An overview of maintenance management strategies for corroded steel structures in extreme marine environments

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Abstract

Maintenance is playing an important role in integrity management of marine assets such as ship structures, offshore renewable energy platforms and subsea oil and gas facilities. The service life of marine assets is heavily influenced by the involvement of numerous material degradation processes (such as fatigue cracking, corrosion and pitting) as well as environmental stresses that vary with geographic locations and climatic factors. The composition of seawater constituents (dissolved oxygen, salinity and temperature content) is one of the major influencing factors in degradation of marine assets. Improving the efficiency and effectiveness of maintenance management strategies can have a significant impact on operational availability and reliability of marine assets. Many research studies have been conducted over the past few decades to predict the degradation behaviour of marine structures operating under different environmental conditions. The utilisation of structural degradation data – particularly on marine corrosion – can be very useful in developing a reliable, risk-free and cost-effective maintenance strategy. This paper presents an overview of the state-of-the-art and future trends in asset maintenance management strategies applied to corroded steel structures in extreme marine environments. The corrosion prediction models as well as industry best practices on maintenance of marine steel structures are extensively reviewed and analysed. Furthermore, some applications of advanced technologies such as computerized maintenance management system (CMMS), artificial intelligence (AI) and Bayesian network (BN) are discussed. Our review reveals that there are significant variations in corrosion behaviour of marine steel structures and their industrial maintenance practices from one climatic condition to another. This has been found to be largely attributed to variation in seawater composition/characteristics and their complex mutual relationships.

Keywords Maintenance management; Steel structures; Degradation; Marine corrosion; Extreme climatic conditions.

1. Introduction

The maritime sector plays an extremely important role in the economic growth of many countries around the world [1]. However, the costs associated with maintenance and repair of the assets operating in this sector (such as ship structures, offshore renewable energy platforms and subsea oil and gas facilities) are extremely high and continue to rise. Currently, the maintenance costs in the maritime sector account for between 20 and 40 percent of the total operating expenses (OPEX) [2–5]. The high cost of maintenance for marine assets is mainly attributed to the involvement of various degradation/deterioration processes in aquatic environments which pose detrimental effects on technical integrity, safety and reliability of the assets.

The degradation of marine assets usually occurs due to a variety of mechanisms such as fatigue cracking, corrosion, pitting, scour, etc. Many recent research studies have identified the *corrosion* as the most prominent degradation mechanism in the maritime sector, which can result in catastrophic failures [6, 7]. The marine assets are either totally or partially immersed in corrosive seawaters. Most of the fixed and floating marine structures located near the harbors are exposed to domestic or industrially polluted seawaters, which further accelerate the pace of structural degradation, in particular corrosion. Additionally, non-submerged structures in the vicinity of coastal areas are vulnerable to corrosion damage due to the accumulation of salt and other corrosive compounds in marine environments.

To control the rate of degradation, increase the operational uptime, reduce the life-cycle costs, and extend the service lifetime in marine assets, a number of maintenance practices including preventive maintenance (PM), condition-based maintenance (CBM), risk-based maintenance (RBM), and structural health monitoring (SHM) have been deployed by marine industry professionals [8]. In today's world, the improvement of operational and environmental safety has been the prime objective of maintenance operations in the maritime sector. Historically, maintenance was seen as more of an economic liability than an effective tool to improve productivity in organisations. However, after experiencing some serious incidents and environmental disasters such as Macondo oil spill in the Gulf of Mexico in 2010, it has become incumbent for the industry to comply with requirements set out by regulatory bodies such as the International Maritime Organisation (IMO), European Maritime Safety Agency (EMSA), United States Coast Guard (USGC), etc. [9–11]. These regulations have created enormous hurdles for maritime operators, necessitating continuous improvement in their existing monitoring systems and maintenance regimes. One such example is the IMO law on sulphur content control in fuel, which is going to be implemented from 2020 onwards. It dictates that the sulphur content which is currently 3.5% m/m (mass/mass) (equivalent to 35,000 ppm) must be capped at 0.50% m/m (equivalent to 5,000 ppm) [12]. Such legislations will increase the pressure on maritime industries to develop more reliable, risk-free and cost-effective maintenance strategies for their critical assets.

The commercial maritime industry is currently more reliant on conventional time-based maintenance procedures, which in general are inefficient and labour intensive. In order to increase safety, operational uptime, effectiveness and reliability while reducing maintenance costs [13, 14], the maritime industry must adopt risk-based and reliability-centred asset maintenance practices from some other industries such as the aerospace, nuclear, and chemical.

The maintenance management of marine assets is a complex task because of the uncertainties involved in long-term prediction of the corrosion damage under different environmental conditions. It is a proven fact, supported by the scientific literature, that the selection of a maintenance strategy for marine assets is highly influenced by climatic conditions such as temperature, relative humidity, wind speed and direction, etc. Therefore, it is logical to apprehend that the implementation of the same maintenance regime for systems operating in different environmental conditions and with different degradation modes will not result in an optimal outcome. To optimise maintenance practices and achieve greater reliability, throughput, cost-effectiveness and safety in the marine sector, several advanced data-driven models integrated with condition monitoring (CM) and non-destructive testing (NDT) technologies as well as risk assessment tools have been proposed over the past few decades.

This paper presents an overview of the state-of-the-art and future trends in asset maintenance management strategies applied to corroded steel structures in extreme marine environments. The corrosion prediction models as well as industry best practices on maintenance of marine steel structures are extensively reviewed and analysed. In this regard, we identify several deterministic and probabilistic models that have been developed to predict the corrosion rate of marine steel structures as a function of the exposure period, environmental conditions and material properties. It is shown that the existing models involve considerable uncertainties in data collection and analysis for accurate modeling of the combined effects of environmental factors on overall corrosion loss in marine structures. To overcome this drawback, some applications of advanced technologies such as computerized maintenance management system (CMMS), Bayesian network (BN), artificial intelligence (AI), and multi-criteria decision analysis (MCDA) to maintenance optimization of corroded steel marine structures will be discussed. Our review reveals that there are significant variations in corrosion behaviour of marine steel structures and their industrial maintenance practices from one climatic condition to another.

The rest of the paper is organized as follows. Section 2 describes various contemporary maintenance strategies and their significance in the marine industry. Section 3 presents the impacts of surrounding climatic conditions on the structural degradation (in particular corrosion) of marine assets. Section 4 reports the results of a literature review on various maintenance strategies applied to marine steel structures in corrosive environments. Section 5 provides an overview of some advanced techniques that can be used for corrosion prediction and maintenance planning of marine steel structures. Section 6 discusses the results of the critical analysis of the identified literature. Finally, Section 7 concludes the study with a brief summary and future directions.

2. Maintenance strategies

A maintenance strategy delineates an organization’s vision on how to preserve the health and safety of assets throughout their life-cycle. Generally, it is comprised of procedures for survey/inspection, repair, upkeep and renewal of the systems, subsystems, and components

[15]. In the search for greater efficiency and lower cost, a number of maintenance strategies have been conceived by the researchers over the years [16]. Figure 1 shows the evolution of key maintenance strategies in the marine sector. These strategies are briefly introduced in the following subsections:

**** Figure 1 ****

Figure 1. Evolution of maintenance strategies in the marine sector.

2.1. Corrective maintenance

In corrective maintenance or run-to-failure (RTF) strategy, a correction action is taken to bring the equipment back to a functional state after it unexpectedly stops working. This action includes either repair or replacement of failed component and it can be carried out as and when required. Therefore, this maintenance strategy is preferred only on those equipment whose failure consequences are considered minimal. The investment required for the execution of this maintenance strategy is much less than any other maintenance strategy, however, it may incur additional repair costs and increase downtime when applied to critical equipment [17].

2.2. Preventive maintenance (PM)

The PM is an interval-based maintenance procedure which is implemented on an operational equipment so as to avoid any potential failure or severe degradation that may impact system reliability in near future [18]. The frequency of PM tasks is often chosen based on the experience of technicians or recommendations from original equipment manufacturers (OEMs). PM strategy has been able to offer higher system availability, reduced failure rates, longer equipment lifespan, and lower cost compared to the corrective maintenance. PM is currently practiced in many marine industries as the most preferred maintenance strategy [19].

Despite several intrinsic benefits, PM does not guarantee elimination of all unexpected failures as it does not take into account the present health state of components. For this reason, PM sometimes results in unnecessary machinery downtime, excessive repair costs and maintenance-induced failures [20, 21]. Some researchers reported that conducting time-based PM actions may lead to misjudgement about the equipment's health condition as the rate of usage may not be constant over time [22].

2.3. Condition-based maintenance (*CBM*)

The CBM includes use of modern CM methods to precisely diagnose faults and predict the future working condition of the system [23]. According to this strategy, a maintenance is performed when one or more indicators show that equipment performance is degrading or that the equipment is about to fail [24]. In other words, the CBM decision is made based on a set of indicators associated with system's physical condition or performance [25]. Many researchers have shown that the CBM strategy is more effective than the time-based PM strategy. It is reported in the literature that the use of CM techniques may extend maintenance overhaul cycles by up to 50% and save between 25% to 45% of maintenance costs [26]. This maintenance strategy is based on the output data collected either online and off-line from different CM technologies, such as vibration analysis, ultrasound analysis, infrared thermography, oil analysis, wear particle analysis, acoustic emission testing, etc. The collected data is analysed to extract meaningful patterns and predict the time for future maintenance. Some researchers have considered diagnostic and prognostic as main features of a CBM system (for example, see [27]).

Even though the CBM is able to deliver substantial savings in maintenance cost and reduction in failure risks, the current surveys reveal that only 10% of industries in the marine sector use CBM as their preferred maintenance strategy [15]. One of the reasons for slow adoption of CBM is the limited access to highly skilled personnel for execution and further interpretation of the results [28]. Nevertheless, with the advancement in prognostic and health monitoring (PHM) methods, the reliance on CM and active/passive SHM techniques in equipment maintenance has grown exponentially in recent years [29].

2.4. Reliability-centred maintenance (RCM)

The RCM concept was conceived for the first time in American Aviation industry in mid-1980s. It is a planned maintenance program that retains the essential functions of a system while improving its reliability, maintainability and availability (RAM) [30, 31]. It is reported in the literature that if the RCM is employed correctly with a thorough understanding of its essence, it can be helpful to reduce maintenance effort by 40% to 70% compared to other maintenance strategies such as the corrective maintenance, scheduled overhaul, scheduled replacement, and scheduled on-condition tasks [32]. The maintenance decisions in RCM are made based on qualitative risk information mainly derived from the knowledge/skills of the operators. RCM necessitates the default maintenance actions to counter failure situations which arise due to unavailability of effective proactive maintenance procedures. These default actions include failure finding, run to fail, and redesign [33].

Within the marine sector, RCM is commonly used for the maintenance of ships and their associated equipment. The RCM strategy uses techniques such as Failure Mode Effect Analysis (FMEA), Failure Mode Effect and Critical Analysis (FMECA) and Fault Tree Analysis (FTA) to identify possible causes of each failure, as well as some statistical techniques to estimate mean time between failure (MTBF), mean time to repair (MTTR), etc. [34, 35]. The FMEA is the essence of RCM, as it provides a procedure to identify and recognize function(s), failure modes, failure causes, and effects and consequences of a failure on the operability of a particular equipment, system or process [36]. For comprehensive literature on RCM and its implementation, readers are referred to [37–41].

2.5. Risk-based inspection (RBI)

The concept of RBI was originated from the nuclear industry in the 1970’s. Over the years, it has been adopted by other sectors such as petrochemical, electrical systems, offshore energy sector and, to a lesser extent, shipping. The RBI emphasizes on the factor of risk in the overall maintenance of equipment. The risk is evaluated based on the likelihood (probability) of occurrence of a hazard and its consequent effects on the operation of the equipment [42, 43]. RBI is an optimized maintenance strategy which offers greater safety and provides an overall risk mitigation plan to minimise the frequency of undesirable events [44, 45]. In this strategy, the risk analysis outcomes are utilized for maintenance scheduling and decision-making. Risk analysis permits flexibility for the use of qualitative/quantitative methods or a combination of both. Some researchers have proposed a risk-based approach for the inspection and maintenance of ship vessels, where the RCM is recommended for mechanical systems and RBI for hull and structures. For further information on RBI, the readers can refer to [46–49].

2.6. Other contemporary maintenance strategies

In recent years, several other developments in maintenance management systems have been evolved and implemented in the marine sector. Reliability database (RDB) is one of novel concepts proposed for the management of reliability datasets. It is a prime source of information for design, development and initial deployment of advanced, cost-effective and optimized maintenance systems. RDB records all significant maintenance activities with a core focus on equipment failures. This is considered to be the prime enabler for maintenance strategies such as Total Life Cycle Systems Management (TLCSM) and CBM plus (CBM+). The TLCSM deals with the total system performance (including hardware, software, and human), its operational effectiveness, and suitability, survivability, safety, and affordability [50]. The CBM+ is a novel maintenance concept which was developed on the basis of CBM strategy but by including various advanced tools and procedures, acquired from real-time health monitoring and sensor technologies [51]. The CBM+ facilitates the shift from conventional maintenance regimes (e.g. time-based PM) to proactive/predictive methods governed by CM programmes.

The term remaining useful life (RUL) in maintenance implies the remaining time of a system/subsystem to perform its function prior to failure or end of useful life [52]. The RUL estimation models are either deterministic or probabilistic, but they generally incorporate degradation factors, material properties, and environmental conditions [53]. The RUL estimation models can be classified into four categories: analytical (physics-based), model-based (data-driven), knowledge-based, and hybrid (fusion) (see Figure 2) [54–57]. The RUL methods can be further refined into a more accurate maintenance model by the use of statistical and Artificial Intelligence (AI) techniques [58]. Sometimes, manufacturers use accelerated life testing (ALT) data to predict the lifetime of equipment under different operating and environmental conditions. Typically, the OEM's maintenance recommendations are based on ALT results [53]. These tests are simulated on an accelerated time scale and then the reliability of the equipment is estimated based on specified failure data settings, operating conditions and design stresses [59].

**** Figure 2 ****

Figure 2. Classification of RUL prediction techniques [55].

3. Impact of environmental conditions on corrosion of marine structures

Marine structures are often exposed to severe and corrosive environmental conditions such as high or low temperatures, high salinity, high or low pH values, etc. These conditions accelerate the material degradation rate and thus shorten the time to failure of structures. The reliability of steel structures in marine environments is highly influenced by the variations in ambient climate, loading conditions, applied protective measures, and the adopted maintenance strategies [60]. Corrosion and fatigue are the most prominent degradation mechanisms in marine steel structures which adversely affect their reliability by inducing strength losses, brittle fracture, thickness reduction, cracking, etc. Static and shock loads, erosion, and turbulent seawater velocity are additional factors contributing to the failure of marine structures. Some research studies have reported that over 90% of ships' structural failures are caused by corrosion [61].

The key factors affecting the corrosion process in marine steel structures have been categorised into different types of physical properties, chemical properties, and biological contents in seawater [62–66]. The most influential factors in physical, chemical and biological properties have been studied widely in the literature. Table 1 lists the most influential factors in the marine corrosion process, including seawater temperature and velocity, pressure, pH level, dissolved oxygen (DO), salinity, pollutants, etc. Some researchers have shown that the biological factors such as sulphur reducing bacteria (SRBs) are the most contributing element in the anoxic seawater conditions.

**** Table 1 ****

Table 1. A list of factors affecting the marine corrosion in steel structures.

The characteristics of marine conditions and seawater specifications are found to be immensely variable across the globe. For example, the temperature of surface seawaters varies from –2ºC along poles to 35ºC along the equator. Consequently, the corrosion rate as well as the health state of marine structures will be different from a region to another [67, 68]. Furthermore, the corrosion rate may be altered with inspection, maintenance and repair actions, which makes the RUL prediction process for marine structures more complicated [69].

Although majority of the marine steel structures are protected with coatings to inhibit corrosion and stress corrosion cracking (SCC), an inspection is needed to assure that the corrosion protection system is working [70, 71]. The prominent corrosion resistant methods used on external surfaces of the ships or offshore structures include: sacrificial anodes, impressed current cathodic protection (ICCP), various types of anti-fouling, anti-corrosive paints, and ultrasonic guided wave methods [72]. However, some marine systems such as heat exchanger tubes are not yet provided with a surface coating, causing them to be more vulnerable to corrosion damage. The maintenance practices in such cases are even more dependent on operating ambient conditions and proportion of detrimental corrosion factors in the seawater composition.

4. Findings of the literature review

This section reports the results of the literature review performed on various maintenance practices and asset management strategies adopted for marine structures in extreme corrosive environments. Our review covers journal papers, conference proceedings, books, academic dissertations, industry reports and government guidelines. The identified studies are categorised with respect to some criteria such as the type of marine structure under consideration (e.g. offshore platforms, ships, oil rigs, subsea pipelines and offshore wind turbines), degradation mechanisms and maintenance planning methodologies, and some key findings will be reported.

4.1. Findings on maintenance management strategies for marine steel structures

Marine structures are designed for operation in hostile environments subject to corrosive sea-water, hot and cold temperature extremes, and static/dynamic loading conditions. Although the corrosion affects the performance of an assets throughout the life cycle, the extent of the damage varies depending on many factors such as the designed allowance for corrosion loss, the effectiveness of preservation methods, and severity of dynamic environmental conditions [73]. The main function of a reliable maintenance scheme is to identify the critical components, functions, failure modes, causes, effects and consequences, and then recommend a cost-effective repair policy to attain optimal operational availability. Nowadays, different aspects of maintenance are considered during the design phase of marine structures; however, some modifications, additions/alterations in the existing engineering design may be necessary in later stages during the operation. Marine structures usually deteriorate more rapidly under extreme conditions than under normal conditions. This causes the gap between designed capability and current performance to become greater and greater over time. The deterioration of the design performance in marine structures over time is illustrated in Figure 3.

**** Figure 3 ****

Figure 3. Deterioration of design performance over time [15].

In commercial ships, the operators/owners either rely on OEM's recommendations or seek the expertise of engineers to determine maintenance support requirements [56]. OEM's maintenance procedures are often based on the age of the ships, not real-time degradation data. The tendency of shifting from time-based PM to CBM, online monitoring, and predictive maintenance is emerging over the years in the marine sector. CBM is considered to be an efficient approach to improve the reliability and reduce the operating costs of marine systems, especially for those assets involving high safety risks. Emovon [4] conducted a comparative study on the application of different maintenance strategies to ships, and finally, offline-CBM was found to be the most effective method for maintenance of seawater pumps in a marine diesel engine. More recently, Michala *et al.* [74] presented a novel concept of CBM on ships using wireless systems, where the CM data about ship machinery components is transmitted to the onshore maintenance experts through a decision support system (DSS).

Lazakis and Ölçer [5] presented a Reliability and Criticality Based Maintenance (RCBM) strategy using fuzzy multi-attributive group decision-making (FMAGDM) technique to identify an optimised maintenance strategy for maritime assets. The study concluded that the time-based PM was the best maintenance strategy, followed by the predictive maintenance. Cicek and Celik [75] used risk priority number (RPN) in FMEA methodology to enhance the reliability and operational safety while decreasing the failure probability of marine diesel engines. Similarly in a comparative study of onshore and offshore wind turbines, Shafiee and Dinmohammadi [76] proposed a FMEA-based risk evaluation methodology integrating qualitative (expert-driven) and quantitative (data-driven) information to formulate a maintenance strategy for wind turbines. Tang *et al.* [77] proposed a novel model based on Analytic Hierarchy Process (AHP) and Fuzzy Borda Count (FBC) for identification of the most risky items in offshore oil and gas equipment. Some researchers opined that the use of RCM in the marine sector is culturally different than that in the aviation sector. Therefore, it is more sensible to consider RCM as a philosophy rather than a methodology [78]. From the commercial ship owners' point of view, the RCM is considered to be exhaustive, time-consuming and complex [3]. Wabakken [79] reported that the RCM is a long-term strategy which requires time and resource-intensive effort. Therefore, RCM has been hesitantly adopted by maritime companies.

RBI is becoming a popular maintenance strategy in the marine sector, in particular for ship's hull and structures. Cullum *et al.* [22] proposed an RBI scheduling framework for naval vessels and ships and concluded that shifting from RCM strategy to RBI is more convenient than shafting from PM or CBM to RBI. Dong and Frangopol [80, 81] proposed quantitative risk assessment (QRA) models for ship structures subject to corrosion and fatigue. The genetic algorithm (GA) and Bayesian networks were used to provide an optimal inspection/repair plan and reliability/risk updating for overall mitigation of lifecycle risk. Similarly, Turan *et al.* [82] proposed an RBI model to estimate the overall reliability of ships and diving support vessels and prioritize the maintenance tasks.

A comprehensive distribution of journal articles and conference papers based on maintenance strategies is shown in Table 2.

**** Table 2 ****

Table 2. Distribution of journal articles and conference papers based on maintenance strategies.

Numerous NDT and SHM methods are used for detection, quantification, and prognostics of surface and subsurface defects (such as cracks, gouges, pits, and erosion/corrosion loss) due to various structural degradation mechanisms like corrosion, pitting, or fatigue cracking [90]. Photographic imaging has been used to measure and bifurcate appearance of marine pitting corrosion [91]. Recently, visual imaging and high-resolution photography were used with integration on remotely operated vehicles (ROV) or autonomous underwater vehicles (AUV) for enhanced safety and efficiency and reduced cost of underwater repair activities. These vehicles can utilize videos that are able to diagnose structural corrosion and anode wear, and thus facilitate the inspection of difficult-to-access areas [92–94]. From literature review, the following CM or SHM techniques were identified for use by marine operators: [95, 96]:

Visual and optical testing; radiographic testing; ultrasonic testing (conventional phased array, and guided waves); metallographic examination; electrochemical and electromagnetic testing; liquid penetrant testing; magnetic particle testing; acoustic emission testing; infrared and thermal testing; mass loss; X-ray; eddy current.

Some newly introduced technologies in metal and composite structures are acoustic emission and guided waves ultrasonic testing (GWUT). These technologies utilize active/passive transducers and contact/non-contact techniques to detect structural cracks, corrosion under insulation (CUI), pits and corroded portions in metallic and composite structures [97–99]. The guided waves have been considered as a useful defect detection technique for large structural assets and as antifouling, ice detection and de-icing missions on marine and aircraft structures. Recently, marine inspection robotic assistant (MIRA) system and micro-aerial vehicle-based have been used for structural fault identification of ship structures [100].

4.2. Findings on factors affecting structural corrosion in marine environments

Structural degradation in marine environments is a time-dependent process, primarily occurring due to corrosion and fatigue [101]. These processes also encourage several other degradation processes such as strength reduction, brittle fracture, buckling, etc. [102, 103]. In a study about reliability-based maintenance of ship's hull under corrosion effects, the replacement of affected plate was recommended to be carried out when the thickness reduces below 75% of its designed thickness [104].

Corrosion is an electrochemical process occurring in marine environments because of reaction between various ingredients of the metallic surface and sea water. It occurs due to the availability of water along with an electron acceptor element, like oxygen [105]. The marine steel structures generally experience several forms of corrosion under immersion state. The most common types of corrosion in ships and offshore structures and their effects on material degradation are presented in Table 3.

**** Table 3 ****

Table 3. Main types of corrosion in ships and offshore structures.

The general corrosion and pitting corrosion are more common in marine applications than other forms of corrosion such as galvanic, crevice, SCC, groove, and edge corrosion [106–108]. In general corrosion, the thinning phenomenon occurs uniformly on the surface of a metallic surface. On the other hand, pitting is a highly localized type of corrosion that occurs randomly in various stages over certain areas; hence it results in perforation and thickness reduction in specific regions of the metal surface [109–111].

When the corrosion attack on metal structures is non-uniform (i.e. pitting or crevice corrosion), the collection of corrosion rate data via conventional methods can be misleading [112]. This phenomenon is more common where the coatings or the base metal itself are deteriorated [113]. Some research studies reveal that the reduction of tensile strength in presence of pit corrosion is 2.5 times more than that in presence of general corrosion [114]. The number of pits increases with the deterioration of coatings which in turn leads to corrosion growth independently [115]. During the pit formation, cathodic oxygen reduction occurs on the adjacent surfaces of pits to reduce the corrosion process. Engelhardt and Macdonald [116] categorized the pitting process into three phases, including: nucleation (pit initiates), propagation (pit grows), re-passivation (pit growth stops).

In general, the marine corrosion can be categorized into short-term and long-term corrosions, depending on duration of the exposure in seawater. The duration of short-term corrosion typically ranges between 6 to 24 months of initial exposure, when the corrosion process is led by activation, concentration, and diffusion phases. Then the long-term corrosion takes place, which is led by biological activities and nutrients in seawater [117]. Some researchers have shown that the duration of short-term and long-term corrosions depends on the constituents of seawater (biological and chemical) and its physical properties, temperature in particular [118].

Marine steel structures exhibit significant variance in corrosion rates with changing zones with respect to the sea surface. These zones include tidal, atmospheric, splash, and submerged zones. Some research literature reported that highest rates of corrosion are observed in splash zones followed by low tidal zones. In the natural seawater conditions, Melchers [62–66] showed that the highest corrosion losses occur in splash zone and immersed zone, followed by half-tide and coastal atmosphere. Figure 4 presents the corrosion rates of marine steel structures in different exposure zones.

**** Figure 4 ****

Figure 4. Corrosion rates of marine steel structures in different exposure zones [62–66].

In natural seawaters, the corrosion rate of low carbon steel structures is estimated to be between 0.1mm and 0.3mm/y; however it can rise up to 2–4 mm/y in the severe marine climatic conditions [72]. It is widely believed that the rate of corrosion decreases with the exposure period, possibly due to the hindrance offered by corrosion deposits for free exchange of ions. However, some studies have reported that the rate of corrosion may increase with the exposure period in cases where the structure is subject to dynamic loads, higher velocity, and pollutant factors in seawater [119, 120]. In moderate marine climates, the corrosion content accumulated on steel structures is primarily comprised of lepidocrocite (γ-FeO(OH)), goethite (α-FeO(OH)), maghemite (γ-Fe_2O_3) and magnetite (Fe_3O_4) [121]. In case of atmospheric marine corrosion, iron samples are initially corroded into lepidocrocite (γ-FeO(OH)) – an unstable rust form. However, because of continuous interaction between oxygen and water in surrounding environment, it is converted into goethite – a more stable form of rust [122, 123]. The corrosion in marine steel structures is oxidation of ferrous iron ions which yields a reddish brown ferrous oxy-hydroxide (FeO(OH)) compound, i.e. rust. As an initial step of oxidation, the rust layer starts building up on to the surface of the metal structure due to the presence of free oxygen in sea water and its continuous access on to the metallic surface. With the increase in exposure period, the surface deposits on metal skin barricade the interaction between free oxygen and metal skin. Subsequently, the rate of metal loss will vary non-linearly [124–126]. Faraday's law is generally used to estimate the initial corrosion rate in which the effects of bacterial actions, corrosion deposition and biofilms are assumed to be negligible [127].

The Pourbaix Potential-pH diagram graphically demonstrates the electrochemical aspects of corrosion process, and it has applications in the corrosion of metals subjected to an aqueous electrolyte, batteries or fuel cells. It is used to establish the types of reaction and stable phases of reaction products in an equilibrium state of a chemical process. This diagram gives a very effective and deep understanding of the possible reactions and yielding products, including passivity regions in a corrosion process. It however cannot predict the rate of corrosion and chemical processes at a given temperature in electrolytic solution [111, 128].

4.2.1. Environmental factors

The environmental conditions play a significant role in degradation of offshore metallic structures and, thus, in selection of the inspection method and its frequency. The metal alloys selected for use in marine structures generally have good corrosion resistance. Melcher [129] reported that the composition of metal structures significantly influences the initial corrosion phase (kinetically controlled oxidation) and the long-term anaerobic corrosion phase, whereas the diffusion phase of oxidation was found to be independent of the alloying constituents. The weather conditions and seawater constituents vary enormously across various oceans around the globe. The seawater reservoirs in colder regions have low seawater temperature and salinity level; thus the DO concentration is higher. However, in the hot countryside of tropical/ sub-tropical regions, the sea surface temperature and hence the salinity levels are higher and DO content ranges up to 3.5–4 mg/L. Typically, the salinity of major natural seawaters ranges between 32,000 to 45,000 ppm [130].

In summer, the sea surface temperature in some tropical regions may reach up to 33-35°. The seawater temperature of the Gulf of Mexico is reported to be in the range of 20–32°C. Nergis *et al.* [131] studied the range of various prominent seawater parameters in the Arabian ocean and reported the seawater surface temperature range to be from 28°C to 41°C in summer seasons. Higher corrosion rates have been reported in warm seawater regions. The significance of seawater temperature can be estimated from the fact that corrosion rate of marine steel structures at a temperature of 25 ºC was twice of that at 10 ºC [125]. During a research study on atmospheric corrosion in coastal regions of the Arabian sea, Jamil *et al.* [132] found out that the corrosion rates were in the category C5, which is placed in 'very high' corrosive environment according to BS EN ISO 9223 [133, 134]. More recently, Jilani [135] discussed various levels of pollutants in coastal waters of the Arabian sea and their impacts on the transformation of intrinsic open seawater properties (like pH, DO, total solid content, etc.). The results of her analysis are presented in Table 4.

**** Table 4 ****

Table 4. The monthly average level of pollutants in coastal waters of the Arabian sea.

4.2.2. Physical and chemical factors

The physical and chemical factors are closely interrelated in contributing to marine structural corrosion. The temperature, DO, salinity and wetting duration are the dominant factors in marine immersion corrosion [136]. The seawater may contain different concentration levels of chlorine ions, carbon dioxide (CO_2), hydrogen sulphide (H_2S) and ammonia [137]. A higher quantity of these compounds adversely affects the surface of the metallic structure by accelerating the rate of corrosion. Higher content of H_2S, CO_2, and seawater temperature have harmful effects on metallic marine structures [138]. The combined action of the chloride as well as the salt deposit provide a conducive environment for flourishing microbial activities, which often results in crack formation in metals [136]. With the initial exposure of metal structures in seawater, a passive layer is formed on its surface that resists further corrosion. Dissociated chloride ions (Cl^-) in seawater may penetrate this protective film and initiate crevice/pitting corrosion. The hydroxide ions (OH^-) in aqueous electrolytic solutions assist in passive layer formation, whereas, Cl^- ions damage the layer and facilitate further corrosion and pit development [91].

The corrosion factor is more detrimental in hot and moist seawater conditions of ship ballast tanks, as it contains a high concentration of entrapped oxygen even at higher temperatures [139]. Some researchers have reported the significant effect of temperature, pH, calcium carbonate solubility, and exposure time on corrosion of structural steels in seawater, brackish and freshwater (see [117, 140]). Melchers [141, 142] showed that the corrosion rate in moderate- and low-temperature seawaters is doubled for each 10ºC temperature rise when controlled by kinetic process; whereas during the diffusion process it is doubled after every 30ºC rise in temperature, given the DO concentration is constant [143]. A series of seawater corrosion tests at various temperatures were carried out by Chandler [144]. It was found out that the corrosion loss of carbon steel at 25ºC was nearly twice larger than that at 10ºC. In the open seawaters, DO is able to discharge freely with increasing the temperature. Corrosion rate tends to increase with temperature up to 80ºC, then onwards it declines sharply due to the rapid decrease in solubility of oxygen.

The standard fluctuation of pH in seawaters lies between 7.8 and 8.2 and it has been reported by several researchers that this variation does not have significant impact on corrosion rate. However, it can indirectly influence accumulation of calcium carbonate on cathode protected structures [118, 144]. The pH variations may exert an active influence on pitting and crevice corrosion of active–passive metals [145].

In ferrous alloys, the effect of CO_2 on corrosion loss is far less than DO at same concentration level. At a CO_2 concentration of 20 mL/L and same temperature conditions, oxygen is found to be ten times more corrosive than CO_2 [145]. Presence of O_2 and CO_2 in seawater can reduce its pH value from slightly alkaline to acidic, which in turn can enhance the corrosion of steel. Several research studies have highlighted that in case of short-term corrosion, the nominal pH level does not affect the corrosion process; whereas, CO_2 can upset the pH value in long-term exposure. The overall pattern of corrosion in marine steel structures is nonlinear. Although the short-term corrosion may initially exhibit a linear pattern, it has been asserted by various researchers that the short-term corrosion pattern can be highly erroneous if it is used for prediction of long-term corrosion. The influencing factors which control the long-term corrosion are identified as exposure time, temperature, salinity, microbiologically influenced corrosion (MIC), SRBs, water velocity and alloy effects [146–148].

Increasing chloride content in seawater can aggravate the pit corrosion in submerged metal [149]. Moreover, the combined effect of DO and chloride concentration highly accelerates the corrosion rate. The corrosivity of structural steel specimens along the coastline of a heavily industrialized region in Baltic Sea was investigated by Zakowski *et al.* [150]. It was concluded that the corrosion rate in low-salinity seawaters is significantly lower (0.0585 mm/year) than that in nominal ocean conditions. Table 5 gives the salinity levels across various sea regions throughout the world. As can be seen, the salinity level is highest in seawaters of hot sea regions (e.g. Mediterranean Sea and Indian Ocean) and lowest in the cold countryside (e.g. Baltic and Caspian seas) [151].

**** Table 5 ****

Table 5. Salinity levels across various sea regions throughout the world.

The DO concentration in seawater is a function of the following factors: temperature, water velocity, salinity and biological activities. The oxygen solubility decreases at a higher temperature. Under standard atmospheric pressure at sea level, the DO concentration is found to be 8.26 mg/L at 25ºC and 12.77 mg/L at 5ºC [152]. Oxygen is the main electron acceptor for the corrosion process; hence its quantity decreases at elevated temperatures which may reduce the overall rate of corrosion. However, this decreasing corrosion factor is compensated by the increasing temperature and salinity level; therefore, the corrosion rate typically increases with the rise in temperature. In addition to temperature effect on DO, its percentage in seawater reduces with an increase in the chemical and biological content, particularly in polluted seawaters. In a study about corrosion on austenitic steel, Malik *et al.* [149] reported that the content of DO decreases with the increase in water temperature. Corrosion rate was found to increase within the temperature range of 25-65ºC; however then onward, the critical pitting potential (E_{pit}) was found to remain constant. The DO concentration in seawater as a function of salinity and temperature is presented in Table 6.

**** Table 6 ****

Table 6. Oxygen concentration in seawater as a function of salinity and temperature.

The influential parameters of seawater vary with the sea depth and this variability is also dependent on the geographical location and season. As the water depth increases, the temperature reduces but the hydrostatic pressure increases; however, the latter does not pose any significant effect on corrosion rate [153]. Due to higher nutrients and higher seawater temperature, the corrosion rate in the shallow sea environment is found to be higher than that in the deep sea environment. In a research study, Venkatesan *et al.* [145, 154] showed that the short-term corrosion rate of mild steel in surface water of Indian ocean is four times more than that in deep water. Melchers [155] showed that the effect of water depth on corrosion rate is subject to the variation in temperature, DO and nutrient levels.

The photosynthesis process in marine ecology system causes a significant increase in DO concentration. Similarly, the air bubbling produced by the wave propagation in open sea serves for seawater oxygenation. Various researchers have reported that the DO concentration in seawater changes with regional surface seawater temperature from about 8.0 mL/L in the Arctic seas to 4.5 mL/L or even less in the tropical seawater. In certain harbour conditions, it further reduces due to the presence of nutrient-rich waters, pollutants and industrial wastages [156–158]. Figure 5 illustrates the relationships between various seawater parameters.

**** Figure 5 ****

Figure 5. The relationships between (a) conductivity and salinity (b) dissolved oxygen and salinity [151].

Effects of seawater velocity on the corrosion rate of immersed or semi-submerged metallic structures have been investigated by several field/laboratory experiments and the results are presented in [159, 160]. Corrosion rate was observed to increase nonlinearly with the water velocity (0 to 1 m/s). This effect was found more prominent in the early phase but slowed down gradually with the rise in growth of biofouling, marine growth, and corrosion products on steel coupons [105, 161]. The material loss in some metals (such as iron, copper alloys, and steel) tends to be higher beyond a critical velocity [162], however minor velocity changes can be ignored during corrosion studies on structural steel [163]. The effect of velocity on marine structural corrosion can be more damaging when the accumulated corrosion growth is removed mechanically or naturally by the wave action [164, 165].

4.2.3. Microbiological factors

The exposure of steel structures into the marine conditions rapidly initiates a complex chain of electrochemical reactions which include colonization of marine growth, biofilms and various forms of bacteria. The structural degradation under the influence of biological activities (microorganism, bacteria, biofilms, etc.) is commonly known as microbiological induced corrosion (MIC) [166]. The microbiological ingredients play a vital role to nourish oxygen depleted regions/anaerobic conditions during the latter phases of corrosion and promote localised corrosion, particularly during long-term corrosion phase. These effects can be visible in all exposure zones; the tidal, splash and coastal atmospheres [167]. The microbial biofilms and biofoulings are undesirable micro-organism/bacterial cells which deposit on metal surface and encourage a conducive environment for anaerobic corrosion [144]. The marine biofouling may be comprised of flora and fauna in the form of micro and macro bio-organisms. SRBs encrusting algae, fungi, seaweeds, molluscs, barnacles, zebra mussels, worms, sea squirts, barnacles, hydroids are few common types of biofoulings in marine environment [72, 127, 168]. The pollutant addition in seawater aggravates the concentration of hydrogen sulphides (H_2S) and nutrient content in the form of dissolved inorganic nitrogen (DIN) which significantly elevate the corrosion rate of low carbon steel [134, 169, 170]. The models presented in Figure 6 highlight the above phenomena as well as the effects of temperature and DO variations on corrosion process.

**** Figure 6 ****

Figure 6. (a) A model indicating the effect of nutrient level on corrosion (b) A model indicating the effect of temperature and DO on corrosion [134].

The heated oil or lubricants inside the ship tanks encourage the growth of microbiological contaminations (MBCs), which further leads to a higher corrosion rate. The seawater temperature in the range of 20-50ºC is found to be ideal for the growth of SRBs. Presence of crucial compounds in seawater such as hydrogen sulphide (H_2S), other sulphides and sulphates form an unstable/corrosive passive film on metal surfaces, which permeates the interaction of these detrimental compounds with the metal surface and aggravates the corrosion process [171]. In addition to the growth of general and localized corrosions, the micro-biofoulings can induce various other types of corrosion such as hydrogen embrittlement and SCC [127, 172]. Seawaters in coastal regions are also engulfed with numerous metal and non-metal ingredients with the addition of industrial and domestic effluents. These factors enhance corrosion of steel structures through galvanic reaction, acidic hydrolysis and cathodic reaction [135, 173].

4.3. Findings on corrosion prediction models for marine structures

Over the years, several corrosion prediction models for marine steel alloys have been proposed in the literature. These models can be divided into different types of empirical, phenomenological (qualitative analysis based on experimental data), probabilistic, and physical models. The empirical models are based on historical data or measurement of corrosion loss, whereas the physical models are based on actual corrosion process [174, 175]. Accurate prediction of corrosion is a challenging task because the available data sometimes is highly scattered due to the involvement of extremely dynamic environmental conditions. Earlier research studies proposed deterministic and linear models for corrosion prediction. However, in recent research, several nonlinear and probabilistic methods have been proposed. In some cases, the uncertainty of prominent corrosion factors are also included in the form of random variables (such as coating life, corrosion rate, and thickness margin) so as to develop more accurate and precise corrosion models [176]. Southwell was the first researcher who proposed two linear and bilinear corrosion models for steel structures [166]. These models are given by:

- *Southwell's linear model:*

$$d(t) = 0.076 + 0.038t \;, \tag{1}$$

where *t* is the time period or exposure time and *d*(*t*) represents the corrosion thickness.

- *Southwell's bi-linear model:*

$$d(t) = \begin{cases} 0.09t & ,\; 0 \le t < 1.46y \\ 0.76 + 0.038t, & 1.46 \le t < 16y \end{cases} , \tag{2}$$

The Southwell models were later improved by Melchers for corrosion prediction of marine structures [177]. These corrosion prediction models are given below.

- *Melchers-Southwell's non-linear model:*

$$d(t) = 0.84t^{0.823}, \quad (3)$$

- *Melchers' tri-linear model:*

$$d(t) = \begin{cases} 0.170t & , 0 \leq t < y \\ 0.152 + 0.0186t & , 1 \leq t < 8y \\ -0.364 + 0.083t & , 8 \leq t < 16y \end{cases}, \quad (4)$$

- *Melchers' power law model:*

$$d(t) = 0.1207t^{0.6257}. \quad (5)$$

The ship hull and offshore structures are often applied with various protective measures (metallic and non-metallic paints including antifouling paints) as corrosion shields. Therefore, some researchers have divided the corrosion process on marine structures into three phases: (i) no corrosion phase or coating (T_0 or T_c), (ii) transition between no corrosion and corrosion initiation (T_t), and (iii) the progress of corrosion (T). In the first phase, it is assumed that no corrosion occurs due to the protective coating being applied on structures; while in the second phase there are slight changes in different models. Some of the most popular nonlinear corrosion models are presented in below:

- *Yamamoto-Ikegami's non-linear corrosion model* [115]

$$d(t) = C_1\,(t - T_0 - T_t)^{C_2}, \quad (6)$$

where C_1 and C_2 are corrosion constants, T_0 is no corrosion zone during which the durability of protective coating is assumed to remain intact, and T_t is the transition period between coating durability and corrosion initiation.

- *Paik's nonlinear model* [175]:

$$d(t) = c_1(t - T_{cl})^{c_2}, \quad (7)$$

where c_1 and c_2 are fixed coefficients and T_{cl} is the life of coating. The coefficient c_2 is usually assumed to be 1/3 or 1, while the coefficient c_1 is the symbolic corrosion rate per year. Paik *et al.* [178] proposed three types of curves for general and localized corrosions on ship structures. These include a convex, a concave and a linear model as shown in Figure 7. The convex curve shows that the corrosion rate rises initially but it tends to slow down with the increase in exposure time, because of the deposition of corrosion content on metal surface. This curve is typically applied to marine structures under statically loaded conditions. Alternatively, in the concave model, the corrosion rate is accelerated with aging. It is considered to be a more suitable trend in structures with dynamic loading conditions because the corrosion trend generally decreases with the exposure period. Paik's model is the only model which shows increment in the corrosion rate with the exposure period, specific to the loaded structures. In some cases, the effects of nutrients and biological content can also increase the corrosion trend; however, the same has not been considered by the Paik's model, purely based on statistical observations.

**** Figure 7 ****

Figure 7. Paik's corrosion prediction model [178].

The implications in Paik's model have been addressed by the nonlinear model of Soares and Garbatov [106] as given below:

$$d(t) = d_{\infty}[1 - e^{(-\frac{t-T_c}{T_t})}] \,, \quad (8)$$

where d_{∞} is the thickness loss during the long-term corrosion, T_c represents the coating life of metallic structure, T_t is the transition time (i.e., the period during which the corrosion process initiates). As shown in Figure 8, the corrosion process in this model is divided into three phases. During the first phase, no corrosion occurs because of the corrosion protection system. The corrosion begins during the transition period (T_t) and increases to a certain depth in plate thickness, until it stops at a depth of d_{∞} . The model has been adopted by numerous studies such as [126, 139, 179–181].

**** Figure 8 ****

Figure 8. Soares and Garbatov's corrosion prediction model [106].

Qin and Cui [61] proposed a prediction model using Weibull distribution, showing an increase in corrosion rate in the second phase and a decrease in the third phase. This model is illustrated in Figure 9. As can be seen, it describes the corrosion process in three stages:

- [0, T_{st}]: There is no corrosion as the corrosion protection system is completely active,
- [T_{st}, T_A]: Corrosion process begins and the corrosion rate increases linearly,
- [T_A, T_L]: It associates with general corrosion,

where T_{st} is the time when corrosion begins, T_A is the corrosion accelerating life, T_L is the life of corrosion protection system where general corrosion starts. Generally T_L ranges between 2 to 10 years, depending on the quality of the protection layer and severity of climatic conditions [182–184].

**** Figure 9 ****

Figure 9. Qin and Cui's corrosion model [61].

All the aforementioned corrsion models are purely based on statistical principles and theoritical or field experimental data. Melchers [142, 185] is the first to propose a five-phase phenomenological corrosion model (encompassing both short- and long-term corrosions) for marine steels, as shown in Figure 10. This model does not consider the surface protection and its age variability factors, which itself is a complete and complex science with a different scope. The research revealed that the long-term corrosion in marine structures is as a result of a complex collaboration between electrochemical process and bacterial colonization in natural (oxygenated) and anoxic seawaters. A nonlinear corrosion equation was formulated for almost every phase of the corrosion model. The DO concentration, seawater temperature, and water velocity have been considered to be the main influencing factors, which may exhibit certain interrelation with the depth of sea [186].

**** Figure 10 ****

Figure 10. Melchers' general corrosion model for steel structures [60].

As can be seen in Figure 10, the first three phases (phases 0, 1 and 2) of the Melchers' model illustrates the short-term corrosion pattern and these phases are almost similar to the post T_{st} or T_0 phase in previous models. The uniqueness of Melchers' model is the explanation of long-term corrosion mechanism with the demonstration and justification of rapid rise in corrosion rate (phases 3 and 4) after a stagnated period. This sharp rise is attributed to the involvement of massive biological activities and nutrients in anaerobic conditions. The stagnation phase of corrosion is generally attributed to the accumulation of corrosion and fouling deposits on the metal surface, which splits its connection with external and stimulates anaerobic conditions. Furthermore, Melchers later extended his model for corrosion prediction of other alloys (aluminium and copper alloys) in marine conditions, fresh water as well as in the coastal or atmospheric conditions. For further reading about corrosion prediction models, the readers are referred to [187–193].

5. Advanced maintenance management techniques

The conventional maintenance management practices in the marine sector are rapidly shifting towards advanced solutions such as e-maintenance, computerized maintenance management systems (CMMS), and remote SHM. The e-maintenance and CMMS can provide refined data at the right time to facilitate decision-making for maintenance. From the literature review, several intelligent techniques, statistical and stochastic analysis tools and MCDA methods were identified that can be used for improved maintenance management of corroded steel marine structures. Some of these modern asset maintenance techniques include BN, genetic algorithms (GA), artificial neural network (ANN), deep learning and fuzzy inference systems [194–196].

Numerous mathematical models have also been proposed to predict the complex nonlinear relationships between corrosion rate and varying environmental conditions [181]. The evolution of advanced modelling and simulation techniques has enabled more sophistication in corrosion prediction of aging marine structures. Various artificial intelligence (AI) and machine learning (ML) tools (such as ANN, support vector machine (SVM)) as well as probabilistic techniques (such as BNs, Markov chain, Monte-Carlo simulation) have been proposed by researchers for corrosion modelling and risk/reliability-based inspection planning of marine structures [197–199]. The results acquired with the use of these methods have been found to be very promising and more accurate (see [68, 107, 200]). The most prominent methodologies used for marine maintenance and corrosion prediction modelling are briefly discussed in followings:

5.1. Fault tree Analysis (FTA)

FTA is one of the most important analytical methods used for fault identification and reliability assessment of systems/components [201]. It is a graphic tool comprised of sequential combinations of faults, which can subsequently result in the occurrence of undesirable events [202]. A typical fault tree consists of a top event and a set of basic events organized with the logic gates (AND, OR, etc.) [203]. FTA has been used for both qualitative as well as quantitative reliability analyses in many industries. Various researchers have used this method individually or in combination with other techniques (such as event tree analysis (ETA), Markov chain Monte-Carlo (MCMC) and BN) for failure analysis of marine structures/equipment [24, 204–206]. Laskowski [207] performed a structural reliability analysis on the marine diesel engine of a ship and its components using qualitative FTA. Lazakis *et. al.* [19] developed a hybrid FTA-FMEA strategy for identification of critical systems/subsystems in a marine engine.

5.2. Bayesian network (BN)

BN is a probabilistic graphical method which uses Bayes' theorem for updating the prior occurrence probability of failures. It indicates a set of random variables and associated conditional dependencies in form of a directed acyclic graph (DAG), containing a set of nodes to represent variables and edges to denote probabilistic causal dependence [208]. It involves independent and dependent variables known as causes and consequences respectively, which are connected via direct arrows pointing from the causes to the consequences [209, 210]. BN signifies the joint probability distribution and it is flexible to perform predictive (forward) as well as diagnostic (backward) analysis [148]. In recent years, BNs have been extensively used for modelling of corrosion in marine structures as well as optimising the RBI plans [148, 191, 211–214]. For an inclusive understanding of BNs, the readers are referred to [210, 215, 216].

5.3. Statistical and stochastic models

Numerous statistical and stochastic techniques have been employed for degradation modelling and maintenance planning of marine assets. These methods have been instrumental to develop the relations between various dependent/independent process variables and estimate the likelihood of occurrence of events. The statistical/stochastic techniques that are commonly adopted by researchers include: multivariate analysis, regression models, Copulas, Markov process, Poisson process, Monte-Carlo simulation, Cox's approximation, and Weibull analysis [35, 56, 118, 217]. Detailed deliberation on the maintenance procedures, their planning, inspection and prediction trends using various statistical models and methodologies are explained in details in [33, 66, 218–220].

5.4. Multi-criteria decision analysis (MCDA)

The MCDA techniques have gained a huge momentum in decision making for the selection of an efficient and effective inspection/maintenance strategy. This approach comprises a finite set of alternatives (i.e. maintenance strategies) amongst which the decision-makers have to select, evaluate or rank, in accordance with the weights of a finite set of criteria (attributes). Each substitute is given an evaluation rating using a suitable measure followed by the aggregation process to acquire the prioritized alternatives from the best to the worst [221]. The simple additive weighting (SAW), AHP, analytic network process (ANP), TOPSIS, PROMETHEE and the elimination and choice translating reality (ELECTRE), etc. are some MCDA methods used in maintenance management [222]. Several research studies on maintenance strategy selection using MCDA techniques were reviewed in [223].

5.5. Artificial intelligence (AI) and machine learning (ML)

AI models and ML techniques have been used as a revolutionary tool in the corrosion and fatigue modelling as well as the optimization of risk/reliability-based maintenance [19, 181]. They require certain input parameters which are processed through single or multiple layers to generate outputs. These methods are sometimes also known as Soft Computing Techniques [55]. Some commonly adopted AI techniques are ANN, fuzzy logic, SVM and GA. Recently, Shirazi and Mohammadi [187] formulated a hybrid intelligent model to predict the corrosion rate of 3C steel using ANN and swarm particle optimization (PSO).

A detailed distribution of the journal papers by methodologies used to model marine corrosion and maintenance strategy is shown in Table 7.

**** Table 7 ****

Table 7. Distribution of papers by methodologies for corrosion prediction modelling and marine maintenance.

6. Discussion and analysis

Over the past few decades, numerous maintenance procedures have evolved for an optimal management of physical equipment and effective planning of inspections to reduce cost and/or risk of failure. Literature reveals that the marine asset maintenance practices started from conventional RTF concept and then shifted towards time-based PM in early 1960s. The PM concept is still the most widely used maintenance strategy in the commercial maritime industry. However, in recent years, some advanced strategies such as CBM, RCM/RBI and CBM plus have been adopted as alternative strategies to achieve maximum system/subsystem availability/reliability with minimal cost, failure risks, manpower and material resources. The advancements in failure sensing equipment and data analytics approaches have provided superior platforms to inculcate improved online and offline health monitoring techniques. The generic concept of reliability-based maintenance has become more effective and optimised by digitalised revolution in marine maintenance industry and its integration with some other sophisticated tools such as NDT and SHM.

This review study has primarily focused on the corrosion aspects of submerged/partially submerged marine and ship structures. The environmental conditions considered in this study were mainly the seawater composition (chemistry), physical factors (such as temperature) and amalgamated pollutants from various domestic, agricultural and industrial sources into the seawater, which tend to affect the ratio of intrinsic seawater constituencies, especially in the coastal seawaters. The reviewed literature revealed that the degradation of marine structures due to uniform and localised corrosions is far more than all other type of corrosion. Since the marine corrosion is known as a highly nonlinear process during the long exposures due to the involvement of numerous dependent/independent variables, a multidisciplinary knowledge of material science, structural mechanics, electrochemistry, topography, and hydrodynamic is required.

The corrosion prediction models developed up to date are subject to several limitations because of the complexities involved in understanding of the relationship between environmental factors and corrosion rate. Many researchers have highlighted the variation in corrosion behaviour in the various zones above and below the seawater surface; however, it has been agreed that higher corrosion rates are generally found in the splash zone, mean lower tidal region, and just below the low-tide level, respectively. The corrosion phenomenon in the latter region is known as accelerated low water corrosion (ALWC) which is more common in the pollutant near-coast seawaters and generally is attributed to the high presence of bacterial activities, and high DIN content [225]. Some researchers have also attributed the high corrosion to the formation of local galvanic cells due to the difference in corrosion potential in high and low aerated zones, just below the water line [226].

The water temperature, DO, salinity, water velocity, pH and biological activity are found to be the most influencing factors in corrosion of marine steel structures. Both laboratory and experimental based research studies have concluded that corrosion initiates rapidly within hours of immersion in seawater. However, there is a continuous variation in corrosion rate with the rise in exposure duration and the rate of corrosion stagnates during the diffusion phase of Melchers' modal, prior initiation of biological activity led by anaerobic conditions. The long-term corrosion mostly comes into play during anaerobic conditions with subsequent involvement of nutrients, SRB activity, MIC, biofoulings. Due to highly nonlinearity in marine corrosion process, the prediction of long-term corrosion based on the short-term corrosion data is not recommended. Moreover, the field experiment results in comparatively larger corrosion losses than the simulated laboratory-based experiments using artificial seawaters, probably due to absence of biological corrosion factors in the controlled laboratory environments and higher variability in the influential corrosion parameters during the field experiments.

It has been deduced that certain interdependent relationships exist between some prominent environmental contributors, which further complicate corrosion mechanism in marine conditions. The DO in water generally tends to accelerate corrosion rate by rapid oxidation, however its concentration declines with the rise in temperature. Similarly, salinity goes high in warm seawaters and DO decreases in these conditions. A significant rate of corrosion has been reported with the increase in seawater velocity but it slows down with extended exposure durations because of the adhesion of marine growth and corrosion deposits on metallic skin. The DO and pH values of coastal seawater decrease and become more acidic with the influx of effluents and nutrients. Moreover, the corrosion rate in cold seawaters is found to be far less than the seawaters of hot countryside, because of the direct relationship between the corrosion rate and seawater temperature.

Although the changing climatic conditions across the globe are found to be highly effective in dictating corrosion rate of marine assets, an amalgamation of pollutants, various industrial

/agricultural wastes, heavy metals and effluents near coast regions further complicates the understanding and modelling of corrosion process. The final product formed after incorporation of these run-offs in seawater becomes highly detrimental towards structural deterioration. Therefore, it has been recorded from the literature that the severity of ambient conditions in harbours and coastal regions flooded with wastewater addition is more detrimental towards corrosion than the open seawater environments. It also implies that the installed marine assets (such as wind energy, oil rigs, and harbour infrastructures) and vessels stationed for long durations in pollutant mixed harbour or coastal areas may experience more rapid deterioration than seagoing vessels or fixed platforms, away from coastal/harbour areas.

The marine structures are protected from corrosion using various organic/nonorganic coatings as well as other protection methods. The life expectancy of the protective coating has been reported to range between 3 to 5 years, depending on the severity of climatic conditions, seawater chemistry, nature of pollutant contamination, etc. Some corrosion prediction models have been developed based on the assumption that no corrosion takes place as long as the protective coating is intact. Corrosion process is believed to kick on with the fracture initiation in the protective coating. The paint-fracturing phenomenon may also result in highly localized corrosion as the exposed bare metal acts as an anode, while the remaining protected areas act as a cathode. Similarly, several corrosion models have been developed based on historical data from ship structures applied with the protective surface coatings as well as other corrosion protection measures such as sacrificial zinc anodes and ICCP system. Therefore, it implies that actual corrosion rates are much higher in the bare surface metal. Hence, these models may underestimate the actual corrosion losses in the absence of any of the protective measures. Secondly, majority of the corrosion models in the literature have purely been developed statistically based on experimental data, which do not have any link with the theoretical knowledge of electrochemistry. Therefore, these empirical and mathematical models may have several limitations, particularly in the seawater with higher pollutant content where corrosion rates are mainly led by the biological activities and nutrients and sulphide content. The basic phenomenological corrosion models of Melchers [142, 185] have the ability to correlate the various phases of corrosion and variability in the environmental factors with the scientific knowledge on corrosion and electrochemistry.

It can be deduced from the detailed literature review that despite the enormous research studies on how to model the corrosion in steel structures, substantial uncertainties still exist because of the involvement of various potential contributors and their complex relation with the rate of corrosion. Therefore, there is still room for further improvement in corrosion modelling accuracy. Recently, various AI and ML algorithms (such as BN, ANN and SVM) have been successfully used to model the corrosion process with involving all influential environmental factors such as temperature, DO, pH level, salinity level, SRBs, etc. Inculcation of the sophisticated and rational digital technologies, such as big data, Internet of Things (IOT), AI, and digital twins can significantly improve the accuracy of corrosion process modelling.

From literature review, it has been revealed that the maritime sector is still more reliant on time-based PM concept. The CBM has also been used in recent years as part of the PM strategy. In the shipping industry, the RCM and CBM plus approaches have been widely adopted for the maintenance of naval ships. Advanced technology driven fault diagnosis and prognosis, SHM, remote maintenance and e-maintenance technologies have provided great opportunities for the marine industry to adopt more efficient and optimised maintenance procedures. Using MCDAs, integrated maintenance methodologies, advanced sensing technologies, realistic prediction modelling for structural degradation mechanisms can be instrumental to develop data-driven, risk-based maintenance plans for the marine assets operating in extreme environmental conditions.

7. Conclusion and future works

The aim of this review paper was to analyse the effect of marine environmental conditions on corrosion-based degradation of steel structures. It also highlighted the prognostic models on marine corrosion phenomenon and its impact on the reliability, health assessment, inspection intervals and overall maintenance strategy selection of assets. Due to significant variability of environmental factors, the corrosion in marine steel structures shows a great variation in different immersion zones. Hence, it is necessary to update corrosion models or their parameters according to the metal loss in different immersion zones, phases of corrosion, compositions of seawater, geographical regions, etc. Subsequently, it warrants a dynamic approach for inspection/maintenance planning of marine assets, capable of updating its interval according to the severity of climatic conditions by dynamic degradation prediction models integrated with the online/offline SHM tools.

In this review paper, the following conclusions have been deduced regarding the impact of environmental factors on corrosion mechanism, its complexities in marine steel structures, and the challenges associated with their maintenance:

- In natural seawater conditions, the sensitivity of environmental factors towards structural corrosion is fairly complex. This is partly because of the complicated relationships between the coexisting factors (e.g. temperature, DO concentration, salinity level, pH level, velocity, etc.) and corrosion rate of marine steel structures.
- For the same duration of exposure in natural seawater conditions, sensitivity of sea water temperature towards corrosion is found to be the most influencing factor. Therefore, the majority of the corrosion models are based on either seawater temperature or exposure period.
- Variability of temperature in natural seawater around the globe is enormous (-2^{0}C to 35^{0}C). Therefore, the corrosion rate tends to be tremendously higher in hot seawater conditions by the combined effect of high temperature and subsequently higher salinity level. Although DO concentration tends to reduce with higher seawater temperature, the influence of temperature surpasses the effect of DO. Subsequently, the rate of structural degradation as well as frequency of inspection and maintenance actions are also dependent on the extremeness of environmental conditions.
- Seawater salinity and pH level can influence the rate of corrosion; however, under normal sea conditions their sensitivity for corrosion loss is merely insignificant. Nevertheless, a great variation of seawater salinity has been found in specific hot regions, where corrosion

rates have been reported on the higher side than other regions. In the highly polluted seawaters, pH level tends to be more acidic (5.5-6.6); therefore, susceptible for accelerated uniform and localized corrosions.

- The influx of effluents causes significant chemical variation in seawater chemistry that can substantially increase the corrosivity factor by transforming the intrinsic specifications of seawater, such as DO content, salinity, bacterial content, total dissolved solids (TDS), heavy metal ion concentration, turbidity, and pH level. In addition, presence of nutrients in the form of DIN (compounds of nitrates, nitrides, ammonia) rapidly increases the rate of biological activity and promotes MIC.
- Influence of pollutants in seawater in the form of DIN, sulphides, etc. on corrosion rate can be far higher than the effect of physical factors such as seawater temperature.
- The inspection/maintenance of structures in polluted seawater conditions (rich in DIN and sulphides) needs to be more frequent than that in the nearest natural seawater condition because of the susceptibility for higher corrosion losses in polluted waters. A PM schedule in the absence of online/offline CM, SHM or prior knowledge of the corrosion rates in the specific climatic conditions will be likely to fail or ineffective to predict the PF curve for the exposed structure.
- Very few studies have been reported on integration of the outcome of degradation process models (such as corrosion and fatigue prognostic models) as an input for scheduling/optimizing the inspection and maintenance management system (see [227]).

The degradation of ships and other marine structures is a highly complicated phenomenon, mainly because of their inherent extreme operating conditions, corrosive environment, and extended operations away from maintenance facilities. The technology-driven advancement in marine equipment have its own risks and the maintenance demands have been amplified subsequently. Over the years, various maintenance practices and inspection methods have been adopted in the marine industry in order to attain higher reliability, safety and maintenance efficiency. It has been observed that the use of prognostic and health management (PHM) techniques, degradation prediction models, integrated risk- and reliability-based analysis and decision-making techniques have enhanced the overall maintenance paradigm of marine assets. However, with this need of highly skilled workmanship, the budget requirement for acquisition of advanced health monitoring technologies has also enhanced accordingly.

Developments in remote sensing and diagnostics, prognostics, SHM, and wireless data transferring methods play a significant role in the modern day maintenance of marine asset. To some extent, the novel maintenance strategies of RCM and CBM+ have been adopted by the naval shipping sector. The PM scheme currently holds the highest market share in commercial ship maintenance. Although a paradigm shift towards more advanced concepts such as CBM, RCM, and RBI has been noticed in recent years, the pace of this transformation may take several years. It is probably due to the certain precincts of the ship maintenance industry, including the high initial cost of implementing new strategies and training of operators/maintenance teams, prevailing hired maintenance concept in offshore energy and shipping sectors.

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