Recent advances and future trends on maintenance strategies and optimisation solution techniques for offshore sector

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Recent Advances and Future Trends on Maintenance Strategies and Optimisation Solution techniques for Offshore sector

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Abstract

Maintenance plan development of offshore assets is a complex activity due to its impact on the operational and safety risks and consequences, dependence on personnel resource availabilities, site constraints due to operational requirements and environmental factors, and uncertainties related to various vulnerabilities on asset. This paper elaborates the challenges on offshore maintenance frameworks and have carried out a review of recent state-of-the-art literature from which have observed that the current state-of-the-art does not incorporate site constraints of the asset related to offshore personnel resource availability, into the maintenance plan and its impact on other activities due to the maintenance. Also, no dynamic and autonomous resource allocations for maintenance activities take place in the offshore maintenance planning systems that allows each maintenance item to independently adjust its resource allocation based on the time required to complete the activity, to improve the resource utilisation. Most of the existing literature on optimisation of maintenance activities use a common objective function in their optimisation such as cost, rate and overall quality of service, to allocate resources to the maintenance items, which would not lead to efficient resource utilisations, as it would not take into consideration the impact of site constraints on the various activities.

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1. Introduction

With the emergence of nuclear industry in the 1900s, the risks associated with any accidents in that industry became a main concern, due to the very high consequences involved. With that, there was a wide emphasis on the predictive methodologies with the aim to lower any potential risks. This approach was subsequently passed on to other industries including, petrochemical, offshore and marine sectors. The offshore and marine assets are an integration of various floating systems, having individual needs on maintenance, governed by their design features, operating conditions, deterioration mechanisms and risks involved in not doing the maintenance activity. The practical site constraints encountered have an impact on the maintenance execution and the utilisation of resources, which generally not get accounted for in the maintenance strategies. This in turn reduce the effectiveness and confidence of the maintenance framework.

This paper reviews existing literature on maintenance strategies, and optimisation solution techniques for offshore sector. Maintenance strategies are a prominent factor in offshore maintenance management due to the high resource costs involved and due to the fact that they are a mitigation against the rate of deteriorations through age. The maintenance strategies of offshore systems are governed by the operational requirements and regulatory compliance in terms of seaworthiness and safety of the asset. The key maintenance performance indicators include maximising the asset availability and reliability, maintaining safety and regulatory compliance and minimising the costs. The maintenance activities are planned and prioritised based on the associated consequences, within the constraints of manpower and material availability. The prioritisation of offshore maintenance activities is based on the activity's impact on the control measures that liquidate the risks to the asset's performance. On one hand, offshore maintenance planning is facing expectations to optimise the maintenance regimes to minimise the costs related to resources and labour, and to improve the asset availability and reliability, while maintaining safety compliance. It is expected that the offshore maintenance planning system enables carry out activities that have minimal site constraints, to get higher resource utilisation and reduce operating costs. It would be challenging to have different offshore systems served independently with a proper resource allocation and resource utilisation, taking into consideration the site constraints, while maintaining interference between production critical and safety critical activities.

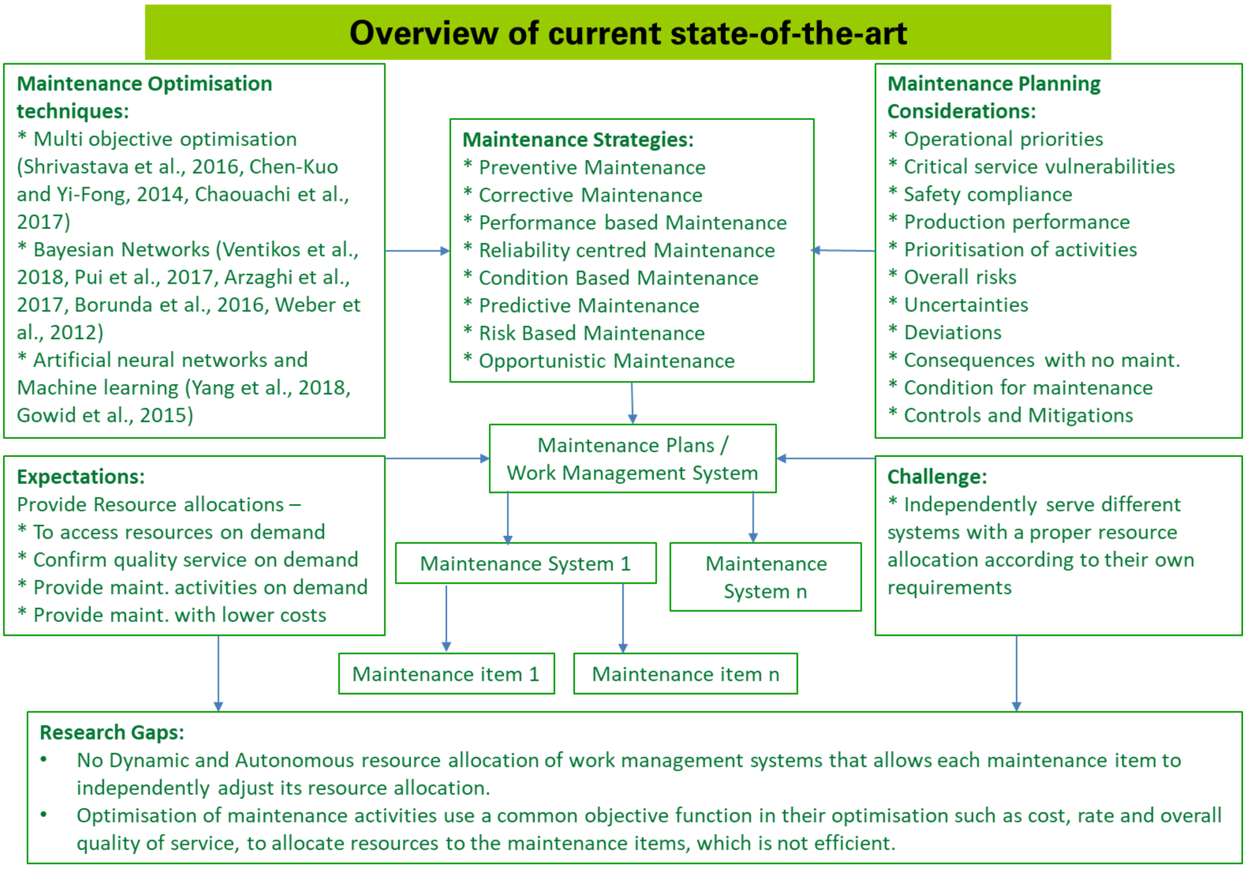

Figure 1. Overview of current state-of-the-art

An overview of current state-of-the-art of offshore maintenance planning frameworks has been indicated in Figure 1.

Major contribution made by this paper is that, by carrying out an extensive and comprehensive literature survey, the following gaps were found:

• The current state-of-the-art does not incorporate site constraints of the asset related to offshore resource availability for the maintenance activity, due to maximum allowable bed space, impact of time required to carry out activities and its impact on other activities due to this maintenance. The personnel function has been considered as a cost factor by way of their salary in few literatures, but the availability of beds offshore was not factored in any of the frameworks identified in the literature review. This is a major limitation of the existing state-of-the art maintenance frameworks.

• Even though many good maintenance models and frameworks are available in the literature, there still remains a big gap in incorporating the overall risks and site operational constraints related to weather, wind and sea state and its impact on the plan. The maintenance models also need to be integrated with the overall activity plans and offshore resource availability to achieve a credible implementation plan incorporating the overall risks in the maintenance planning system. Most of the existing literature on optimisation of maintenance activities use a common objective function in their optimisation such as cost, rate and overall quality of service, to allocate resources to the maintenance items, which would not lead to efficient resource utilisations, as it would not take into consideration the impact of site constraints on the various activities.

• Also, there are no evidence to support that dynamic and autonomous resource allocations for maintenance activities take place in the offshore maintenance planning systems that allows each maintenance item to independently adjust its resource allocation based on the time required to complete the activity, to improve the resource utilisation. It would be expected that maintenance planning enables resource allocations, such that the resources are accessible on demand, confirm quality service on demand, provide maintenance activities on demand and provide maintenance with lower costs. However, it would be challenging to have different systems served independently with a proper resource allocation made according to their own requirements. In that respect, the maintenance models have to incorporate the site operational constraints related to personnel resources, environmental factors, and its impact on the overall activities in the maintenance planning system.

• There exists scope for further research work that would incorporate overall risks and site constraints into the maintenance plan, its impact on other activities due to the maintenance execution, and impact of time required to carry out activities. The criticality of other systems in the Offshore asset would also need to be incorporated employing the current condition data, to enhance the confidence of the strategy.

2. Significance of offshore maintenance planning and associated key factors

The maintenance would be required on an offshore equipment or component when its properties deteriorate by age and reach the point of affecting the performance and safety. Maintenance would control or slow down the rate of deterioration and an optimum maintenance plan would fulfil the requirements and repair strategy. The maintenance frequency would be based on the age, the maintenance history, findings from inspections and the rate of deteriorations. The various considerations include operational priorities and critical service vulnerabilities, safety compliance and production performance, prioritisation of activities and overall risks, uncertainties on damage and deterioration mechanisms and deviations from design assumptions and conditions, criticality of maintenance and impact assessment of consequences in the absence of maintenance and condition for maintenance, controls, and mitigations.

The typical damage and deterioration mechanisms on offshore assets includes corrosion, cracks, and deformations/imperfections, which forms the basis for what normally goes wrong in an asset's life. An evaluation of the deterioration mechanisms, deterioration rates, the associated uncertainties and their acceptance criteria would be required to accurately quantify the risk and failure events. The assumptions made during the component design and risk evaluations could become invalid due to various operational and environmental factors such as unexpected scenarios due to extreme weather conditions, loading/offloading patterns, functionality of critical equipment, faults/errors in gauging and monitoring devices. Also, the deviations during the fabrication and manufacturing phases such as geometric and material imperfections, workmanship depending on quality control, regulatory and shipyard practices, plays a vital role on the state of degradations. The skills of the maintenance personnel and performance of maintenance tools, which varies on individual cases would play a critical role in the effectiveness of the maintenance program. A review of causes behind incidents in offshore oil and gas facilities has found that >50% of the fire incidents analysed were related to piping system and machinery equipment failure, as per Halim S.Z. et al., [1].

Figure 2. Corrosion on gratings and Cracks on plates of Offshore structures [86]

The Figure 2 above shows the corrosion on gratings and cracks on plates found on offshore platform structures.

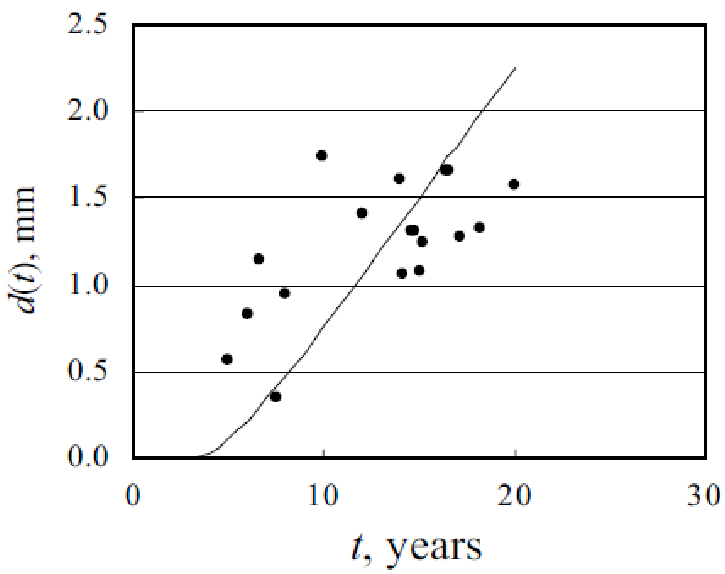

Figure 3. Loss of plating thickness from corrosion, for inner bottom plates [87]

The Figure 3 shows the corrosion rate for the inner bottom plates, based on statistics of measurement data.

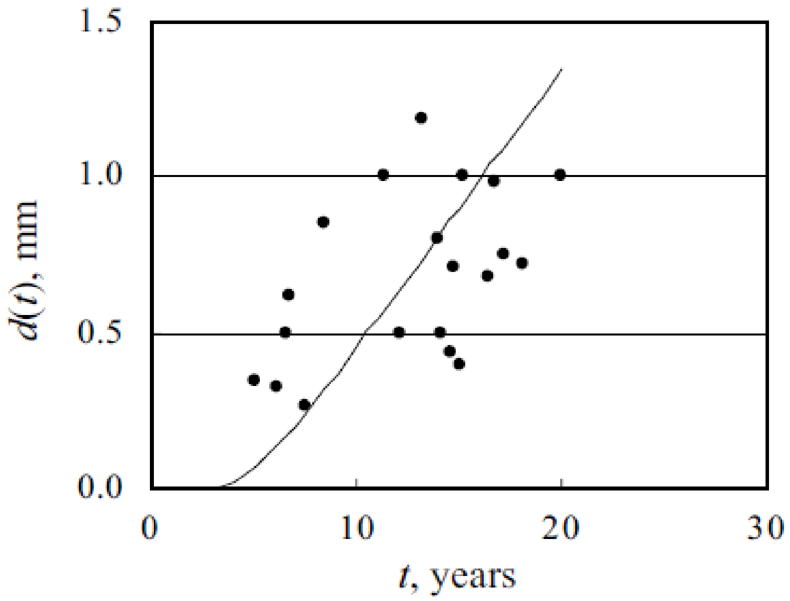

Figure 4. Loss of plating thickness from corrosion, for side shell plates [87]

The Figure 4 shows the corrosion rate for the side shell plates of bulk carriers, based on statistics of measurement data.

Corrosion rates of offshore structures depends on the effectiveness of cathodic protections, cargo composition, inert gas properties, temperature of cargo and maintenance activities on the structures. The corrosion rate varies depending on the function and location of the structural component, as indicated in Figures 3 and 4.

Coatings and cathodic protection systems forms the major controls and mitigations in offshore environment against corrosion, whereas the safety factors and allowances incorporated in the design forms the controls against fatigue cracks and deformations, as detailed by Paik J.K. et. al., [88, 89]. The condition of coating systems determines the level of fabric maintenance to be carried out on the structural and piping system component, whereas the consequent metal loss determines the amount of metal repair work to be executed. In the case of machinery equipment, the running hours and the equipment performance results determine the level of maintenance to be carried out.

3. Different types of offshore maintenance strategies

The offshore maintenance strategy contains guidelines, activities and decision support systems that would be employed to maintain an equipment and prevent occurrence of a failure event. There are various possible ways to classify the current practices in maintenance activities. In this work, the maintenance strategies have been classified as condition based, risk-based, predictive, planned, preventive, reliability based, reliability centred, performance based, corrective, run-to-failure, and opportunistic maintenance.

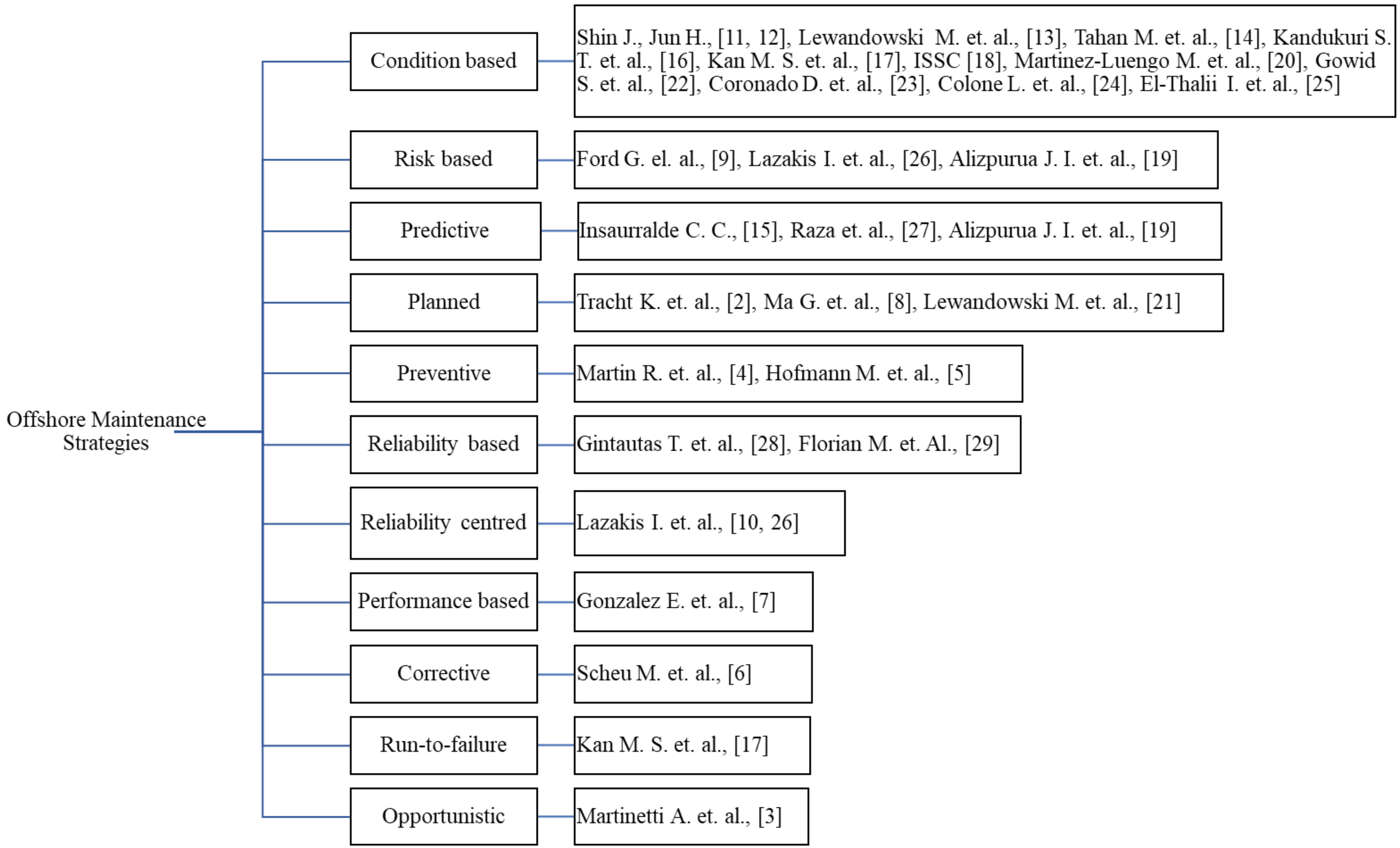

Figure 5. Offshore Maintenance Strategies employed in current state-of-the art literature

The Figure 5 indicates the main offshore maintenance strategies employed in current state-of-the art literature. A brief discussion of these strategies has been provided in the following section:

- **Condition based Maintenance:** The condition-based maintenance is a maintenance plan carried out on a regular or real time basis that is based on the use of Condition Monitoring to determine when a remedial action is required. This involves carrying out maintenance action before the failure event occurs [11], by assessing the equipment condition including operating environments and predicting the risks of failure in a real time, based on data collected. The advantages and limitations of condition-based maintenance frame works that carry out maintenance actions by assessing offshore asset condition and operating environments and predicts the risks of failure events in real-time, based on the gathered data has been presented by Shin J. et. al., [12]. A major limitation of the approach is in the accuracy of diagnostics and prognostics that plays a crucial part in the effectiveness of condition-based maintenance optimisations. Also, the reliability of the condition sensors has a great impact on the effectiveness of this approach. A pre-active offshore maintenance strategy has been presented by Lewandowski M. et. al., [13] that implement autonomous control aspects to plan and control personnel, equipment, resources through decentralised decision-making systems. It has been highlighted that for effective prioritisation of maintenance activities, different maintenance concepts such as corrective and condition monitoring must be combined to handle the uncertainty related to unexpected faults, access conditions and resource availability. A major limitation of this strategy is that it is based on the condition of the equipment and operating environment relative to the design assumptions but does not incorporate the other aspects such as the design features, consequences of not doing the maintenance and the availability of the resources to carry the activity. Therefore, this methodology doesn't integrate with the overall risks and priorities associated with the system.

  The various forms of age-related structural degradation of ship hull structures, measures for mitigating structural degradation, condition assessment of ship structures and consequence of various degradations has been detailed by ISSC [18]. This approach needs to be refined by combining the consequences of not doing the activity and the criticality of other systems included in the overall maintenance plan of the Offshore asset, to address the failure mechanisms realistically. The degradation mechanisms need to be incorporated into the maintenance plans taking into consideration the reliability and failure probability of a selection of target reliabilities, to obtain an optimum maintenance plan for the asset. An online system maintenance method that employs a predictive diagnosis algorithm that differentiate the criticalities in marine systems has been developed by Alizpurua J.I. et. al. [19]. The system maintenance planning algorithm uses this information and interacts with the dynamic dependability model, which is updated with prognostics information, to incorporate the condition-based maintenance strategy and predict the consequence on system health. It is noted that the fatigue and uniform wear degradations would not be dealt with efficiently by this strategy.

- **Risk-based Maintenance:** Risk based maintenance focuses on optimising the maintenance programs recognising that the main goal of maintenance is to prevent failures that affect the safety and reliability of the operating assets. This would be achieved by developing the program that focuses the maintenance resources at areas and components of greater concern and providing a methodology that determines the optimum combination of maintenance frequency and methods, as indicated in the works of Ford G. et. al. [9]. Hence, there is a continuous improvement aspect to the risk-based maintenance process that allows re-evaluation of risk and maintenance activities. The development of offshore risk-based maintenance involves identifying the potential failure events of each component or area; identify the initiating events that lead to those failures; determining the progression of failure sequences and the consequences of the failure events; prioritise and rank the risk associated with that event; selecting an appropriate maintenance program that could mitigate the failure events and the events that lead to those failures. Provided, the design features, operating conditions, deteriorations, and site constraints are incorporated in the risk-based approach, that would lead to a comprehensive maintenance strategy for the asset.
- **Predictive Maintenance:** The predictive maintenance involves condition monitoring using measurement and signal processing methods, that enables diagnose and predict system condition during operation. A mathematical model for predictive offshore maintenance based on prognosis and health management, has been developed by Raza et.al., [27] for a periodically inspected system. A major limitation of this strategy is that it is dependent on the reliability of the smart technologies and sensors. Also, the approach does not incorporate the other aspects of design features, consequences of not

doing the maintenance and the availability of the resources to carry the activity. Therefore, this methodology does not integrate with the overall risks and priorities associated with the entire system.

- **Planned Maintenance:** The planned maintenance is a scheduled maintenance activity that involves getting rid of a component at or before a specified age limit regardless of its condition at the time, as indicated in the works of Tracht K. et. al. [2]. It could be noted that this activity would restore the capability of the equipment at or before a specified age limit and regardless of its condition at the time, to an acceptable probability of survival to the end of another specified interval. This approach considers the design features, assumptions on operating conditions, deterioration rates and the consequences of not doing the maintenance, however, does not consider the impact of site constraints, deviations on operating conditions and resource availabilities.
- **Preventive Maintenance:** The preventive maintenance is a task carried out regularly on an equipment to minimise the likelihood of failure event and restores the inherent reliability or performance of the equipment as indicated in the works of Martin R. et. al. [4]. It could be noted that this activity would be performed at set intervals regardless of whether a failure is about to happen and involves all maintenance activities that would be identified as necessary to provide an acceptable probability of survival to the end of a specified interval for the system. This approach considers the design features, operating conditions, deterioration rates and the consequences of not doing the maintenance, however, does not consider the impact of site constraints and resource availabilities.
- **Reliability based Maintenance:** In the reliability-based maintenance, a system would be selected for evaluation and the criticality of the equipment and components in the system would be determined, as indicated in the works of Gintautas T. et. al., [28] and Florian M. et. al., [29]. The developed maintenance model would act as the foundation for applying selective reliability techniques to create an effective reliability strategy. It could be noted that the maintenance prioritisation would be carried out based on this design features, deteriorations, criticality of the equipment and the consequences of not doing the maintenance, however, does not consider the deviations in operating conditions, site constraints and the resources.
- **Reliability centred Maintenance:** The reliability-centred maintenance is the process that ensures the systems continue to do as required, in their present operating context,

as indicated in the work of Lazakis I. et. al., [10]. It could be noted that a systematic analysis of the system would be carried out to understand its functions, failure modes of its equipment and to choose an appropriate maintenance to prevent the failure mode from occurring or to detect the failure mode before failure occurs. This involves identifying actions that when implemented would reduce the probability of failure and those actions that would be most cost effective. The reliability of the examined system defines the maintenance plan and does not consider the impact of site constraints, deviations on operating conditions, resource availabilities and does not integrate with the overall risks and priorities associated with the entire system.

- **Performance based Maintenance:** The performance-based maintenance involves specifying the performance standards for equipment, instead of the maintenance techniques, as indicated in the work of Gonzalez E. et. al., [7]. It could be noted that this involves defining equipment requirements such as minimum and maximum ranges of operating conditions, availability, and reliability requirements. If there are any changes to the conditions, that would lead to an operational risk assessment and mitigations, however, this approach does not consider the impact of site constraints and resource availabilities.
- **Corrective Maintenance:** The corrective maintenance is a remedial work carried out to identify and rectify a failure event so that the failed system could be restored to an operational condition within the allowable tolerances, as indicated in the work of Scheu M. el. al., [6]. This involves all engineered or administrative procedures implemented to reduce the likelihood of a failure event. This kind of maintenance would be a reactive activity and not a proactive method of maintenance. This approach would be appropriate for less critical systems and increases the uncertainty of the asset availability and reliability with additional cost involved.
- **Run-to-failure Maintenance:** The run-to failure maintenance involves allowing an equipment to run until failure and thereafter a remedial activity is carried out, as indicated in the work of Kan M.S. et. al., [17]. However, it could be noted that this approach would be acceptable only if the risk of failure is acceptable and would be applied mainly for low priority equipment and could lead to increased downtime if not implemented appropriately.
- **Opportunistic Maintenance:** The opportunistic maintenance is a type of preventive maintenance that employ convenient replacement of equipment or components by

taking advantage of an unplanned or planned shutdown of the system, with maintenance resources available on location, as indicated in the work of Martinetti A. et. al., [3]. This approach could be employed for activities that cannot be carried out during normal operations due to redundancy issues, and the equipment for which there is no imminent integrity, safety or production risks identified, however, this approach impacts the preventive replacement cost on economic benefit.

4. Performance indicators for offshore maintenance activities

The major offshore maintenance performance indicators include asset availability, reliability, safety compliance, regulatory compliance, manpower costs, requirement of beds offshore, activity completion, offshore practices, onshore practices, increase in efficiency and consistency. The main factors that influence offshore maintenance performance are rate of deterioration mechanisms, measures to mitigate deteriorations, rectification of anomalies and the failure consequences. The typical damage and deterioration mechanisms on offshore assets includes corrosion, cracks and deformations, imperfections that forms the basis for what normally goes wrong in an asset's life. An evaluation of the deterioration mechanisms, deterioration rates, the associated uncertainties and their acceptance criteria would be required to accurately quantify the risk and failure events. The assumptions made during the component design and risk evaluations could become invalid due to various operational and environmental factors such as unexpected scenarios due to extreme weather conditions, loading-offloading patterns, functionality of critical equipment, faults-errors in gauging and monitoring devices. Also, the deviations during the fabrication and manufacturing phases such as geometric and material imperfections, workmanship depending on quality control, regulatory and shipyard practices, plays a vital role on the state of degradations. The skills of the offshore maintenance personnel and performance of maintenance tools, which varies on individual cases would play a critical role in the effectiveness of the maintenance program.

The key factors that influence the offshore maintenance planning involves maintenance duration, maintenance frequency, regulatory compliance, owners strategy, design conditions, design assumptions, environment conditions, operational conditions, operational requirements, safety compliance, resource availability with respect to man power and materials, costs, failure probability, risks of not carrying out the maintenance, risks with doing the maintenance, business risks, safety risks and environment risks.

The offshore maintenance activities would be prioritised to address top vulnerabilities that impact safety and reliability of the asset and based on the activity's impact on barriers that will liquidate the risks to the asset's performance. The critical component prioritisation would be done by a risk assessment that needs to be carried out based on the probability of occurrences of the failure events, the consequences of failure events and those events that lead to those failures, anomalies, repairs, and planned maintenance activities. The probability of failure would be determined by the relative frequency of failure; influence of degradation mechanisms on the relative frequency; analysis of data and detailed analysis. The various allowances and safety factors for various components determine the probability of the failure mode occurrence.

The corrective activities would reduce the likelihood of the safety event occurrence, by addressing the failure modes related to that event. The maintenance activities on production impacting equipment would liquidate the risks to the asset's production performance and hence would be prioritised accordingly. The corrective repair and preventive maintenance activities on safety critical and production impacting equipment would take priority over other general service activities while planning the maintenance activities in each schedule window. The plan would be primarily constrained by the available bed space on board that limits the number of activities executed in a scheduled period. The offshore operational constraints related to material availability, execution readiness on support activities, isolations, risk assessments and permit requirements would determine the readiness of the activity at a schedule window. Also, environmental constraints related to weather, wind and sea state conditions that impacts execution of activities would define the execution priority.

The risk models categorise the offshore activities to - high, medium, low - based upon the probability of failure event occurrence and the consequence on safety, economics, and the environment. The activity with the highest consequence and probability rating would be used to determine the overall risk. The risk would be dependent on the business plans and procedures of the asset's operating companies. The risk evaluations would identify potential events, their mitigated and unmitigated consequences with respect to safety and economic inputs, their likelihood of occurrence and the associate risk with respect to safety, environment and economic impacts, barriers that are in place, their effectiveness and any other factors that could change the magnitude of the risk.

The safety consequence assessment of not doing the activity employs the acceptance criteria for relevant component, whereas the environmental consequence would be estimated using the data on material volume and the environmental sensitivity of the area affected. The economic consequence assessment relies on the remedial cost and financial impact of the failure event on the business. This involves estimating the time required to design and implement a repair, estimating the business impact during the outage period and defining the lost or deferred revenue.

The economic consequence assessment relies on the remedial cost and financial impact of the failure event on the business. This involves estimating the time required to design and implement a repair, estimating the business impact during the outage period and defining the lost or deferred revenue. The machinery and structural failure consequences could generally be managed in a more controlled manner when compared with that of the pressure system failures. Some maintenance activities could be carried out while the equipment is online, whereas others require equipment or system shut down. This defines the window when the maintenance could be scheduled in and nested with.

In the case of FPSO's, the asset availability and reliability form the basis for production performance and relates to the actual quantity of oil and gas produced, water and gas injected, and gas flared, with respect to the respective target values. Any deviations from the target values would impact the production performance and business objectives. The maintenance activities on production impacting equipment would liquidate the risks to the asset's production performance and hence would be prioritised accordingly.

5. Optimisation techniques for maintenance plans

The following sections investigate the recent developments in optimisation techniques for maintenance plans that could be employed at operational stages and to investigate their relationship to this research problem scenario.

The rationalisation of the offshore maintenance plans could be assisted by numerous procedures applied in a wide variety of areas. However, a rational or optimum maintenance plan could not be developed by introducing only one procedure; to achieve the object, every important aspect must be taken into consideration. In an offshore maintenance plan optimisation problem, the decision variables cannot be chosen arbitrarily; rather, they must satisfy certain specified functional and other requirements. The offshore maintenance plan development is a typical optimisation problem involving multiple and frequently contradictory objective functions and constraints.

Depending on the nature of expressions for the objective functions and the offshore constraints, optimisation problems could be classified as linear as indicated by Gass S I, [30], nonlinear as indicated by Zener C M, [31], geometric as indicated by Duffin R J et al., [32], and quadratic programming problems as indicated by Fox R L, [33]. This classification is extremely useful from the computational point of view, as there are many special methods available for the efficient solution to a class of problems.

As the objective functions and constraints in the offshore maintenance plan optimisation problem would be considered as linear functions of the design variables, the problem could be classified as a linear programming problem, which could be stated in the following form, as stated by Gass S I, [30]:

$$\text{Find } X = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ . \\ . \\ . \\ x_n \end{Bmatrix} \text{ which minimizes } f(X) = \sum_{i=1}^{n} c_i x_i \quad (1)$$

Subject to the constraints

$$\sum_{i=1}^{n} a_{ij} x_i = b_j, \quad j = 1,2, \dots \dots, m$$

$$x_i \geq 0, \quad i = 1,2, \dots \dots, n$$

Where c_i, a_{ij} *and* b_j are constants.

A classification framework for the maintenance optimisation and inspection planning of offshore wind energy systems and structures, was presented by Shafiee M. et. al., [34]. The work has identified that developing an optimised maintenance plan for the life span of wind farms is a complex job considering the uncertainties related to damage mechanisms, dependencies between the asset components, weather dependency on the maintenance execution, unpredictive spare parts demand, accessibility for maintenance, resources such as support vessels, specialised equipment, and workforce. This emphasises the need for effective models and efficient techniques that could incorporate all factors, uncertainties and overall risks associated.

6. Recent applications of modelling techniques for maintenance planning

Some of the recent applications of modelling techniques for offshore and marine system operations have been briefly explained in the following sections.

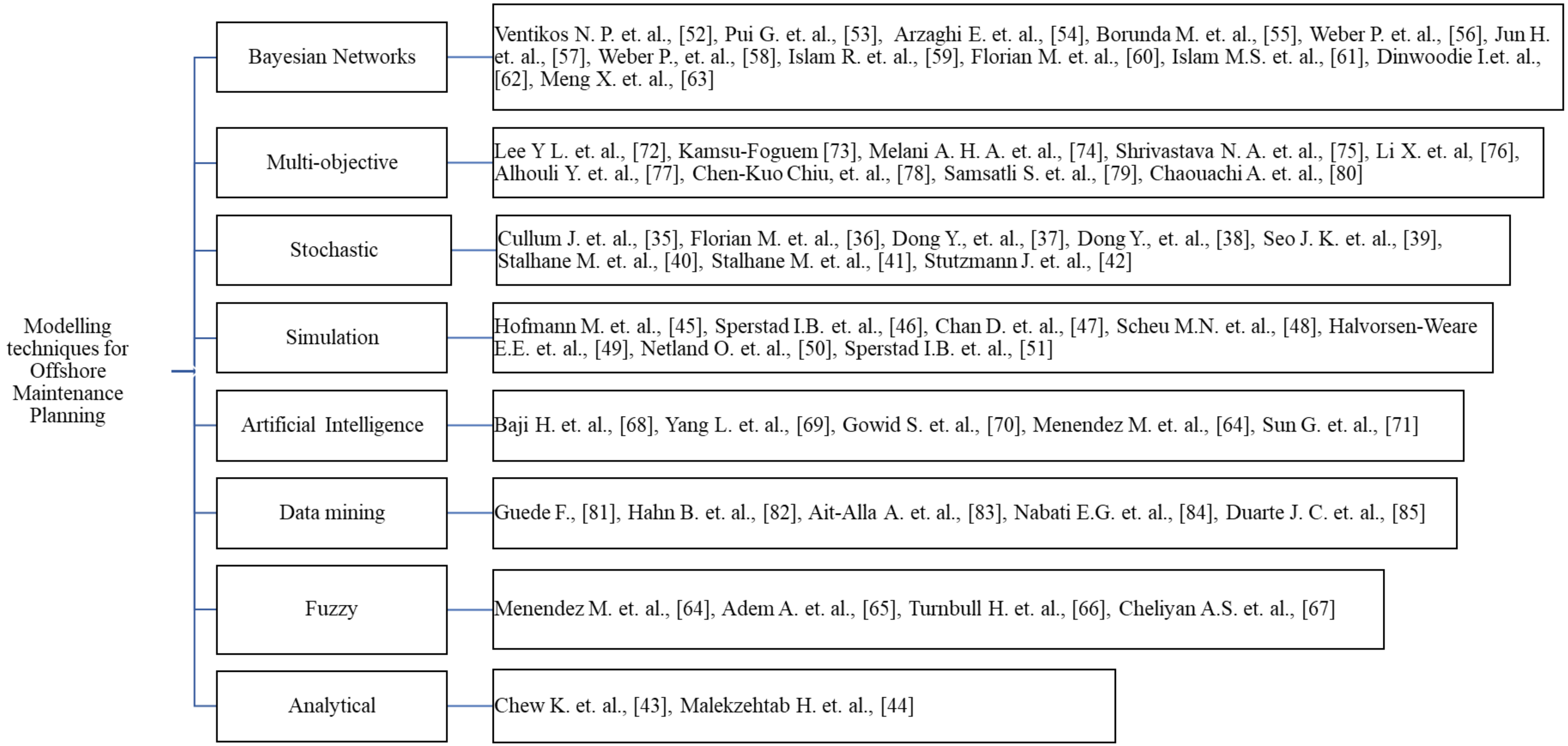

Figure 6. Modelling techniques for offshore maintenance planning employed in current state-of-the art literature

A brief discussion of these modelling techniques has been provided in the following sub-sections.

6.1 Bayesian Networks

The Bayesian Network modelling is a probabilistic machine learning model, which represent the interaction of variables through graph and conditional dependency of causes and symptoms. The Bayesian Network consist of nodes that represent a set of random variables, and edges joining the nodes that represent the dependencies among the variables, as indicated in the work of Ventikos N. P. et. al., [52]. This represents a joint probability distribution of a set of random variables with a potential mutual relationship that models the posterior conditional probability distribution of outcome variable after observing new evidence. A model based on Bayesian Networks that evaluates qualitatively the risk-based inspection of ships, considering the degradation mechanisms of corrosion, fatigue and deformations and the risks associated with the safety and environmental impacts, was developed by Ventikos N. P. et. al., [52]. It is to be noted that the developed model could work within the defined spectrum, and not able to learn any patterns that were not defined in the programming of the network. Also, there are no standardised methods for constructing the relationship from the data, which could be a major weakness of this approach

A risk-based maintenance methodology based on Bayesian Networks for risk estimation of offshore drilling operations, was developed by Pui G. et. al., [53]. In this work, the maintenance frequency of managed pressure drilling systems and their critical components and subsystems were defined independent of the risks associated with the remaining systems. The failure analysis was conducted on the selected systems by collecting the data on undesired events from historic failures and expert judgements and incorporating the estimated likelihoods into the Bayesian Networks. The safety, environmental and economic risks associated with the failure event were incorporated into the Network. The developed methodology considers the failure events of the selected critical systems and their components and does not incorporate the overall risks of the Offshore drilling operations and associated priorities.

A risk-based methodology for maintenance planning of subsea pipelines subjected to fatigue cracks, was developed by Arzaghi E. et. al., [54]. A Bayesian Network based on the deterioration process was developed in their work to model the failure state and failure probability. The fatigue crack growth was modelled using a fracture mechanics-based method and the Bayesian Network was extended to an influence diagram to estimate the expected utility of decision alternatives such as welding, major repair or to continue operations. It could be noted this approach is characterised by approximation of the problem, without understanding of the deeper issues.

A classification framework for the application of Bayesian Networks in offshore renewable energy systems, considering the areas of resource evaluation, operation and applications was presented by Borunda M. et. al., [55]. It has been concluded in this work that for problems with a high degree of uncertainty and incomplete evidence, it has been highlighted that Bayesian networks would be one of the most effective techniques for planning decisions and for forecasting the outcome of stochastic processes. It could be noted that assumptions are inherent within all learning models, however, they are made obvious within the Bayesian approach.

A Bayesian network-based approach for the fault analysis in a marine centrifugal compressor was developed by Jun H. et. al., [57]. The framework and procedure for Bayesian Network based fault analysis in maintenance, including fault identification and sensitivity analysis have been proposed in their work. It could be noted that by following the Bayesian approach, the approximation of complex models have been estimated where complex interactions of variables are present and without having relevant training data. An overview of management of complex marine systems, using Bayesian networks applications for maintenance, dependability, and risk analysis, whereby enabling to make prediction as well as diagnostics, to compute the probability of occurrence of an event, was presented by Weber P., et. al., [58]. This approach uses a statistical analysis, and the failure rates are based on the trends observed in the past, requires initial knowledge of various probabilities and could become computationally hard to deal with.

Following this work [58], a review on the application of Bayesian network applications to dependability, risk analysis and maintenance of offshore systems, was carried out by Weber P. et. al., [56]. Bayesian networks appeared to be capable of modelling complex systems since they perform the factorisation of variables joint distribution based on the conditional dependencies. They compute the distribution probabilities in a set of variables according to the observation of some variables and the prior knowledge of the others. It has been found in their work the Bayesian Networks have been limited by the modelling aspects that they can deal with. Hence, it was required to make Bayesian Networks interoperable with other risk tools, to enable better representation of the system characteristics.

6.2 Multi-objective models

The multi-objective modelling involves simultaneous optimisation of more than one objective function. Minimising operational and maintenance cost while maximising the reliability and availability of a system is a classic example of multi objective optimisation problem. For multi-objective optimisation problems, no solution vector exists that minimises all the objective functions simultaneously and hence the Pareto optimum solution is used in multi-objective optimisation problems, as indicated in the work of by Lee Y L. et. al., [72]. In their work, optimal greedy algorithms have been used for the classification and multi-objective optimisation of data flow traffic towards resource management for Long Term Evolution based cellular networks. It could be noted that this model has the potential to adapt to other applications such as offshore maintenance plan development to support or to benchmark a maintenance planning model, as the method do not require complex mathematical equations and the solutions could be described in Pareto optimal frontiers.

A methodology for risk-based inspection of offshore oil pipelines, was developed by Kamsu-Foguem [73], whereby an organised analysis with knowledge sharing in a multidisciplinary context has been proposed for improving the maintenance management strategy of the pipelines. A risk matrix incorporating the consequences of failures relating to Safety, Environment and Business have been employed for the inspection and maintenance preparation, whereby optimal decisions would be taken in the with trade-offs between conflicting objectives. Following this work [73], a methodology that identifies the criticality of the energy system components, was developed by Melani A. H. A. et. al., [74], to prioritise the maintenance activities of energy systems. The multi-criteria decision method of Analytic Network Process has been employed to identify the criticality of the components, to obtain the optimised results. It has been noted that the approach was more powerful compared to learning algorithms with a scalar cost function in addressing knowledge extraction with limited data.

A multi-objective framework to quantify the uncertainty associated with the forecast of wind speed for offshore wind farms was developed by Shrivastava N. A. et. al., [75]. It has been noted that the uncertainty associated with the forecast variable under consideration would be the main reason for forecast errors. Multi-objective differential evolution algorithm developed to optimise multiple contradictory objectives were integrated with the Support Vector Machine learning to generate the Pareto-optimal solutions of the Prediction Intervals. The best solution determined by the fuzzy approach was found to generate high quality prediction intervals. However, it has been noted that it is impossible to eliminate forecast errors in totality.

A decision support system for strategic maintenance planning in Offshore Wind Farms, was presented by Li X. et. al, [76], using two optimisation models – first a deterministic model and the second a stochastic model, in order to draw the failure rate data. In this work a multi-objective optimisation was carried out to minimise the resource cost including personnel cost and operational costs and maximising the overall availability of the asset. It could be noted that there is potential to include in this approach, the operational constraints related to weather, wind and sea state and the site constraints and its impact on the plan, whereby providing a holistic approach to support decision making. A framework for ship maintenance performance measurement, was developed by Alhouli Y. et. al., [77], based on ten thematic criteria that can impact the planning of ship maintenance programmes. This approach uses a qualitative assessment on defining and validating the maintenance processes, which would be dependent on the experience of the personnel involved and the sample size and potential bias. The work carried out must be supplemented by analysing the real data related to the component parameters and deterioration factors, to increase the credibility of the approach.

An optimised maintenance strategy for energy systems, was developed by Chen-Kuo Chiu, et. al., [78], and applied particle swarm optimisation and Pareto optimal solution for multi-objective optimisation. The objectives of cost minimisation, maximising safety, minimising serviceability, maximising rationality, and minimal maintenance times have been investigated. Probabilistic assessment models for maintenance strategy have been employed to enhance the efficiency of optimisation, however, they do not constitute a sufficient base of information to address the complex issues to ensure compliance with regulations, safety margins and address all considerations related to the risk severities.

6.3 Stochastic models

The stochastic models are those models having stochastic factors with a random probability distribution that could not be predicted precisely but might be analysed statistically, as indicated in the work by Cullum J. et. al., [35]. A critical analysis of risk assessment and maintenance scheduling techniques used for ships and naval vessels has been carried out in their work. As an improvement to the existing scheduling framework, a probabilistic approach supported by condition monitoring data in combination with decision theory has been proposed in this work that would result in reduced maintenance costs while achieving the availability requirements for ship and naval vessel applications. However, in this approach an extremely complex series of events have been modelled with few parameters and hence its assumptions are far too simple and less convincing. Also, as the approach is quite stringent there is minimal scope to include extra factors into the model.

A probabilistic degradation model along with Bayesian networks to estimate the likelihood of having a failure event in offshore wind farms has been developed by Florian M. et. al., [36]. The work focuses on maintenance of wind turbine blades using a fracture mechanics-based degradation model and a reliability estimate of the cracking of the blades. The lifetime cost and availability savings have been estimated using the cost and degradation models using a discrete event simulator and Monte Carlo sampling. It could be noted that this approach would be computationally complex to perform and need to supplement with more detailed statistical and computational models to validate the results.

A probabilistic framework for risk-based inspection and maintenance of ship structures considering corrosion and fatigue has been developed by Dong Y., et. al., [38]. A multi-objective optimisation that considers the structural deterioration, failure and associated uncertainties have been developed to obtain the optimum inspection and repair plans. The proposed methodology employs optimisation techniques based on genetic algorithms to obtain optimum inspection plans that minimise the extent of adverse consequences related to the failure event and that minimises the maintenance costs. It is to be noted that with this approach even very small variations could lead to a high probability of detrimental outcome on the validity of generated solutions. Following the work done in [38], a probabilistic framework for fatigue reliability of ship structures and risk assessment, incorporating inspection events has been developed by Dong Y., et. al., [37]. The work employs fracture mechanics to perform fatigue damage and a quantitative risk assessment model with rating functions to identify inspection priorities. Bayesian networks have been utilised for reliability and risk ranking assessment and updating. A methodology to evaluate risk using rating functions that can consider different consequences have been developed. It could be noted that to understand the risk effectively, it would be required to differentiate the inherent influences affecting the events and random variations observed in the data.

A methodology for risk-based inspection planning and fit for service assessments of corroded subsea pipelines has been developed by Seo J. K. et. al., [39]. The probability of corrosion defect has been calculated as probability of failure, which is a time-variant model from measured data in the subsea industry and the consequence of failure estimated from the burst strength for the corroded pipelines. Consequence modelling was carried out using Regulation design codes to simulate strength and probability calculation. The proposed methodology provides a standardised procedure for incorporating design, inspection, and maintenance planning of pipeline systems, whereby providing a more effective procedure for risk-based inspections. It is to be noted that the ability of this approach to model the features of the system was found to be limited, whereby many features at the system level including the correlations and common causes of failures were approximated.

6.4 Simulation models

Simulation models creates and analyse a digital prototype of a physical model and predicts its performance by considering the associated uncertainties that exist in the real world, as indicated in the work of Hofmann M. et. al., [45]. A simulation study with a discrete event simulation model for the operational phase of an offshore wind farm, comparing the operational and maintenance costs of turbines of differing capacities, was carried out in their work. It is to be noted that this approach would be prone to errors inherent on the simulation or model.

The use of single and multi-parameter wave criteria for accessing wind turbines in two strategic maintenance and logistics models for offshore wind farms – one using a simulation model and other using an optimisation model was compared by Sperstad I.B. et. al., [51], and the simulation model has been found to give too pessimistic results. The quality of modelling carried out could have a major influence on the results obtained.

6.5 Artificial Intelligence models

The application of artificial intelligence models could be used to identify system characteristics and produce results comparable to mathematically derived models. It is to be noted that artificial neural networks could be successfully employed to model and learn a variety of real, discrete and vector-valued functions. Due to their ability to associate patterns, the neural networks could easily model correlations which are difficult to model through physical modelling, as could be found in the work by Baji H. et. al., [68]. A maintenance strategy for marine structures based on risk cost optimisation, was developed in their work, by taking into consideration various failure events of the components. A time dependent reliability method has been employed and a stochastic model for structural responses have been developed. Genetic Algorithm method has been used to minimise the risk function to optimise the maintenance frequencies. It is to be noted that the network configuration has to be selected by trial and error for a successful generalisation and that the long training time could be a problem for this approach. A quick convergence could not be guaranteed in the algorithm. Also, any theoretical knowledge about the data could not be transferred to the parameters, although that knowledge would help in the selection of network structure.

A multi-level maintenance strategy for an energy system subject to two competing failure processes, was presented by Yang L. et. al., [69], by performing a finite number of inspections before replacement, to achieve a reasonable maintenance resource allocation and a two-stage inspection plan consisting of normal and defective frequencies. Genetic Algorithm has been employed in this work for maintenance optimisation and the uncertainties related to maintenance, repair and inspection have been incorporated into the maintenance model. It is to be noted that this approach employs a combination of approximate models and approximated fitness functions to solve complex problems on the uncertainties. Also, this approach tends to converge towards local optima rather than the global optimum of the problem.

A review of profitability, reliability, and condition-based monitoring techniques of LNG floating platforms, was carried out by Gowid S. et. al., [70]. It has been noted that majority of existing automated features selection tools utilise artificial intelligence methods of Artificial Neural Networks, Adaptive Neuro-Fuzzy Inference System, Genetic Algorithm and Support Vector Machine. It has been noted that the accuracy of these methods would be related to the values of their various design parameters. The functional relationship provided by artificial intelligence approaches have no similarity to the known and established mathematical models. Also, it has been found that there would be high computing cost and high developing time associated with the artificial intelligence-based methods.

Recently, the advancement of deep reinforcement learning has led to the rapid development in the field of artificial intelligence applications. A dynamic resource reservation and deep reinforcement learning based autonomous virtual resource slicing framework for radio access networks has been employed by Sun G. et. al., [71]. Deep reinforcement learning was used by slices to autonomously increase or decrease the resource allocation in proportion to the radio resource reservations in the base station. Due to the satisfaction and resource utilisation feedback the Deep Q Reinforcement Learning Network (DQN) agent received from the slices, the resources were adjusted improving resource utilisation and satisfaction. It is to be noted that this approach of modelling requires to quantify all variables the environment describes and to have access to these variables at each time step, to model the problem. Also, an optimised reward function has to be determined for taking actions by the agent in the environment and would not be suitable when the reward function is not evident. It could be noted that this model has the potential to adapt for other applications with resource and time constrains such as optimisation of offshore maintenance planning, such that the system would allow customising their own utility and objective functions based on their requirements, leading to the development of a smart offshore maintenance planning tool.

6.6 Data mining

The data mining techniques discover patterns in large datasets and extract meaningful data and build models, to examine the effect of one or a set of variables on the system performance, as could be found in the work by Guede F., [81]. A method for risk-based inspection plan development of offshore jacket platform structures in line with API standard for structural integrity management of fixed offshore platforms, was provided in their work. The method employs semi-quantitative and quantitative approaches based on available data of structural analysis results on fatigue failures and the met ocean data, for global and local risk assessment to enable selection of locations to provide representative overall structural condition. The need for a database containing generic parameters of typical structural components of the platform have been highlighted, to enable development of suitable inspection plans. It is to be noted that this approach could provide accuracy of data with its own limits. The scalability of algorithm determines the amount of data that could be dealt with without impacting computational efficiency.

6.7 Fuzzy models

Fuzzy models are mathematical means of representing vague and imprecise data, as indicated in the work by Menendez M. et. al., [64]. A framework for infrastructure maintenance in energy systems based on maintenance data and knowledge expertise, was developed in their work.

With the qualitative data from experts and the deterioration models of the assets, an optimised maintenance schedule has been developed employing fuzzy and computational intelligence techniques. It is to be noted that this approach lacks real time responses and not capable to receive feedback for learning strategy implementation.

6.8 Analytical models

The analytical models are mathematical models with a closed form solution, as could be found in the work by Chew K. et. al., [43]. An analytical gradient based method to optimise the design of offshore wind turbine support structures subjected to fatigue and extreme loads, was presented in their work. The influence of various design constraints on the structural design and optimisation procedure was evaluated; however, this approach requires employing a number of modelling assumptions. The recurring events are not accounted for in this method and ignores the interaction between the various design constraints. The application of finite element model updating was investigated in damage detection of an offshore jacket platform, by Malekzehtab H. et. al., [44]. The objective function in their work was based on the measured and analytical data, and genetic algorithm was employed as a search tool to update the model. It is to be noted that there is rarely any guarantee of finding global maxima by this approach, and there is increased likelihood of getting stuck with a local maximum. Also, a decent sized population and a lot of generations needed to get good results.

7. Conclusion

An optimised strategic planning of maintenance activities would be required for offshore systems satisfying regulatory and owners' requirements, without compromising safety and reliability of the asset, within the constraints of maintenance duration, activity completion, resource availability due to offshore bed space restrictions. It has been noted that the maintenance performance indicators widely considered relates to the asset availability, reliability, and safety compliance, whereas the site constraints and impact of time required to carry out activities are not regarded as a performance indicator in the existing literature, which is a major limitation of the existing frameworks, as the availability of bed space offshore for any activity is the prime performance indicator for any maintenance execution. The quantitative condition assessment methods have been widely employed in the existing literature, whereas few literatures have considered the qualitative assessment of operational and inspection data for condition assessment, which could be due to the difficulty in obtaining actual data from existing assets. It has been noted that probabilistic assessment models, Bayesian Networks and Multi-objective optimisation techniques have been widely used in the literature for optimisation of maintenance activities. Most of these methods mainly generate a set of pareto optimal solutions and use some additional criterion or rule to select one particular pareto optimal solution as the solution of the multi-objective problem. Towards this, there exists scope for further research work that would incorporate site constraints and impact of time required to carry out activities including the Offshore resource availability into the maintenance plan and its impact on asset condition due to the maintenance execution, in order to achieve the optimal maintenance strategy.

Most of the methodologies identified in the literature take into account the failure events of only few selected critical components and criteria, without integrating with the complete system and associated overall risks. In order to achieve the optimum maintenance plan, the operational and environmental uncertainties related to weather, wind and sea state and its impact on the plan, maintenance uncertainties, unpredictive resource availability for maintenance execution, uncertainties related to damage and degradation mechanisms, uncertainty of failure occurrence and the deviations from design assumptions needs to be assessed and considered.

The maintenance planning also needs to be integrated with the inspection plans and offshore resource availability to achieve a credible implementation plan incorporating the overall risks. The criticality of other systems in the Offshore asset would also need to be incorporated employing the current condition data. The constraints of offshore personnel availability for the maintenance activity due to maximum allowable bed space is a factor not considered in any of the frameworks identified in the literature review. This is a major limitation of the existing state-of-the art maintenance frameworks. There are still research gaps in frameworks, towards incorporating the overall risks, practical site constraints encountered mainly with regards to the availability of bed space onboard for the personnel, impact of time required to carry out activities and its impact on other activities due to this maintenance.

Also, no dynamic and autonomous resource allocations for maintenance activities take place in the offshore maintenance planning systems that allows each maintenance item to independently adjust its resource allocation based on the time required to complete the activity, to improve the resource utilisation. It would be expected that maintenance planning enables resource allocations, such that the resources are accessible on demand, confirm quality service on demand, provide maintenance activities on demand and provide maintenance with lower costs. However, it would be challenging to have different systems served independently with a proper resource allocation made according to their own requirements. In that respect, the maintenance models have to incorporate the site operational constraints related to personnel resources, environmental factors, and its impact on the overall activities in the maintenance planning system.

It could be concluded that there exists scope for further research work that addresses the above-mentioned gaps by examining machine learning and deep Q reinforcement learning network based artificial intelligence approach, considering the design features, actual condition of the component, site constraints, deterioration factors, consequences of not doing the activities, time required to complete the activities and investigating the impact on key maintenance performance indicators regarding resource allocations and resource utilisations.

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