jia, J., Fischer, G. W., & Dyer, J. S. (1998). Attribute weighting methods and decision quality in the presence of response error: A simulation study. *Journal of Behavioral Decision Making*, *11*(June 1997), 85–105.

Keeney, R., & Raiffa, H. (1993). *Decision with multiple objectives: Preferences and value tradeoffs*. Cambridge & New York: Cambridge University Press.

Kolios, A., Mytilinou, V., Lozano-Minguez, E., & Salonitis, K. A. (2016). Comparative study of multiple-criteria decision-making methods under stochastic inputs. *Energies*, *9*, 566.

Kolios, A., Read, G., & Ioannou, A. (2016). Application of multi-criteria decision-making to risk prioritisation in tidal energy developments. *International Journal of Sustainable Energy*, *35*(1), 59–74.

Kolios, A., Umofia, A., & Shafiee, M. (2017). Failure mode and effects analysis using a fuzzy-TOPSIS method: A case study of subsea control module. *International Journal of Multicriteria Decision Making (IJMCDM)*, *7*(1), 29–53.

Kolios, A. J., Rodriguez-Tsouroukdissian, A., & Salonitis, K. (2016). Multi-criteria decision analysis of offshore wind turbines support structures under stochastic inputs. *Ships and Offshore Structures*, *11*(1), 38–49.

Linares, P. (2002). Multiple criteria decision making and risk analysis as risk management tools for power systems planning. *IEEE Transactions on Power Systems*, *17*(3), 895–900.

Lozano-Minguez, E., Kolios, A. J., & Brennan, F. P. (2011). Multi-criteria assessment of offshore wind turbine support structures. *Renewable Energy*, *36*(11), 2831–2837.

McDermott, R., Mikulak, R., & Beauregard, M. (2011). *The basics of FMEA* (2nd ed.). New York, NY 10016: Taylor & Francis.

Moan, T. (2005). *Safety of offshore structures*. CORE Report No. 2005–04, Singapore: National University Singapore.

Moan, T. (2007). Fatigue reliability of marine structures, from the Alexander Kiell and accident to life cycle assessment. *International Journal of Offshore and Polar Engineering*, *17*(1), 1–21.

Moan, T. (2008). Life-cycle assessment of marine civil engineering structures. In F. Biondini, & D. M. Frangopol (Eds.), *Proceedings of the first international symposium on life-cycle civil engineering* (pp. 73–89). Lake Como, Italy: CRC Press, Taylor & Francis Group.

Montibeller, G., & von Winterfeldt, D. (2015). Cognitive and motivational biases in decision and risk analysis. *Risk Analysis*, *35*(7), 1230–1251.

Muhlbauer, W. K. (2004). *Pipeline risk management: Idea, techniques, and resources* (3rd ed.). Linacre House, Jordan Hill, Oxford OX2 8DP, UK: Gulf Professional Publishing.

National Aeronautics and Space Administration. (2013). The case for safety – the north sea piper alpha disaster, *NASA Safety Center, System Failure Case Studies*, 7(4), 11–44.

National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011). *Deep water—The gulf oil disaster and the future of offshore drilling: Report to the president*. US: GPO.

Neill, M. (2016). The future of offshore risk management., *Risk and Compliance Innovation Forum* Available at: https://www.offshore-mag.com/articles/print/volume-76/issue-5/departments/beyond-the-horizon/the-future-of-offshore-risk-management.html (Accessed: 20 February 2018)

Officer of the watch. (2013). *Allexander L. Kielland platform capsize accident investigation report*., *Accident investigation reports* Available at: https://officerofthewatch.com/2013/04/29/alexander-l-kielland-platform-capsize-accident/ (Accessed: 29 January 2017)

Okoro, U., Kolios, A., & Cui, L. (2016). Multi-criteria risk assessment approach for components risk ranking—The case study of an offshore wave energy converter. *International Journal of Marine Energy*, *17* Elsevier Ltd, 21–39.

Paté-Cornell, M. E. (1993). Learning from the piper alpha accident: A postmortem analysis of technical and organizational factors. *Insurance: Mathematics & Economics*, *13*(2), 165.

Puskar, F. J., Ku, A. P., & Sheppard, R. E. (2004). Hurricane Lili's impact on fixed platforms and calibration of platform performance to API RP 2A. Proceedings of Offshore Technology Conference (OTC)., pp. 1–9.

Ren, J., Jenkinson, I., & Wang, J. (2009). An offshore risk analysis method using fuzzy Bayesian network. *Journal of Offshore Mechanics and Arctic Engineering*, *131*(4), 1–28.

Robinson, O. C. (2014). Sampling in interview-based qualitative research: A theoretical and practical guide a theoretical and practical guide. *Qualitative Research in Psychology*, *11*(1), 25–41.

Rogers, M., & Bruen, M. (1998). A new system for weighting environmental criteria for use within ELECTRE III. *European Journal of Operational Research*, *107*(3), 552–563.

Roman, H. A., Walker, K. D., Walsh, T. L., Conner, L., Richmond, H. M., Hubbell, B. J., & Kinney, P. L. (2008). Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the U.S. *Environmental Science and Technology*, *42*(7), 2268–2274.

Sakai, S. (2010). Risk-based maintenance. *East Japan Railway Company*, *17*, 29–44.

Shell, B. P., (2001) Structural inspection of offshore installations *Manual*. ; DEP 37.19.60.10-Gen. DEPs (Design and Engineering Practice) publications, Netherlands.

Sheppard, R. E., Puskar, F. J., & Waldhart, C. (2010). Inspection guidance for offshore wind turbine facilities turbine. *Offshore Technology Conference*. :OTC 20656: OTC, pp. 1–10.

Stewart, T. J., & Belton, V. (2002). *Multiple criteria decision analysis: An integrated approach*. US: Springer Science+Business Media, B.V.

Sun, L., Zhang, Q., Ma, G., & Zhang, T. (2017). Analysis of ship collision damage by combining Monte Carlo simulation and the artificial neural network approach. *Ships and Offshore Structures*, *12*(1), S21–S30.

Tsinker, G. P. (2004). Repair, rehabilitation, maintenance, and upgrading of waterfront structures. In G. P. Tsinker (Ed.), *Port engineering*. Ontario Canada: John Wiley & Sons, Inc.

U.S. Energy Information Administration (2016). *International Energy Outlook 2016: With projections to 2040*. Washington, DC, United States: U.S. Department of Energy.

Ven, A. V., & Delbecq, A. L. (1971). Nominal versus interacting group processes for committee decision-making effectiveness. *Academy of Management Journal*, *14*(2), 203–212.

Wang, J. J., Jing, Y. Y., Zhang, C. F., & Zhao, J. H. (2009). Review on multicriteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278.

Wang, Y., Cheng, G., Hu, H., & Wu, W. (2012). Development of a risk-based maintenance strategy using FMEA for a continuous catalytic reforming plant. *Journal of Loss Prevention in the Process Industries*, *25*, 958–965.

Weber, M., & Borcherding, K. (1993). Behavioral influences on weight judgments in multiattribute decision making. *European Journal of Operational Research*, *67*(1), 1–12.

Yang, J., Huang, H.-Z., He, L.-P., Zhu, S.-P., & Wen, D. (2011). Risk evaluation in failure mode and effects analysis of aircraft turbine rotor blades using Dempster–Shafer evidence theory under uncertainty. *Engineering Failure Analysis*, *18*(8), 2084–2092. https://doi.org/10.1016/j.engfailanal.2011.06.014 (Accessed: 16 January 2017)

Zardari, N. H., Ahmed, K., Shirazi, S. M., & Yusop, Z. B. (2015). *Weighting methods and their effect on multi criteria decision making model outcomes in water resources management*. Malaysia: Springer.

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