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Novel multi-objective optimisation for maintenance activities of floating production storage and offloading facilities

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ABSTRACT

An investigation of the recent advancements in modelling and optimisation techniques to develop maintenance strategies for offshore floating systems have been carried out in this paper and identified that the impact of time required to carry out activities have not been considered as an influencing factor in any of the existing formulations reviewed. The influence of time required to complete the activity, on the prioritisation of activities have been demonstrated in this work by means of a novel optimisation problem formulation for Floating Production Storage and Offloading Facility (FPSO) that maximises maintenance personnel resource utilisation and enables FPSO condition enhancement. To find the Pareto-optimal solution, an overall objective function has been developed considering the priorities with respect to design features, operating conditions, deteriorations, and the consequences of not doing the maintenance, taking into consideration the personnel resource time required for activity completion. This formulation provides flexibility to direct the focus of the overall objective function towards any one or more of the objective functions by adjusting their respective weight according to the maintenance strategy followed, which would supplement Regulatory oversight requirements of the FPSO.

1. Introduction

Since the introduction of steel hull vessels and facilities around 130 years ago, the maintenance of these facilities became a prime driver in defining the safety of the asset, remaining life of the asset, and the cost-effectiveness of the operations. The maritime, offshore, and environmental safety standards were consistently challenged by academia and industry, embracing latest technologies with the aim of enhancing the safety standards and cost-effectiveness to achieve sustainable developments. Presently, renewable energy is being widely used and promoted in all applications, whereby we do not impair the ecosystems and preserve the resources for future generations. We must also be clear of our intentions and goals that is to protect the environment with safe operations, and not just to satisfy the legal requirements. Since marine and offshore operations are rather conservative and are linked to many other sectors, such as supply chains and commodities, any remodelling would take considerable time before it would be extensively accepted and implemented.

An investigation of the recent advancements in modelling and optimisation techniques to develop maintenance strategies for offshore floating systems have been carried out in this paper and identified that the impact of time required to carry out activities have not been considered as an influencing factor in any of the existing formulations reviewed. It is to be noted that George et al. (2022) have demonstrated that the current state-of-the-art literature does not incorporate site constraints of the asset related to offshore resource availability for the maintenance activity, due to maximum allowable bed space, which is another limitation of the existing state-of-the art maintenance frameworks. There exists scope for development of maintenance optimisation formulations that incorporate impact of time required to carry out activities, site constraints related to availability of personnel resources for the maintenance activity, and its impact on other activities due to the maintenance execution.

In this paper, it is demonstrated that the above-mentioned gaps could be addressed by examining machine learning, 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.

In summary, the following contributions are made in this paper:

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- An investigation of the recent advancements in modelling and optimisation techniques to develop maintenance strategies for offshore floating systems have been carried out in this paper and identified that the impact of time required to carry out activities and site constraints of available beds offshore have not been considered as main influencing factor, consideration, or performance indicator in the formulation of maintenance systems in any of the literature reviewed in this work, which is a major limitation of the existing frameworks.
- The influence of time required to complete the activity, on the prioritisation of activities have been demonstrated in this work by means of a novel optimisation problem formulation for Floating Production Storage and Offloading Facility (FPSO) that maximises maintenance personnel resource utilisation and enables FPSO condition enhancement, considering the priorities with respect to design features, operating conditions, deteriorations, and the consequences of not doing the maintenance, taking into consideration the personnel resource time required for activity completion. Depending on the priority of the objective function when compared to other objective functions, a relative weight could be associated to the prioritised objective function, using the weighted sum approach, which provides flexibility to direct the focus of the overall objective function towards any one or more of the objective functions, by adjusting their respective weight according to the maintenance strategy followed.
- A novel approach has been utilised to formulate a maintenance plan optimisation problem, whereby the decision variables for each location on the FPSO have been normalised between the maximum and minimum values along the length of FPSO to bring the variables related to the functionality in proportion with that at other locations along the FPSO, and to enable scaling all the decision variables and whereby their respective objective functions to the same magnitude.

2. Notations

α_i	Relative weight of prioritised objective function
ε	Shape parameter of Weibull distribution
σ	Scale parameter of Weibull distribution
σ^2	Extent of maintenance activity completion
σVM	von Mises stress
σy	Yield strength
B	Resource availability in the maintenance window
BMs	Bending moment experienced in situ
BMa	Bending moment allowable
C	Diminution ratio
C(i)	Total Task Completion time
$C_{k_m,n}$	Maintenance window
CIC	Coating intact condition
D	Fatigue damage ratio
Fi	Financial Risks
F_i	Objective Function
$f_i(t)$	Probability density function
FD	Fatigue damage at considered no. of cycles
FL	Fatigue life at constant amplitude loading
FPSO	Floating Production Storage and Offloading Facility
$h_{k_m,n}$	Quality of service
$h_{k_m,l}$	Quality of service
$[i]$	Decision variables
$IGPt$	Intact gross plate thickness
k_m	Maintenance activity
LPt	Loss in plate thickness
M	Bending moment ratio
$MTTF_i$	Mean time to failure
N	Maintenance plan
$OCBa$	Observed coating breakdown area
OCS	Observed corrosion scale
P[i]	Priority
P_l	Space of all polynomials of degrees less than or equal to l
P_n	Space of all polynomials of degrees less than or equal to n
$R_i(t)$	Reliability function
R	Ratio of coating breakdown area
R_i	Degree of corrosion scale
S	Shear Force ratio
Sa	Safety Risks
SFs	Shear force experienced in situ
SFa	Shear force allowable
t	Time to failure of the component i
T[i]	Time required to complete the task
$TCIa$	Total coating intact area
UC	Stress unity check
x_1	Stress unity check
x_2	Fatigue damage ratio
x_3	Bending moment ratio
x_4	Shear force ratio
x_5	Degree of corrosion scale
x_6	Diminution ratio
x_7	Safety risks
x_8	Financial risks
y_i	Overall objective function

3. Maintenance planning overview

The maintenance planning comprises a series of maintenance strategies, driven by maintenance processes and optimisation techniques, taking into account the key influencing factors, key considerations, key performance indictors and evaluated against defined performance criteria, so as to restore the desired functionalities and goals. A brief discussion of various elements of the maintenance planning have been provided below.

3.1. Maintenance strategy

The maintenance strategy contains guidelines, activities and decision support systems, which would be utilised to maintain an equipment and avoid occurrence of a failure event. There are various possible ways to classify the maintenance strategies. In this work, the maintenance strategies have been classified as corrective maintenance, preventive maintenance, condition-based maintenance, run to failure maintenance, opportunistic maintenance, planned maintenance, predictive maintenance, selective maintenance, and risk-based maintenance. The existing literature related to maintenance strategies have been reviewed and an insight to the current research have been summarised below.

The corrective and risk-based maintenance strategies for offshore installations have been detailed in the works of Yazdi et al. (2020), whereas, corrective and preventive maintenance have been used in the works of Ferreira et al. (2020), and a combination of corrective, preventive, predictive and risk based maintenance have been employed by Ibrion et al. (2020).

The corrective and preventive maintenance of offshore wind farms have been detailed in the works of Zhong et al. (2019), whereas, corrective, preventive, opportunistic and planned maintenance have been employed in the works of Stock-Williams and Swamy (2019), corrective, preventive and condition based maintenance have been utilised by Allal et al. (2021), and a combination of corrective, preventive, condition based, opportunistic, planned, predictive and risk-based maintenance have been used by Ren et al. (2021).

The corrective, preventive, condition and risk based maintenance of marine structures have been considered by Abbas and Shafiee (2020), and a combination of corrective, preventive and condition based maintenance for subsea equipment have been detailed by Fan et al. (2021), whereas, corrective, preventive and planned maintenance of offshore oil and gas industry have been employed in the works of Olugu et al. (2021).

The condition based maintenance of FPSO have been detailed in the works of Hwang et al. (2018) and that of offshore wind turbines by Lu et al. (2018). The preventive, condition based and run to failure maintenance of marine and offshore machinery have been employed by Asuquo et al. (2019), whereas, a combination of condition based and selective maintenance have been employed for aircrafts in the works of Yang et al. (2018).

3.2. Maintenance processes

The maintenance processes develop the maintenance strategies to restore the desired functionalities and goals. There are various ways to classify the maintenance processes. In this paper, maintenance processes have been classified as reliability-centred maintenance, reliability-based maintenance, and performance-based maintenance. The existing literature related to maintenance processes have been reviewed and an insight to the current research have been summarised below.

The reliability centred maintenance of offshore floating wind farms has been employed in the works of Garcia-Teruel et al. (2022), whereas reliability based maintenance utilised by Lin et al. (2020). Also, reliability based maintenance of FPSO hull was considered by Hageman et al. (2022), and that of offloading mooring system of FPSO in the works of Ni et al. (2021). The reliability based maintenance of offshore wind support structures was employed by Viera et al. (2022).

The performance based maintenance of offshore structures has been detailed by Dehghani and Aslani (2019), that of FPSO in the works of Ozguc (2020) and that of offshore wind farm in the works of Zhou and Yin (2019). Also, similar maintenance processes for offshore installations have been detailed by Han et al. (2019) and that for safety critical equipment on offshore installations by Han et al. (2021).

3.3. Optimisation techniques

The analyses techniques develop a sequence of maintenance strategies to achieve the appropriate goals, with feedback loop for continuous improvement of the maintenance program. This section investigates the recent developments in optimisation techniques for maintenance planning that could be employed at operational stages. The optimisation methodologies allow developing algorithms based on models, which enables to rank different options according to various priorities. There would be a compromise in which one aspect could be improved at the expense of some other feature, and the best compromise has to be found for the required design and operating conditions. An optimum maintenance planning could not be carried out by introducing only one procedure; to achieve the objective, every important aspect must be taken into consideration. In an offshore maintenance planning optimisation problem, the decision variables cannot be chosen arbitrarily; rather, they must satisfy certain specified functional and other requirements. The existing literature related to optimisation techniques for maintenance planning have been reviewed and an insight to the current research have been summarised below.

A Deep Learning mathematical programming optimisation technique for aero-propulsion system of a turbofan engine has been employed by Hesabi et al. (2022), whereas, an unsupervised machine learning optimisation for offshore wind turbines was used by Yeter et al. (2022), a mathematical nondominated sorting genetic algorithm by Zhang and Yang (2021) and a deterministic non-linear programming problem by Zhang and Zhang (2021).

A weighted sums approach for a selective maintenance problem of multi-component systems was employed in the works of Diallo et al. (2019) and a constrained optimisation mathematical programming technique for continuous and discontinuous operating systems was utilised in the works of Galante et al. (2020). A bayesian network with monte carlo simulation technique for marine pipelines has been employed by Adumene et al. (2021), and a mixed integer non-linear programming based selective maintenance optimisation for engineering systems has been detailed by Ikonen et al. (2020).

3.4. Desired functionalities and goals of maintenance program

This section categorises the desired functionalities and goals of maintenance program into key influencing factors, key considerations and key performance indicators, so as to assess the effectiveness of the program.

The key maintenance performance indicators include asset availability and reliability, safety and regulatory compliance, manpower costs, activity completion, cost related to activity duration, increase in efficiency, consistency, offshore and onshore practices, and site constraints. The key influencing factors of maintenance performance are rate of deterioration mechanisms and measures to mitigate deteriorations, rectification of anomalies, failure consequences, owners strategy, design conditions and assumptions, environment and operational conditions, operational requirements, safety compliance, resource availability with respect to man power and materials, failure probability, risks of not carrying out the maintenance, risks with doing the maintenance, and risks to business, safety and environment.

The 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 risk assessment based on the probability of occurrences of the failure events and the consequences of failure events. The various allowances and safety factors for various components determine the probability of the failure occurrence.

The corrective activities would reduce the likelihood of the safety event occurrence, by addressing the failure modes related to that event. 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 execution slot. 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 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.

The existing literature related to desired functionalities and goals of maintenance program have been reviewed and an insight to the current research have been summarised in Table 1.

It could be noted from the Table 1 that site constraints of available beds offshore and the impact of time required to carry out activities have not been considered as a key performance indicator or desired goal in any of the literature reviewed in this work, 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. Towards this, there exists scope for further research work that would incorporate site constraints of available beds offshore 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, to achieve the optimal maintenance strategy.

4. Maintenance resources and site constraints

Offshore resources referred in this paper are the professional technicians available to perform the tasks, which include personnel already doing the work, or could do the work that needs to be done on the various systems, which require a portion of the resource allocations. The maintenance activities have personnel resource requirement based on the time required to complete the task. The minimum resource requirement for the activity would be the initial resource allocation for

Table 1
Desired functionalities and goals of maintenance program.

Desired functionalities and goals of maintenance program								
Ref/Year	Equipment	Design features	Operational conditions	Degradations	Environmental conditions	Measures to mitigate deteriorations	Consequence of not doing maintenance	Maintenance Duration, and frequency
(Fan et al., 2019)	Offshore wind				✓		✓	✓
(Mentes and Turan, 2019)	Offshore wind		✓				✓	
(Li and Hu, 2021)	Offshore oil and gas		✓				✓	
(Scheu et al., 2019)	Offshore wind		✓	✓				
(Zagorowska et al., 2020)	Offshore turbo			✓			✓	
(Kang and Soares, 2020)	Offshore wind							✓
(Li et al., 2020)	Offshore wind	✓		✓	✓			✓
(Lazakis and Khan, 2021)	Offshore wind	✓			✓			
(Jamshidi et al., 2019)	Offshore wind				✓			
(Teixeira et al., 2020)	Industrial application	✓	✓					
(Schrotenboer et al., 2018)	Offshore wind							✓
(Werneck et al., 2021)	Wells	✓	✓					
(Seiti et al., 2019)	Process Units							✓
(Ahmadi et al., 2020)	Storage tanks		✓			✓		
(Liu et al., 2020)	Coal Transport	✓						✓
(Hernandez et al., 2021)	Offshore wind				✓			
(Zou et al., 2021)	Marine Structures			✓			✓	✓
(Yazdi et al., 2019)	Process facilities	✓			✓		✓	✓
(Matias et al., 2020)	Gas lift oil well		✓	✓			✓	
(Yazdi et al., 2020)	Chemical Plant						✓	
(Rinaldi et al., 2021)	Offshore wind	✓	✓					
(Chaabane et al., 2020)	Manufacturing							✓
(Khatab et al., 2019)	Manufacturing	✓					✓	✓
(Schouten et al., 2021)	Offshore wind	✓					✓	✓
(Schrotenboer et al., 2020)	Offshore wind						✓	✓
(Ramirez-Ledesma and Juarez-Islas, 2022)	Offshore oil	✓		✓			✓	
(Liu et al., 2022)	Transportation							✓
(Liu et al., 2018)	Transportation		✓					✓
(Li et al., 2021)	Offshore wind	✓						✓
(Zhang et al., 2019)	Wind turbine		✓		✓			✓
(Zhang and Yang, 2021)	Wind turbine				✓		✓	✓
(Hageman et al., 2022)	FPSO hull	✓	✓		✓			

the activity based on the estimations from previous experiences. The resource estimations take place by adapting the quality-of-service requirements of individual systems. Further allocation of resources would be carried out by monitoring the status of the activity based on the predicted progress as per pre-defined results.

The performance of resource allocation could be evaluated by resource utilisation and the quality-of-service satisfaction of the maintenance activity with a time varying number of maintenance activities. The expectation would be that the performance of one maintenance system does not affect the other, and thus the performance isolation for quality of service would be important. The overall resource availability would be split up for the individual maintenance activities, and there would be a need to map and schedule the resources efficiently. In this paper, the resource utilisation has been used to check if the allocated maintenance window for the maintenance activity is utilised. Also, resource utilisation would indicate the usage of the available maintenance window effectively for the maintenance activity, such that higher weighted sum of the task completion times at as short time as possible, would lead to higher resource utilisations and enables enhancement of FPSO conditions.

The site constraints that are experienced for maintenance activities include shadow areas and locations with accessibility issue, restricted access spaces that require additional risk assessment prior accessing, overside sections of the deck that need boat cover and additional risk assessment prior accessing, locations having presence of continuous water and need special equipment for carrying out maintenance, locations with accessibility issues during normal operations and need to be dealt during a pre-specified period such as plant shut down as an opportunistic work Also, access restrictions, condition of work, personnel and equipment availability, weather, repair days, personnel capabilities and impact on other activities are typical site constraints on a FPSO.

However, differing from the existing literature, this paper considers a new important constraint factor, the impact of time required to carry out offshore maintenance activities to achieve the optimal personnel resource utilisations.

5. Maintenance window and degradations

Let n denotes the maintenance plan, k_m a single maintenance activity, in the maintenance window denoted by $C_{k_m\ ,\ n}$. Let B be the resource availability in the window, $h_{k_m\ ,\ n}$ and $h_{k_m\ ,\ l}$ the quality of services, $\sigma^2$the extent of activity completion, then the minimum maintenance window required for a maintenance activity could be expressed as follows, as in the works of Sun et al. (2019).

$$C_{k_m\ ,\ n} = B\ .\ log_2\left(1 + \frac{P_n\ \left|h_{k_m\ ,\ n}\right|^2}{\sum_{l\in N,\ l\neq n} P_l\ \left|h_{k_m\ ,\ l}\right|^2 + \sigma^2}\right) \tag{1}$$

where P_n and P_l denotes the space of all polynomials of degrees less than or equal to n and l respectively, and the log_2 transformation normalises the expression and enables proportional changes rather than additive changes.

During the life of FPSO, the lifetimes of components would be randomly generated by employing the Weibull distribution. The component considered for maintenance degrades as the time goes by until their failure. Modelling the time to failure t, of the component i, at equipment k would be modelled by employing the Weibull distribution

Desired functionalities and goals of maintenance program							
Resources for activity completion	Operational priorities	Acceptance criteria	Uncertainties, Failure probabilities	Deviations	Site constraints related to environmental factors	Site constraints of available beds Offshore	Impact of time required to carry out activities
✓			✓		✓		
		✓					
			✓		✓		
			✓				
			✓		✓		
✓					✓		
					✓		
			✓				
✓				✓			
✓					✓		
			✓		✓		
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✓			✓		✓		
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	✓				✓		
			✓		✓		
			✓		✓		
	✓				✓		
✓	✓				✓		
			✓		✓		

with scale parameter σ_{ik}, and shape parameter ε_{ik}, the component probability density function $f_{ik}(t)$, reliability function $R_{ik}(t)$, and mean time to failure $MTTF_{ik}$, could be expressed as follows, as in the works of Li et al. (2021).

$$f_{ik}(t) = \frac{\varepsilon_{ik}}{\sigma_{ik}}\left(\frac{t}{\sigma_{ik}}\right)^{\varepsilon_{ik}-1} e^{-\left(\frac{t}{\sigma_{ik}}\right)^{\varepsilon_{ik}}} \tag{2}$$

$$R_{ik}(t) = e^{-\left(\frac{t}{\sigma_{ik}}\right)^{\varepsilon_{ik}}} \tag{3}$$

$$MTTF_{ik} = \int_0^{\infty} tf_{ik}(t) = \sigma_{ik}\,\Gamma\left(\frac{1}{\varepsilon_{ik}}+1\right) \tag{4}$$

where, $\Gamma\left(\frac{1}{\varepsilon_{ik}}+1\right)$ denotes the Gamma function.

Let $\alpha_{ik} = \sigma^{-\varepsilon_{ik}}$, inverse Weibull model would be used to generate Weibull distributed random numbers, beginning with the random number, γ, which is in the range from 0 to 1. The new independent random numbers that have the Weibull distribution with the mean and variance depending on shape and scale parameters could be obtained by the following equation.

$$t_{ik} = \left[-\frac{1}{\alpha_{ik}}\ln(1-\gamma)\right]^{\frac{1}{\varepsilon_{ik}}} \tag{5}$$

These random numbers would be assigned to the corresponding components to represent their lifetimes, as in the works of Li et al. (2021).

6. System formulated multi-objective problem formulation for FPSO Main Deck maintenance

A Floating Production Storage and Offloading Facility (FPSO) main deck modelled in this work is estimated to be of a 15-year-old hull with the principal dimensions as indicated in Table 2. The hull age estimation was made to align with a general 15-year replacement assurance of protective coating systems from the coating manufacturer, towards application and product manufacture errors.

The commercially available loading calculator has been employed to parametrically define the geometric model.

The Profile view of the modelled FPSO has been shown in Fig. 1, and the Elevation and Plan views shown in Fig. 2.

6.1. Decision variables

The decision variables considered in this work are the design features, operating conditions, deteriorations experienced and the consequences of not doing the maintenance activities.

6.1.1. Design features

The strength design of the FPSO hull ensures that the structure could withstand the von mises stresses experienced on the hull. The calculated

Table 2
Principal Dimensions of modelled FPSO.

Length between perpendiculars	340m
Moulded Breadth	50m
Moulded Depth	30m

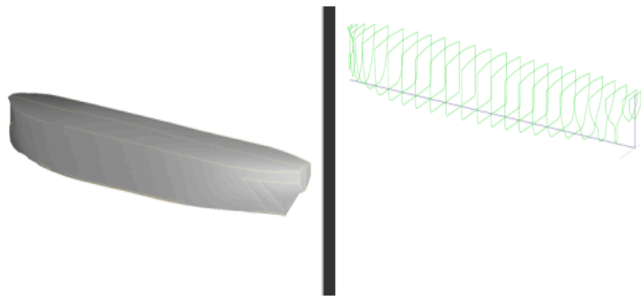


Fig. 1. Profile of the modelled FPSO.

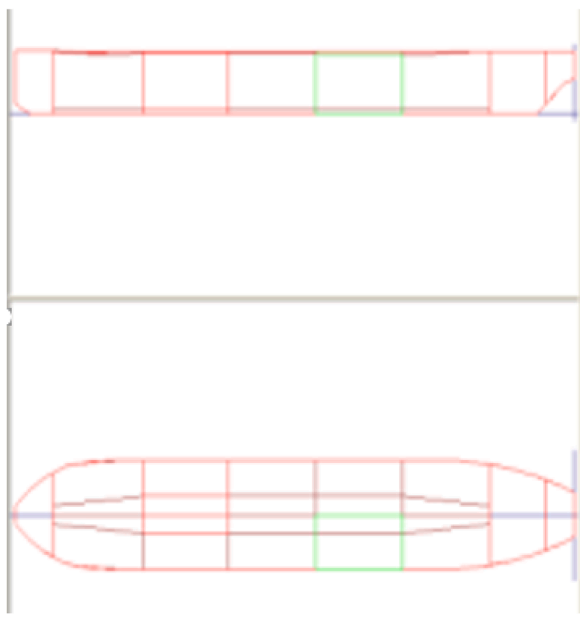


Fig. 2. Elevation and Plan views of modelled FPSO.

von mises stresses determines whether the location would lead to a hot spot for deterioration and failures. The von mises could be evaluated by considering the stress unity check value, such that,

$$Stress\ Unity\ Check\ UC = \frac{\sigma VM}{\sigma y} \quad (6)$$

where, σVM is the von Mises stress and σy is the yield strength.

Stress Unity Check, $\{x_1\}$, UC is the inverse of factor of safety. UC value high, means high stress locations and need to be prioritised for maintenance.

A fatigue design ensures that the FPSO hull structure has an adequate fatigue life. The calculated fatigue lives form the basis for the operational life of the FPSO hull. Fatigue could be evaluated by considering the fatigue damage ratio, such that,

$$Fatigue\ Damage\ ratio\ D = \frac{FD}{FL} \quad (7)$$

where, FD is the fatigue damage at considered no. of cycles and FL is the fatigue life at constant amplitude loading.

Fatigue Damage ratio, $\{x_2\}$, D value high, means location has low fatigue life and need to be prioritised for maintenance.

6.1.2. Operating conditions

The bending moment experienced on the FPSO hull during operating conditions defines how much indicates the reaction in a cross-section of the hull due to the external forces and moments induced by the loads that the structure gets subjected to. The bending moment experienced could be evaluated by considering the bending moment ratio, such that,

$$Bending\ Moment\ ratio\ M = \frac{BMs}{BMa} \quad (8)$$

where, BMs is the bending moment experienced in situ and BMa is the bending moment allowable.

Bending Moment ratio, $\{x_3\}$, M value high, means high bending moment experienced at the location and need to be prioritised for maintenance.

The shear force experienced on the FPSO hull during operating conditions indicates the resultant shearing forces on the hull due to the external forces induced by the loads that the structure gets subjected to. The shear force experienced could be evaluated by considering the shear force ratio, such that,

$$Shear\ Force\ ratio\ S = \frac{SFs}{SFa} \quad (9)$$

where, SFs is the shear force experienced in situ and SFa is the shear force allowable.

Shear Force ratio, $\{x_4\}$, S value high, means high shear force experienced at the location and need to be prioritised for maintenance.

As the stresses in hull section induced by the bending moment and shear force are carried by hull girder structural members, namely strength deck plating and deck longitudinal, side shell plating and longitudinal, bottom shell plating and longitudinal, inner bottom plating and longitudinal, double bottom girders and bilge plating, any deterioration of these structural members during the life of the FPSO impacts the design envelopes of M and S, whereby reducing the still water bending moment and shear force allowable limits.

6.1.3. Deteriorations

The dominant deterioration mechanism expected on FPSO structures has been considered as the corrosion. The structures exposed to weather or sea water would be protected by paint coating and the expected lifetime of the coating would generally exceed that of the FPSO. The intact coating condition would be achieved when the coating has been applied to a clean surface with good surface preparation. The areas with degraded coating could become anodic compared with areas with intact coating and would lead to corrosion. The assessment of extent of coating breakdown and corrosion scale could be determined by the degree of corrosion observed, based on degree of rusting derived from (BS EN ISO 4628-3 2016). The degree of corrosion scale would be decided by the % area rusted and the Fig. 3 assist in the interpretation.

The coating breakdown and scattered corrosion in excess of approx. 8% of the area considered would generally be recommended for remedial action, while other minor blisters and coating breakdowns are classed as insignificant findings. The corrosion scale could be evaluated by considering the degree of corrosion scale, such that,

$$Degree\ of\ corrosion\ scale\ R_i = \frac{OCS}{CIC} \quad (10)$$

where, OCS is the observed corrosion scale and CIC is the coating intact condition.

Degree of corrosion scale, $\{x_5\}$, R_i value high, means high corrosion scale at the location and need to be prioritised for maintenance.

The unattended corrosion eventually leads to thickness loss of the parent metal, and the observed corrosion and metal wastage in this work were estimated to be within the substantial corrosion range, which is 75% of the maximum allowable wastage associated with the deck plating, defined by the corrosion margin employed in design and fabrication and verified by structural analysis. When extensive areas of metal wastage are observed, thickness measurements are to be carried out and the individual component thickness to be maintained within the diminution allowances considered in the strength assessment. The

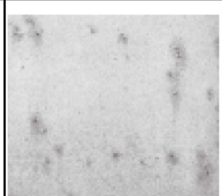
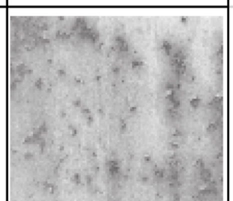
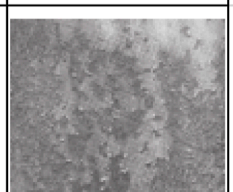
Degree of Rusting	Rusted area %	Extent of coating breakdown and corrosion scale	
Ri 0	0	Coating intact and in good condition	
Ri 1	0.05	Coating intact with some corrosion spots	
Ri 2	0.5	Coating intact with minor blisters	
Ri 3	1	Coating shows breakdown and signs of blistering	
Ri 4	8	Coating shows breakdown with signs of blistering and surface corrosion	
Ri 5	40 - 50	Coating shows breakdown with signs of blistering and surface corrosion	

Fig. 3. Assessment of coating breakdown and corrosion scale (BS EN ISO 4628-3 2016).

resultant structural thickness diminution and metal loss could be evaluated by the diminution ratio, such that,

$$Diminution\ ratio\ C = Degree\ of\ metal\ loss = \frac{LPt}{IGPt} \tag{11}$$

where, *LPt* is the loss in plate thickness and *IGPt* is the intact gross plate thickness.

Diminution ratio, $\{x_6\}$, *C* value high, means high degree of metal loss at the location and need to be prioritised for maintenance.

6.1.4. Consequences of not doing maintenance

The consequences of corrosion have significance on strength, operability, and operating life of the FPSO hull structures. The main consequences of hull structural failures could be the impacts on Safety and Financial aspects, resulting in the scenarios such as release of hydrocarbon gas to the atmosphere and a potential explosion; release of hydrocarbon oil to the environment; internal structural failure leading to contaminations between compartments; global Hull girder and local structural failures; and loss of stability, resulting in capsizes. The associated risks could be quantified as safety risks and financial risks of high, medium, and low grades, based upon the probability of failure event occurrence and the consequence such that,

* High risk grade are the scenarios of a major safety event such as fatality, one or more severe injuries or a financial event estimated at a cost > US$ 1 Million is likely to occur at the asset within the next 5 years.
* Medium risk grade are the scenarios of a minor safety event such as single injury or a financial event estimated at a cost > US$ 100K < US$ 1Million is likely to occur at the asset within the next 5 years.
* Low risk grade are the scenarios of an incidental safety event such as first aid events or a financial event estimated at a cost < US$ 100K is likely to occur at the asset within the next 15 years.

whereby,

Safety risks, $\{x_7\}$,

$$Criticality\ Sa = 3\ High.\ Sa = 2\ Medium.\ Sa = 1\ Low \tag{12}$$

Safety risks, $\{x_7\}$, *Sa* value high, means high safety risks involved in case of not doing the maintenance, and hence need to be prioritised for maintenance.

Financial risks, $\{x_8\}$,

$$Criticality\ Fi = 3\ High.\ Fi = 2\ Medium.\ Fi = 1\ Low \tag{13}$$

Financial risks, $\{x_8\}$, *Fi* value high, means high financial risks involved in case of not doing the maintenance, and hence need to be prioritised for maintenance.

6.1.5. Personnel resource for activity completion

The personnel resource Time, $\{x_9\}$, required for each maintenance activity towards surface preparation and coating reinstatement could be estimated based on the extent of coating breakdown observed at the FPSO locations. In this work, the personnel resource requirement estimations have been made by a comparison of the extent of coating breakdown on the main deck relative to the other locations that require maintenance. The time *T* required to complete the task, based on the extent of coating breakdown, could be evaluated by considering the ratio of coating breakdown area, such that,

$$Ratio\ of\ coating\ breakdown\ area\ R = \frac{OCBa}{TCIa} \tag{14}$$

where, *OCBa* is the observed coating breakdown area and *TCIa* is the total coating intact area.

R value high, means coating breakdown over a large area at the location and need more time to carry out maintenance. Depending on the observed coating breakdown on maintenance locations, the time required to complete the task has been allotted values in the range {2, 5}, such that when the R is ≤ 0.2, the time required T is assigned a value of 2; when R > 0.2 and ≤ 0.4, the T is assigned a value of 3; when R > 0.4 and ≤ 0.6, the T is assigned a value of 4; and when R > 0.6, the T is assigned a value of 5.

6.2. Objective functions

The main objective of this work was to maximise the maintenance personnel resource utilisation and enable FPSO condition enhancement, considering the priorities with respect to design features, operating conditions, deteriorations, and the consequences of not doing the maintenance, taking into consideration the personnel resource time required for activity completion. The personnel resource utilisation directly relates to the key performance indicators of manpower costs, activity completion, cost related to activity duration and increase in efficiency, whereas the FPSO condition enhancement relates to the availability, reliability, safety and regulatory compliances of the asset.

$$\text{Objective Function, } F_i = \sum\left(\left(\frac{P[i]}{T[i]}\right) \times C[i]\right) \tag{15}$$

where, $P[i]$ is the Priority based on the objectives and $T[i]$ is the time required to complete a maintenance activity. The Time, $T[j]$ is the estimated time of completion of task, as per the order of actual execution of tasks, such that the cumulative task completion time $(i) = \sum T\ [j] = T[1] + T[2] + \ldots T[j]$.

The $[i]$ is the decision variable corresponding to design features, operating conditions, deteriorations, and consequences of not doing the maintenance, such that,

$[i]$ =1, for design feature of Stress Unity Check;

$$\textit{Normalised } \{x_i\} \textit{ at a location on FPSO} = \frac{\textit{Maximum } \{x_i\} \textit{ at the location} - \textit{Minimum } \{x_i\} \textit{ along the length of FPSO}}{\textit{Maximum } \{x_i\} \textit{ along the length of FPSO} - \textit{Minimum } \{x_i\} \textit{ along the length of FPSO}} \tag{16}$$

$[i]$ =2, for design feature of Fatigue Damage ratio;
$[i]$ =3, for operating condition of Bending Moment ratio;
$[i]$ =4, for operating condition of Shear Force ratio;
$[i]$ =5, for deterioration of Degree of corrosion scale;
$[i]$ =6, for deterioration of Diminution ratio;
$[i]$ =7, for Safety risks of not doing maintenance; and
$[i]$ =8, for Financial risks of not doing maintenance.

By aggregating the parameters, Priority P and Time T, into the single score of $P[i]\ /\ T[i]$, when the tasks are sorted from higher score to lower score, that would lead to optimal solution. Higher priorities $\{P\}$ lead to a higher score for the Objective Function. More time $\{T\}$ required to complete the task, would decrease the score of the Objective Function.

The objective function corresponding to maintenance priorities with respect to design features of Stress Unity Check $\{x_1\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_1 = \sum\left(\left(\frac{P[1]}{T[1]}\right) \times C[1]\right)$. The objective function corresponding to maintenance priorities with respect to design features of Fatigue Damage Ratio $\{x_2\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_2 = \sum\left(\left(\frac{P[2]}{T[2]}\right) \times C[2]\right)$. The objective function corresponding to maintenance priorities with respect to operating conditions of Bending Moment Ratio $\{x_3\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_3 = \sum\left(\left(\frac{P[3]}{T[3]}\right) \times C[3]\right)$. The objective function corresponding to maintenance priorities with respect to operating conditions of Shear Force Ratio $\{x_4\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_4 = \sum\left(\left(\frac{P[4]}{T[4]}\right) \times C[4]\right)$. The objective function corresponding to maintenance priorities with respect to deteriorations of Degree of Corrosion Scale $\{x_5\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_5 = \sum\left(\left(\frac{P[5]}{T[5]}\right) \times C[5]\right)$. The objective function corresponding to maintenance priorities with respect to deteriorations of Degree of Metal Loss $\{x_6\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_6 = \sum\left(\left(\frac{P[6]}{T[6]}\right) \times C[6]\right)$. The objective function corresponding to maintenance priorities with respect to Safety Risks in the event of not doing maintenance $\{x_7\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_7 = \sum\left(\left(\frac{P[7]}{T[7]}\right) \times C[7]\right)$. The objective function corresponding to maintenance priorities with respect to Financial Risks in the event of not doing maintenance $\{x_8\}$ taking into consideration the personnel resource time required for activity completion has been termed as $F_8 = \sum\left(\left(\frac{P[8]}{T[8]}\right) \times C[8]\right)$.

6.3. Implementation of multi-objective problem formulation and optimisation model

To enable the problem formulation, a novel approach has been utilised such that the decision variables for each location on the FPSO have been normalised between the maximum and minimum values along the length of FPSO in order to bring the variables related to the functionality in proportion with that at other locations along the FPSO, and to enable scaling all of the decision variables and whereby their respective objective functions to the same magnitude, such that,

It was estimated that there would be no coating breakdown on the main deck for the first 15 years of the FPSO life and thereafter an 8% annual coating breakdown deterioration is anticipated on the main deck structures for the next 3 years if no maintenance is carried out. The input data for the design values, x_1, x_2 were estimated from the real life experience of the Authors, operating condition values, x_3, x_4 obtained from running various load cases on the geometrical model of the FPSO in commercially available loading calculator, deterioration values, x_5, x_6 developed employing the information from published literature of corrosion rates of ships from Tanker Structure Co-operative Forum (1992) and the consequence values of not doing the tasks, x_7, x_8 were estimated from the real life experience of the Authors. The time required to complete the task, x_9 was estimated based on the extent of coating breakdown considered at the main deck locations, dependent on the age of the FPSO. The proposed FPSO main deck maintenance planning system problem has been shown in Fig. 4.

To find the Pareto-optimal solution, an overall objective function has been developed as a linear combination of the multiple objective functions, similar to the approach proposed in the works of Steuer (1986).

The objective functions F_1 ,F_2 , F_3 , F_4 , F_5, F_6 , F_7 *and* F_8 corresponding to maintenance priorities with respect to normalised Stress Unity Check $\{x_1\}$, Fatigue Damage Ratio $\{x_2\}$, Bending Moment Ratio $\{x_3\}$, Shear Force Ratio $\{x_4\}$, Degree of Corrosion Scale $\{x_5\}$, Degree of Metal Loss $\{x_6\}$, Safety Risks in the event of not doing maintenance $\{x_7\}$ and Financial Risks in the event of not doing maintenance $\{x_8\}$ respectively, taking into consideration the personnel resource time required for activity completion, were combined into an overall objective optimisation problem. Depending on the priority of the objective function when compared to other objective functions, a relative weight has been associated to the prioritised objective function, using the weighted sum approach, such that

$$\{y_i\} = \sum(\pm\alpha_i \times F_i) \tag{17}$$

where, α_i indicates the relative weight of the prioritised objective function when compared with the priority of other objective functions. Any of the prioritised objective function could be either maximised or minimised depending on the maintenance strategy followed. The positive weight, *Sign* $+$, means the corresponding objective function would

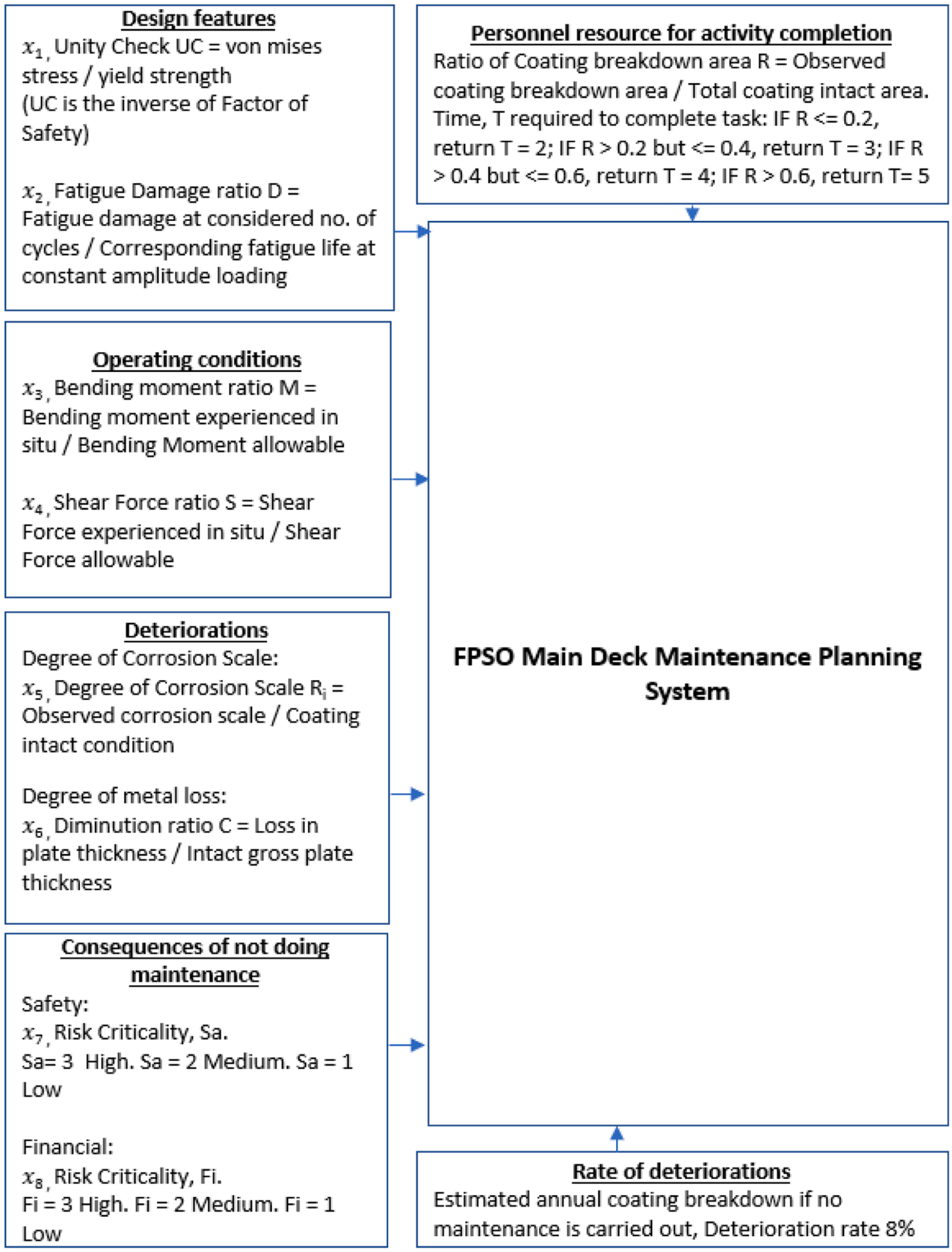


Fig. 4. FPSO Main Deck maintenance planning system problem.

be maximised, and negative weight, *Sign* − , means the corresponding objective function would be minimised. This formulation provides flexibility to direct the focus of the overall objective function, $\{y_i\}$, towards any one or more of the objective functions by adjusting their respective weight according to the maintenance strategy followed.

7. Novel Greedy Algorithm for formulation of FPSO main deck maintenance

The novelty of this work is that a greedy algorithm approach, which follows the problem-solving pattern of making the locally optimal choice at each step with the hope of finding the globally optimal solution has been employed in this work, for the problem formulation of FPSO main deck maintenance. The greedy algorithm was chosen for this work, as it works step by step looking at the immediate situation and chooses the steps that provide immediate benefits at that point of time, which in turn leads to achieving the most feasible solution that enables higher resource utilisation with the consideration of site constraints and facilitate FPSO condition enhancement. In the FPSO main deck maintenance optimisation problem, if more activities could be done before completing the ongoing activity, these activities could be performed within the same time. Also, the greedy algorithm enables dividing the problem iteratively based on a condition and makes one greedy choice after another and reduces the problem, without need to combine all the solutions.

In this problem formulation, the greedy algorithm makes greedy choices to get the optimum overall objective function, developed as a linear combination of the multiple objective functions. The objective function $\left\{F_i = \sum\left(\left(\frac{P[i]}{T[i]}\right) \times C[i]\right)\right\}$ is the weighted sum of the completion times based on the priorities with respect to design features, operating conditions, deteriorations, and the consequences of not doing the maintenance, and the objective is to have higher weighted sum of the completion times at as short time as possible.

The following algorithm returns the optimal value of the objective functions:

Algorithm 1 Greedy Algorithm:

Algorithm (P, T, N)
{
Minimum x_i; Maximum x_i.
Normalised x_i = (Maximum x_i at the location - Minimum x_i value along the FPSO) / (Maximum x_i value along the FPSO - Minimum x_i value along the FPSO)
Priority for the task, P, could be classified based on Offshore Practices, such that:
IF $x_i \leq 0.25$, return 2, Priority $P4$ – Lowest Priority.
IF $x_i > 0.25$ *but* ≤ 0.5, return 3, Priority $P3$ – Low Priority.
IF $x_i > 0.5$ *but* ≤ 0.75, return 4, Priority $P2$ – Medium Priority.
IF $x_i > 0.75$, return 5, Priority $P1$ – High Priority.
Ratio of Coating breakdown area R = Observed coating breakdown area / Total coating intact area.
Estimated annual coating breakdown if no maintenance is carried out, Deterioration rate 8%.
Time, T required to complete the task, such that:
IF $R \leq 0.2$, return $T = 2$;
IF $R > 0.2$ *but* ≤ 0.4, return $T = 3$;
IF $R > 0.4$ *but* ≤ 0.6, return $T = 4$;
IF $R > 0.6$, return $T = 5$
Algorithm: $(P[i] \ / \ T[i])$
Aggregating the parameters (Priority P & Time T) into a single score, such that when the tasks are sorted from higher score to lower score, lead to optimal solution.
* Higher priorities $\{P\}$ lead to a higher score for the Objective Function
* More time $\{T\}$ required to complete the task, would decrease the score of the Objective Function
Algorithm: Order the tasks by decreasing value of $(P[i] \ / \ T[i])$.
Time, T_j, estimated shifts required to complete the task, as per the new order of tasks by decreasing value of $(P[i] \ / \ T[i])$.
Algorithm: Cumulative Task Completion time $C(i) = \sum T[j] = T[1] + T[2] + \ldots T[j]$
Algorithm: Weighted completion times, for the $\{N\}$ number of activities that need to be completed in the maintenance window.
$\sum (P[i] \ / \ T[i]) \times C(i) = (P[i] \ / \ T[i]) \times C(i), \ldots, (P[N] \ / \ T[N]) \times C(N)$
Algorithm: Objective function F_i: Weighted sum of the completion times based on the priorities to address locations with high x_i
$(P[1] \ / \ T[1]) \times C(1) + (P[2] \ / \ T[2]) \times C(2) + \ldots (P[N] \ / \ T[N]) \times C(N)$
}

The methodology of FPSO main deck maintenance planning problem has been shown in Fig. 5.

8. Benchmarking and Evaluation of Greedy Algorithm for FPSO main deck maintenance

The prioritisation of various maintenance activities and inclusion in a schedule window is dependent on what risks the activity would liquidate by its execution using the available manpower and material resources, considering the operational and environmental constraints considered. In this regard, safety and financial risks have been considered in this work as the prominent drivers in rationalisation of the maintenance plans and for efficient utilisation of resources.

The benchmarking of the algorithm has been carried out by comparing the parameters, with and without considering the time required to complete the task, which reflects influence of the time required to carry out the activity, on the prioritisation of activities. In the simulations, the performance of the greedy algorithm has been evaluated in terms of the personnel resource allocation and resource utilisation.

To evaluate the satisfaction of resource allocation, the weighted sum of the task completion times based on the priorities have been considered. To evaluate the satisfaction of resource utilisation, it has been considered that the higher weighted sum of the completion times at as short time as possible, would lead to higher resource utilisations and enable FPSO condition enhancement.

The evaluation of the model has been carried out by comparing the parameters based on three different loading conditions of the FPSO – light, medium and full load conditions.

The schematic representation of the FPSO system optimisation problem has been shown in Fig. 6.

The graphs shown in Figs. 7–10 of the following sections indicate three different loading conditions of the FPSO such that, yellow coloured graph corresponds to the full load condition of the FPSO, grey coloured graph corresponds to the light load condition of the FPSO, and the orange and blue coloured graph corresponds to the medium load condition of the FPSO. It was observed that the priorities remain almost identical for full load and light load conditions of the FPSO, and hence a single plot of yellow colour corresponds to the full and light loading conditions in the Figs. 7–10.

Also, the Figs. 7–10 demonstrate the influence of time required to carry out activities on the prioritisation and execution of activities, for FPSO condition enhancement and to achieve optimised utilisation of resources. The blue coloured graphs indicate the execution priorities and weighted task completion times respectively without considering the time required to complete task, whereas the other graphs of orange and yellow colour indicate them by considering the time required to complete the task.

8.1. Resource allocation based on Consequences of not doing the tasks – Safety Risk over Time required to complete task

In this simulation in Fig. 7, the performance of the greedy algorithm is being evaluated in terms of the personnel resource allocation, in terms of the priorities based on Safety Risk over Time required to complete tasks, $(P[i] \ / \ T[i])$.

The simulation results obtained for the priority based on Consequences of not doing the tasks – Safety Risk over Time required to complete task are shown in Fig. 7.

The bending moment experienced on the hull girder would always be maximum at the midship region of the FPSO, which extends one fourth length of the FPSO forward and aft of the midship. The bending stress reach a peak at this region, irrespective of the loading condition the FPSO is subjected to in its lifetime. This makes the midship region vulnerable to exceed the threshold of bending strength of the material in the event of an improper loading and any eventual failures affecting the ability to control the FPSO stability during a damage event leading to Safety risks. The Fig. 7 shows that the midship region need to be prioritised for maintenance and the relative order of execution at this region has become clearer from the plots, which leads to condition enhancement of the FPSO.

It could be observed in Fig. 7 that when the maintenance activities are prioritised solely based on the Consequences of not doing the tasks – Safety Risk, the highest priority is to allocate resources to the locations on the FPSO at a distance of 60-253m from the Aft Peak of FPSO, followed by locations 50-59.9m, 253.1-275m and so on.

When the time required to complete the maintenance activities have been considered along with the priorities based on the Consequences of not doing the tasks – Safety Risk for Full load condition of the FPSO, it could be observed that the highest priority is to allocate resources to the locations on the FPSO at a distance of 209-253m from the Aft Peak of FPSO, followed by locations 195-208.9m, 253.1-270m and so on.

When the time required to complete the maintenance activities have been considered along with the priorities based on the Consequences of not doing the tasks – Safety Risk for Medium load condition of the FPSO, it could be observed that the highest priority is to allocate resources to the locations on the FPSO at a distance of 209-253m from the Aft Peak of FPSO, followed by locations 187-208.9m, 253.1-275m and so on.

When the time required to complete the maintenance activities have been considered along with the priorities based on the Consequences of not doing the tasks – Safety Risk for Light load condition of the FPSO, it could be observed that the highest priority is to allocate resources to the locations on the FPSO at a distance of 209-253m from the Aft Peak of FPSO, followed by locations 195-208.9m, 253.1-270m and so on.

The benchmarking of the algorithm has been carried out by comparing the resource allocations, with and without considering the time required to complete the task, which reflects influence of the time required to carry out the activity, on the prioritisation of activities.

The evaluation of the model carried out by comparing the resource allocations based on 3 different loading conditions of the FPSO – Full load, Medium load and Light load conditions, as indicated in Fig. 7, demonstrates the performance of the greedy algorithm, in terms of the personnel resource allocation based on Consequences of not doing the tasks – Safety Risk over the time required to complete tasks.

In this simulation in Fig. 8, the performance of the greedy algorithm is being evaluated in terms of the personnel resource utilisation, in terms of the weighted task completion time, based on Consequences of not doing the tasks – Safety Risk over Time required to complete tasks,

$$\sum (P[i] \ / \ T[i]) \times \ C(i) \ ,$$

where, Task Completion Time, $C(i) \ = \ \sum T \ [j]$.

The benchmarking of the algorithm has been carried out by comparing the resource utilisations, with and without considering the time required to complete the task, which reflects influence of the time required to carry out the activity, on the prioritisation of activities.

To evaluate the satisfaction of resource utilisation, it could be observed that the higher weighted sum of the completion times at as short time as possible, would lead to higher resource utilisations. The evaluation of the model carried out by comparing the resource utilisations based on 3 different loading conditions of the FPSO – Full load, Medium load, and Light load conditions, as indicated in Fig. 8, demonstrates the performance of the greedy algorithm, in terms of the variation in personnel resource utilisation, based on Safety Risk over the time required to complete tasks.

8.2. Resource allocation based on Consequences of not doing the tasks – Financial Risk over Time required to complete task

In this simulation in Fig. 9, the performance of the greedy algorithm is being evaluated in terms of the personnel resource allocation, in terms of the priorities based on Financial Risk over Time required to complete tasks, $(P[i] \ / \ T[i])$.

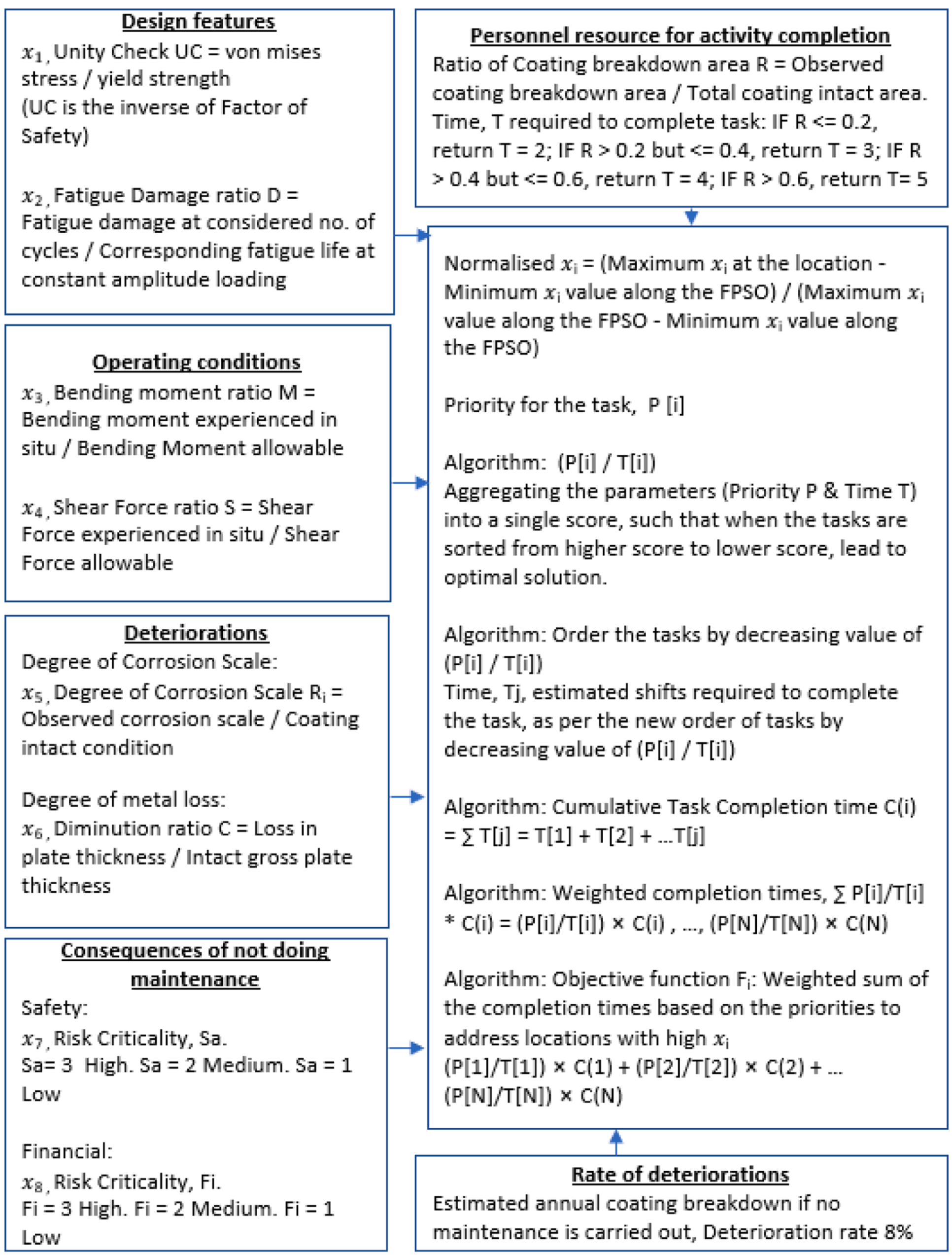


Fig. 5. Methodology of FPSO main deck maintenance planning problem.

The simulation results obtained for the priority based on Consequences of not doing the tasks – Financial Risk over Time required to complete task are shown in Fig. 9.

The excessive corrosion at the midships region of the FPSO could result in overstressed and buckled primary and secondary structures, requiring in situ or dry-docking steel repairs leading to financial impacts. The Fig. 9 shows that the midship region need to be prioritised for maintenance and the relative order of execution at this region has become clearer from the plots, which leads to condition enhancement of the FPSO and thereby eliminating the financial consequences.

It could be observed in Fig. 9 that when the maintenance activities are prioritised solely based on the Consequences of not doing the tasks – Financial Risk, the highest priority is to allocate resources to the locations on the FPSO at a distance of 73-231m from the Aft Peak of FPSO, followed by locations 60-72.9m, 231.1-250m and so on.

When the time required to complete the maintenance activities have been considered along with the priorities based on the Consequences of not doing the tasks – Financial Risk for Full load condition of the FPSO, it could be observed that the highest priority is to allocate resources to the locations on the FPSO at a distance of 209-231m from the Aft Peak of FPSO, followed by locations 195-208.9m, 231.1-253m and so on.

When the time required to complete the maintenance activities have been considered along with the priorities based on the Consequences of not doing the tasks – Financial Risk for Medium load condition of the FPSO, it could be observed that the highest priority is to allocate resources to the locations on the FPSO at a distance of 209-231m from the Aft Peak of FPSO, followed by locations 187-208.9m, 231.1-253m, and so on.

When the time required to complete the maintenance activities have been considered along with the priorities based on the Consequences of not doing the tasks – Financial Risk for Light load condition of the FPSO, it could be observed that the highest priority is to allocate resources to the locations on the FPSO at a distance of 209-231m from the Aft Peak of FPSO, followed by locations 195-208.9m, 231.1-253m and so on.

The benchmarking of the algorithm has been carried out by comparing the resource allocations, with and without considering the time required to complete the task, which reflects influence of the time required to carry out the activity, on the prioritisation of activities.

The evaluation of the model carried out by comparing the resource allocations based on 3 different loading conditions of the FPSO – Full load, Medium load, and Light load conditions, as indicated in Fig. 9, demonstrates the performance of the greedy algorithm, in terms of the personnel resource allocation based on Financial Risk over the time required to complete tasks.

In this simulation in Fig. 10, the performance of the greedy algorithm is being evaluated in terms of the personnel resource utilisation, in terms of the weighted task completion time, based on Consequences of not doing the tasks – Financial Risk over Time required to complete tasks,

$$\sum(P[i]\ /\ T[i]) \times\ C(i)\ ,$$

where, Task Completion Time, $C(i)\ =\ \sum T\ [j]$.

The benchmarking of the algorithm has been carried out by comparing the resource utilisations, with and without considering the time required to complete the task, which reflects influence of the time required to carry out the activity, on the prioritisation of activities.

To evaluate the satisfaction of resource utilisation, it could be observed that the higher weighted sum of the completion times at as short time as possible, would lead to higher resource utilisations. The evaluation of the model carried out by comparing the resource utilisations based on 3 different loading conditions of the FPSO – Full load, Medium load, and Light load conditions, as indicated in Fig. 10, demonstrates the performance of the greedy algorithm, in terms of the variation in personnel resource utilisation, based on Financial Risk over the time required to complete tasks.

9. Analysis on maintenance priorities and productivity if no maintenance is carried out

This section evaluates the proposed Greedy Algorithm, to optimise

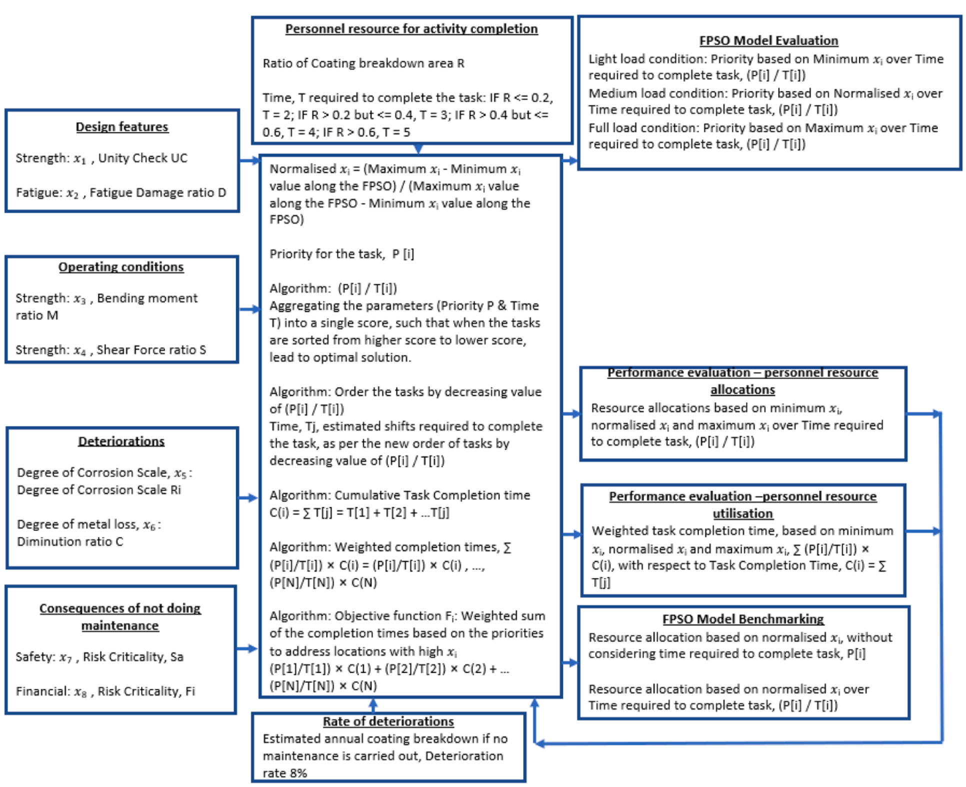


Fig. 6. FPSO system optimisation problem.

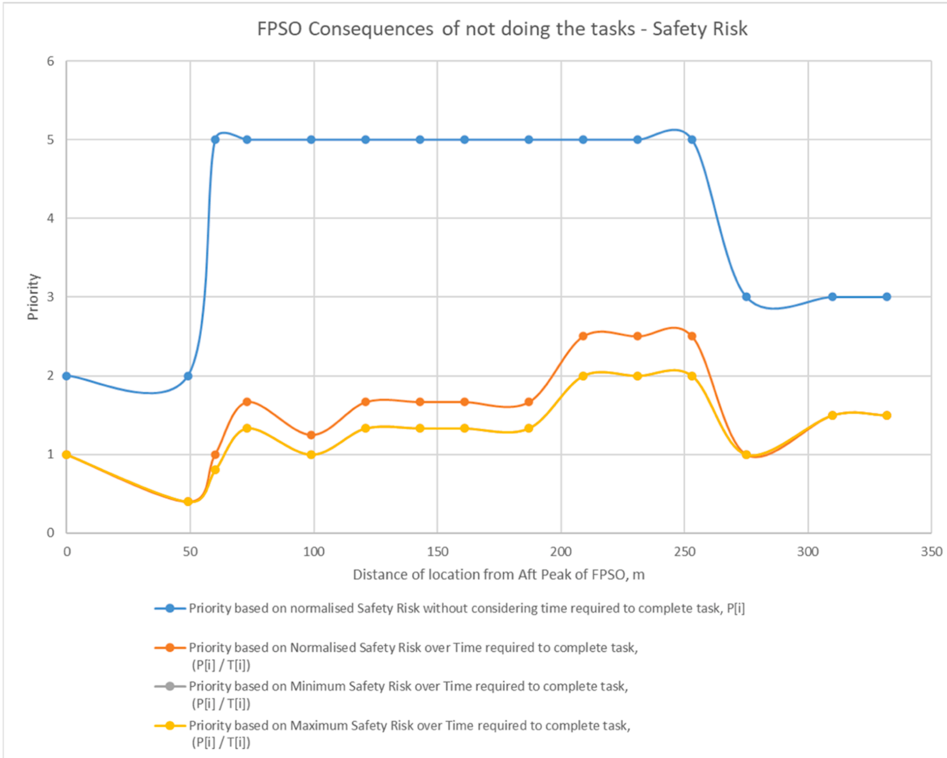


Fig. 7. Resource allocation based on Consequences of not doing the tasks – Safety Risk over Time required to complete task, $(P[i] \ / \ T[i])$.

maintenance personnel resources based on knowledge of the design, equipment condition, operating condition, deterioration mechanisms involved, rate of deteriorations, inspection, and maintenance history, involved risks. Towards this, the changes in maintenance priorities and productivity if no maintenance is carried out within a period - years' time and two years' time has been simulated and compared with the present planned priorities and productivities, taking into account the $P[i] \ / \ T[i]$ change based on change in T only, as a function of coating break down, and ignoring the effect of coating breakdown on other decision variables.

The schematic representation of the FPSO system evaluation on maintenance priorities and productivities over a period of time has been

Fig. 8. Weighted task completion time, based on Consequences of not doing the tasks – Safety Risk over Time required to complete task, $\sum(P[i] \ / \ T[i]) \times \ C(i)$.

shown in Fig. 11.

9.1. *Resource allocation based on Consequences of not doing the tasks – Safety Risk over Time required to complete task*

In this simulation in Fig. 12, the performance of the greedy algorithm is being evaluated in terms of the personnel resource allocation, in terms of the priorities based on Safety Risk over Time required to complete tasks, $(P[i] \ / \ T[i])$.

The recommended resource allocation order along the length of FPSO, based on Consequences of not doing the tasks – normalised Safety Risk over the time required to complete task has been indicated in Fig. 12. The execution priority with reference to the distance from the aft peak of the FPSO has been shown.

The simulation of predicted changes in priorities for resource allocations in a year's time and in two years' time if no maintenance is carried out has also been indicated in Fig. 12. This is based on an estimated annual deterioration rate of 8% on the coating breakdown and the corresponding impact on the resource required for completion of activity, taking into account the $P[i] \ / \ T[i]$ change based on change in T only, as a function of coating break down, and ignoring the effect of coating breakdown on other decision variables.

The changes in resource allocations and resource utilisations, if no maintenance is carried out in 1 years' time and 2 years' time has been simulated and compared with the present planned priorities and productivities based on normalised Safety Risk over the time for task completion, as indicated in Fig. 13.

The simulation of predicted changes in cost functions by way of productivity and the corresponding resource utilisations in a year's time and in two years' time if no maintenance is carried out has also been indicated in Fig. 13. This is based on an estimated annual deterioration rate of 8% on the coating breakdown and the corresponding impacts on the weighted sum of the completion times based on the priorities, taking into account the $P[i] \ / \ T[i]$ change based on change in T only, as a function of coating break down, and ignoring the effect of coating breakdown on other decision variables.

9.2. *Resource allocation based on Consequences of not doing the tasks – Financial Risk over Time required to complete task*

In this simulation in Fig. 14, the performance of the greedy algorithm is being evaluated in terms of the personnel resource allocation, in terms of the priorities based on Financial Risk over Time required to complete tasks, $(P[i] \ / \ T[i])$.

The recommended resource allocation order along the length of FPSO, based on design feature – normalised Financial Risk over the time required to complete task has been indicated in Fig. 14. The execution priority with reference to the distance from the aft peak of the FPSO has been shown.

The simulation of predicted changes in priorities for resource allocations in a year's time and in two years' time if no maintenance is carried out has also been indicated in Fig. 14. This is based on an estimated annual deterioration rate of 8% on the coating breakdown and the corresponding impact on the resource required for completion of activity, taking into account the $P[i] \ / \ T[i]$ change based on change in T only, as a function of coating break down, and ignoring the effect of coating breakdown on other decision variables.

The changes in resource allocations and resource utilisations, if no maintenance is carried out in 1 years' time and 2 years' time has been simulated and compared with the present planned priorities and productivities based on normalised Financial Risk over the time for task completion, as indicated in Fig. 15.

The simulation of predicted changes in cost functions by way of productivity and the corresponding resource utilisations in a year's time and in two years' time if no maintenance is carried out has also been indicated in Fig. 15. This is based on an estimated annual deterioration rate of 8% on the coating breakdown and the corresponding impacts on the weighted sum of the completion times based on the priorities, taking into account the $P[i] \ / \ T[i]$ change based on change in T only, as a function of coating break down, and ignoring the effect of coating breakdown on other decision variables.

10. Overall objective maintenance optimisation

The main objective of this work was to maximise the maintenance personnel resource utilisation and enable FPSO condition enhancement,

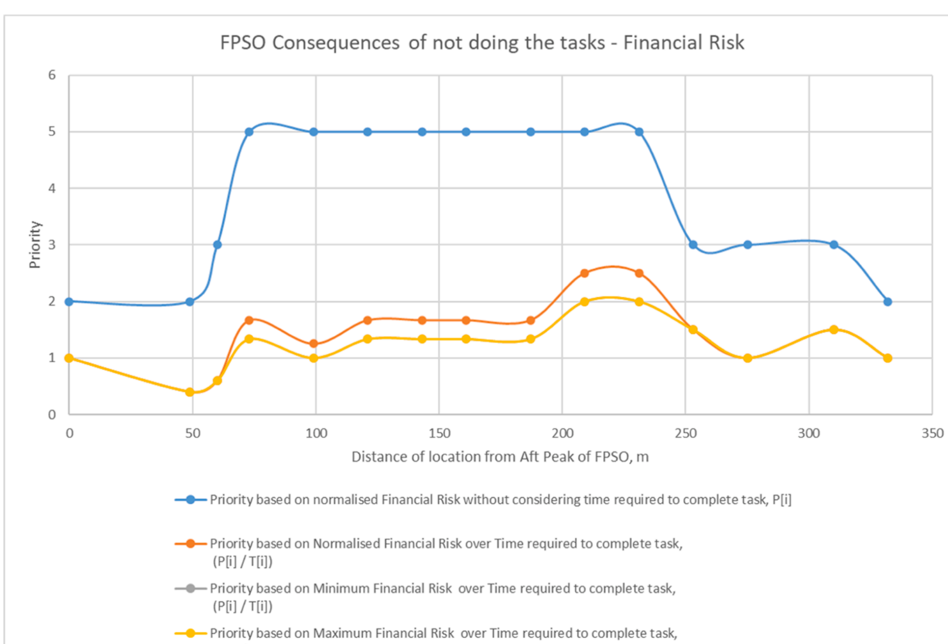


Fig. 9. Resource allocation based on Consequences of not doing the tasks – Financial Risk over Time required to complete task, $(P[i] \ / \ T[i])$.

considering the priorities with respect to design features, operating conditions, deteriorations, and the consequences of not doing the maintenance, taking into consideration the personnel resource time required for activity completion.

$$\text{Objective Function, } F_i = \sum (P[i] \ / \ T[i]) \times \ C(i)$$

where, $P[i]$ is the Priority based on the objectives, and $T[i]$ is the time required to complete a maintenance activity, and $C[i] = \sum T[j]$ the cumulative task completion time.

The objective functions F_1 ,F_2 , F_3 , F_4 , F_5, F_6 , F_7 *and* F_8 corresponding to maintenance priorities with respect to normalised Stress Unity Check $\{x_1\}$, Fatigue Damage Ratio $\{x_2\}$, Bending Moment Ratio $\{x_3\}$, Shear Force Ratio $\{x_4\}$, Degree of Corrosion Scale $\{x_5\}$, Degree of Metal Loss $\{x_6\}$, Safety Risks in the event of not doing maintenance $\{x_7\}$ and Financial Risks in the event of not doing maintenance $\{x_8\}$ respectively, taking into consideration the personnel resource time required for activity completion, were combined into an overall objective optimisation problem. Depending on the priority of the objective function when compared to other objective functions, a relative weight has been associated to the prioritised objective function, using the weighted sum approach, such that

$$\{y_i\} \ = \ \sum (\pm \alpha_i \times F_i)$$

where, α_i indicates the relative weight of the prioritised objective function when compared with the priority of other objective functions. The positive weight, *Sign* $+$, means the corresponding objective function would be maximised, and negative weight, *Sign* $-$, means the corresponding objective function would be minimised. This formulation provides flexibility to direct the focus of the overall objective function, $\{y_i\}$, towards any one or more of the objective functions by adjusting their respective weight according to the maintenance strategy followed.

The schematic representation of the FPSO system overall multi-objective optimisation problem has been shown in Fig. 16.

In the simulation in Fig. 17, the performance of the greedy algorithm is being evaluated in terms of the personnel resource utilisation, based on an overall objective function developed by linear combinations of the multiple objective functions.

The optimisation simulation results obtained for the various scenarios of priorities have been presented in Fig. 17.

In the simulation Fig. 17, the performance of the greedy algorithm has been demonstrated in terms of the personnel resource utilisation, based on an overall objective function developed by linear combinations of the multiple objective functions $\sum(\pm \alpha i \times Fi)$. This simulation demonstrates the performance evaluation of proposed multi-objective optimisation employing weighted sum approach for maintenance planning, in terms of personnel resource utilisation.

The Objective functions of the design features, operating conditions, deteriorations, consequences of not doing the maintenance have been combined in into a single objective maximisation problem using the weighted sum approach, such that depending on the priority of the objective function when compared to other objective functions, a weighting factor has been associated to the prioritised objective function. The higher weighted sum of the completion times at as short time as possible, would lead to higher resource utilisation.

It could be observed from the gradient of the simulations, when equal priorities are provided to all the objective functions, the resource utilisation is much higher than that for individual prioritisation of objective functions. Also, no significant changes to the resource utilisations have been noted when the objective functions were prioritised individually.

11. Discussion

There has been an enhanced emphasis on optimising the maintenance regimes of offshore assets and enable safe operations, whereby the emerging philosophy is to consider alternate arrangements based on the involved risks, and optimise resources without compromising safety,

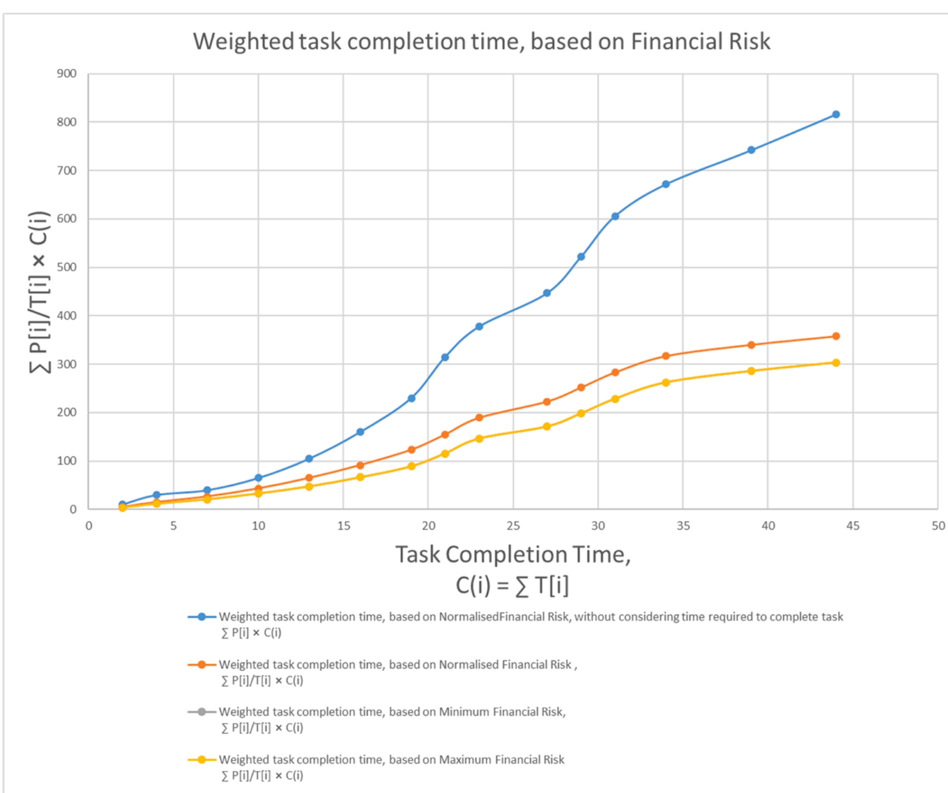


Fig. 10. Weighted task completion time, based on Consequences of not doing the tasks – Financial Risk over Time required to complete task, $\sum (P[i] \ / \ T[i]) \times \ C(i)$.

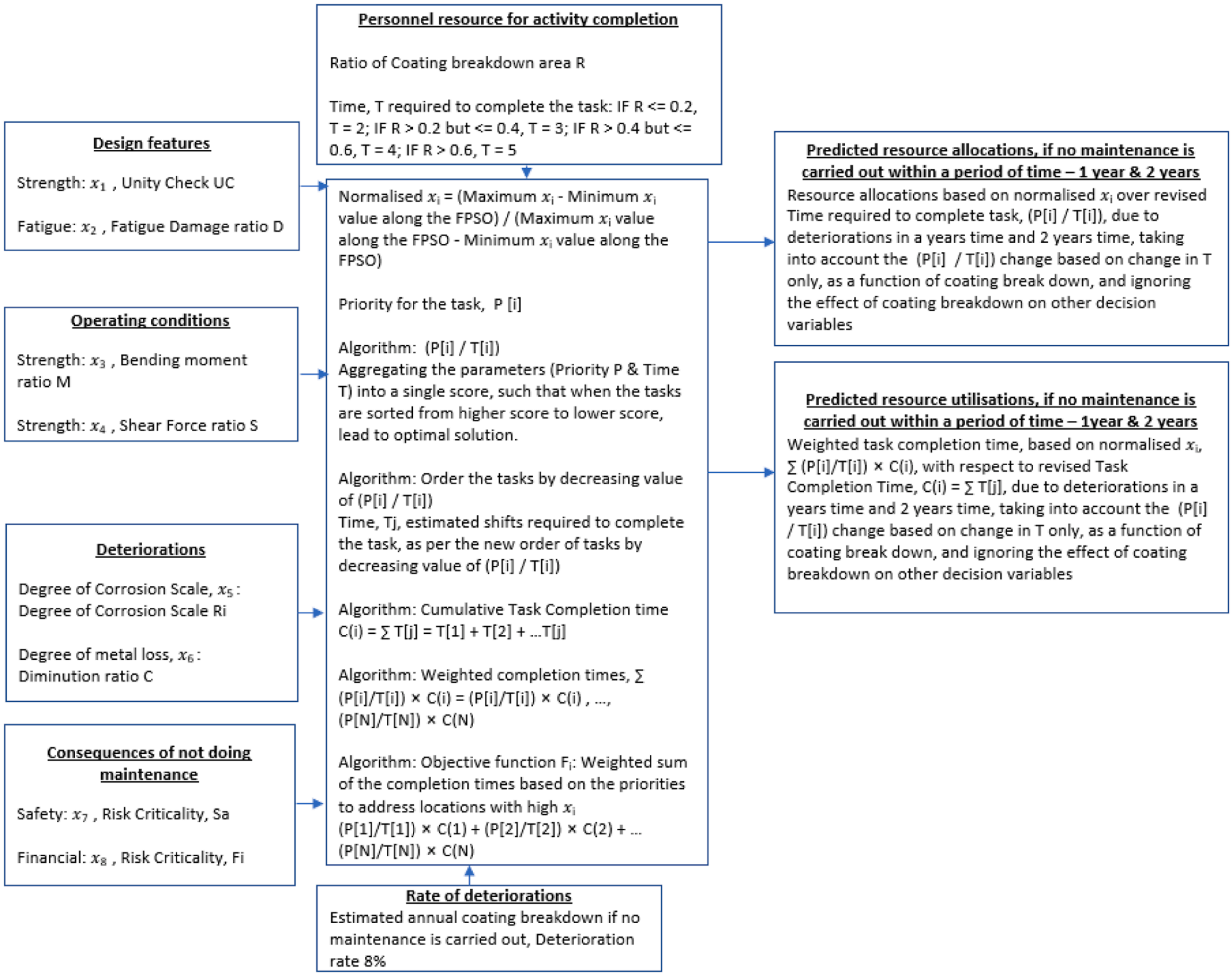


Fig. 11. FPSO system evaluation on maintenance priorities and productivities over a period of time.

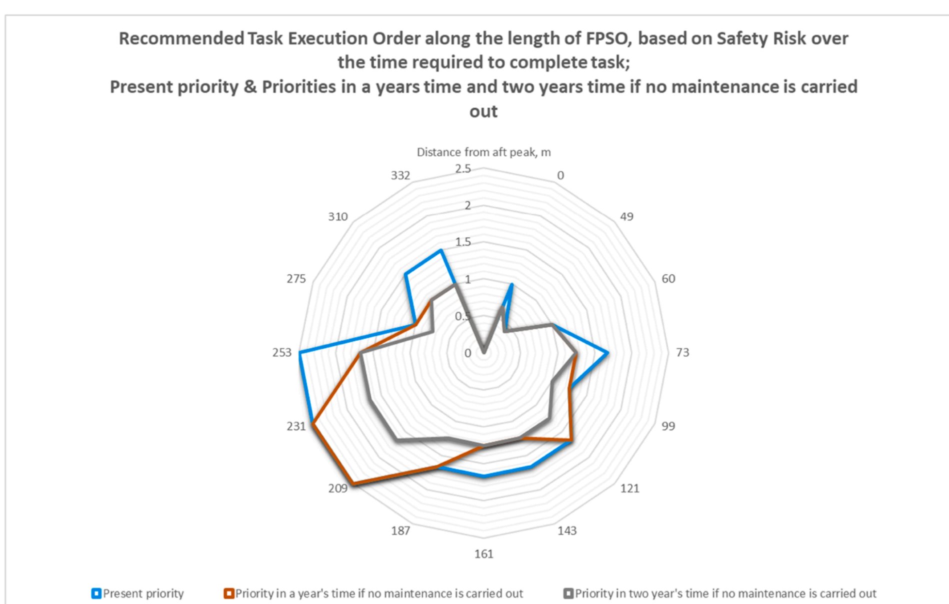


Fig. 12. Changes in resource allocations if no maintenance is carried out, based on Consequences of not doing tasks–normalised Safety Risk over time required to complete task.

Fig. 13. Changes in resource utilisations if no maintenance is carried out, based on Consequences of not doing the tasks – Safety Risk over the time required to complete task.

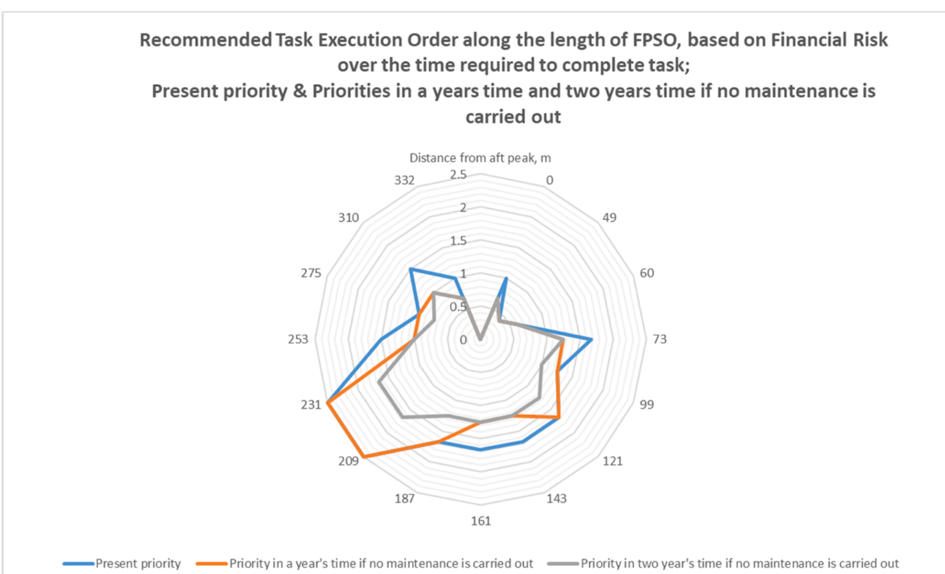


Fig. 14. Changes in resource allocations if no maintenance is carried out, based on Consequences of not doing tasks– normalised Financial Risk over the time required to complete task.

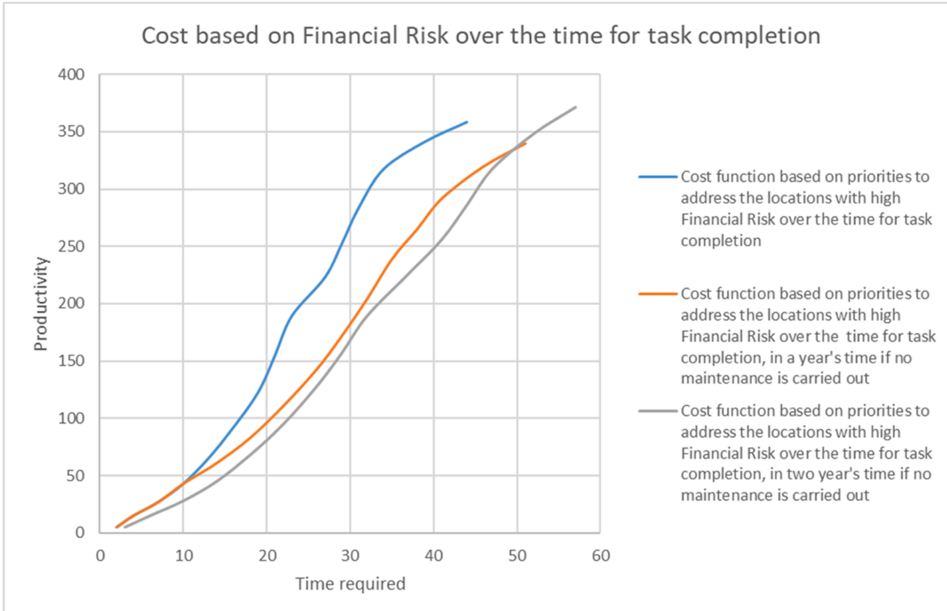


Fig. 15. Changes in resource utilisations if no maintenance is carried out, based on Consequences of not doing the tasks – normalised Financial Risk over the time required to complete task.

while maintaining or lowering the risk levels. It is to be noted that the maintenance regimes focusing on industry and regulatory requirements are developed considering the design, fabrication, and operational experiences from related assets. This in turn lead to inconsistencies governed by the site constraints and the impact of time required to carry out activities.

As a first step in overcoming this, a novel greedy algorithm has been proposed in this paper that incorporate the impact of time required to complete the activities on the optimisation objectives of FPSO design features, operating conditions, deteriorations, consequences of not doing the maintenance and the personnel resource availability for activity completion. Also, the benchmarking of the algorithm has been carried out by comparing the parameters, with and without considering the time required to complete the task, which reflects influence of the time required to carry out the activity, on the prioritisation of activities.

The evaluation of the model has been carried out by comparing the priorities for each scenario based on 3 different loading conditions of the FPSO – light load condition, medium load condition and full load condition. The performance of the greedy algorithm has been evaluated in terms of the personnel resource allocation and resource utilisation. To evaluate the satisfaction of resource allocation, the weighted sum of the task completion times based on the priorities have been considered. To evaluate the satisfaction of resource utilisation, it has been considered that the higher weighted sum of the completion times at as short time as possible, leads to higher resource utilisations.

The changes in priorities and productivity, if no maintenance is carried out in 1 years' time and 2 years' time has been simulated and compared with the present planned resource allocations and resource utilisations, taking into account the (P[i] / T[i]) change based on change in T only, as a function of coating break down, and ignoring the effect of coating breakdown on other decision variables.

Also, an overall objective optimisation problem has been proposed in this paper, by linear combinations of the multiple objective functions, using the weighted sum approach. This formulation provides flexibility to direct the focus of the overall objective function towards any one or more of the objective functions by adjusting their respective weight according to the maintenance strategy followed. This approach enables better decision making for maintenance planning as its based on the available data of design features, operational conditions, deteriorations and risks involved, whereby leading to consistency in assessments for defining the maintenance programmes that would be of more practical relevance for FPSOs that does not have Class oversights.

12. Conclusion

It has been noted that in the formulation of maintenance systems, the main influencing factors and performance indicators widely considered relates to uncertainties, failure probabilities, site constraints related to environmental factors and operations, maintenance duration, maintenance frequency, maintenance scheduling, operational conditions, and operational requirements, whereas the impact of time required to carry out activities and site constraints of available beds offshore have not been considered in the existing literature, which is a major limitation of the existing frameworks.

The influence of time required to complete the activity, on the prioritisation of activities have been demonstrated in this paper by a novel optimisation problem formulation for FPSO that maximises maintenance personnel resource utilisation and enables FPSO condition enhancement, considering the priorities with respect to design features, operating conditions, deteriorations, and the consequences of not doing the maintenance, taking into consideration the personnel resource time required for activity completion. Depending on the priority of the objective function when compared to other objective functions, a relative weight could be associated to the prioritised objective function, using the weighted sum approach, which provides flexibility to direct the focus of the overall objective function towards any one or more of the objective functions, by adjusting their respective weight according to the maintenance strategy followed, which would supplement the Regulatory oversight requirements of the FPSO.

A novel approach has been utilised to formulate a maintenance plan optimisation problem, whereby the decision variables for each location on the FPSO have been normalised between the maximum and minimum values along the length of FPSO to bring the variables related to the functionality in proportion with that at other locations along the FPSO, and to enable scaling all the decision variables and whereby their respective objective functions to the same magnitude, and allows adjusting the values measured on different scales to a notionally common scale.

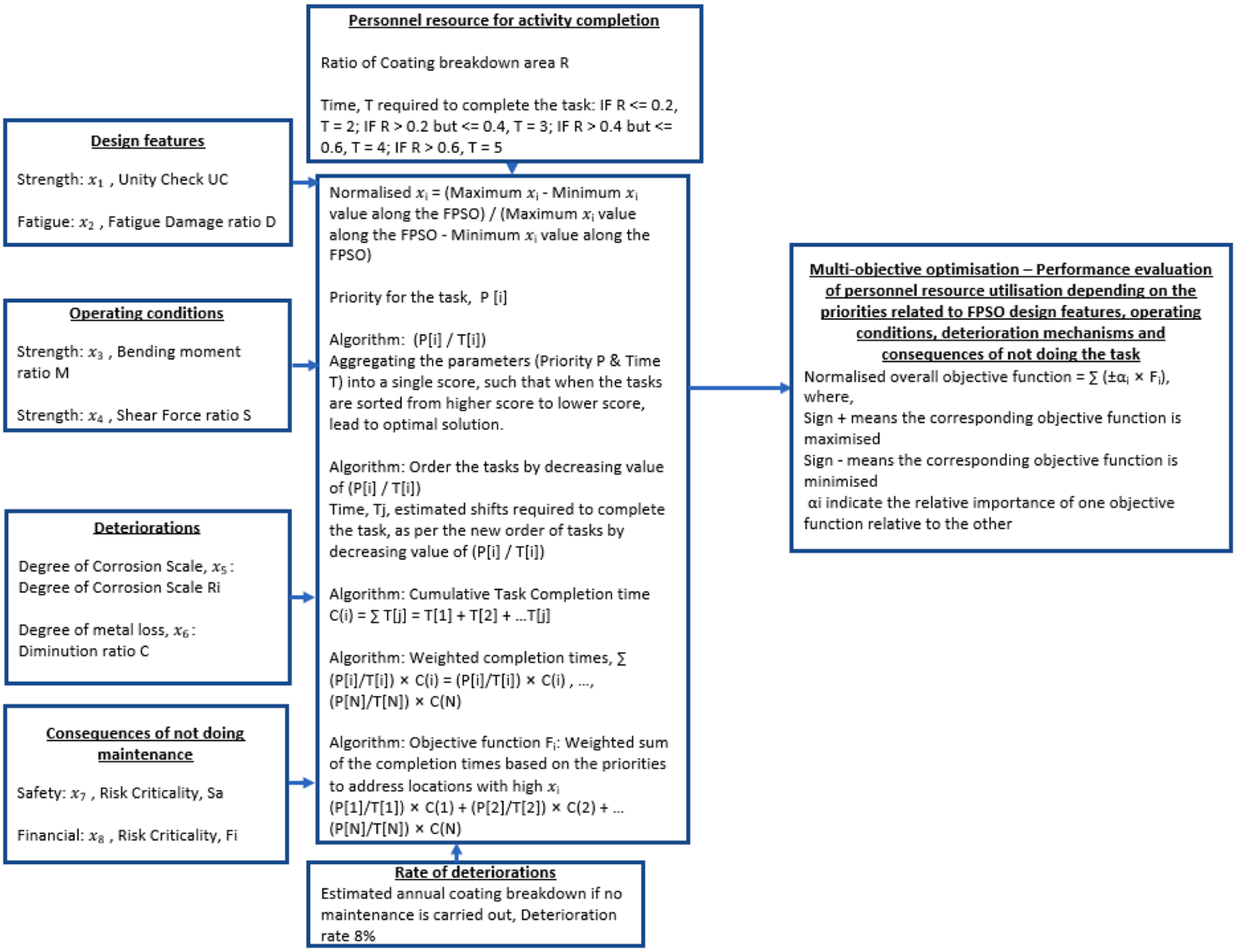


Fig. 16. FPSO system overall multi-objective optimisation problem.

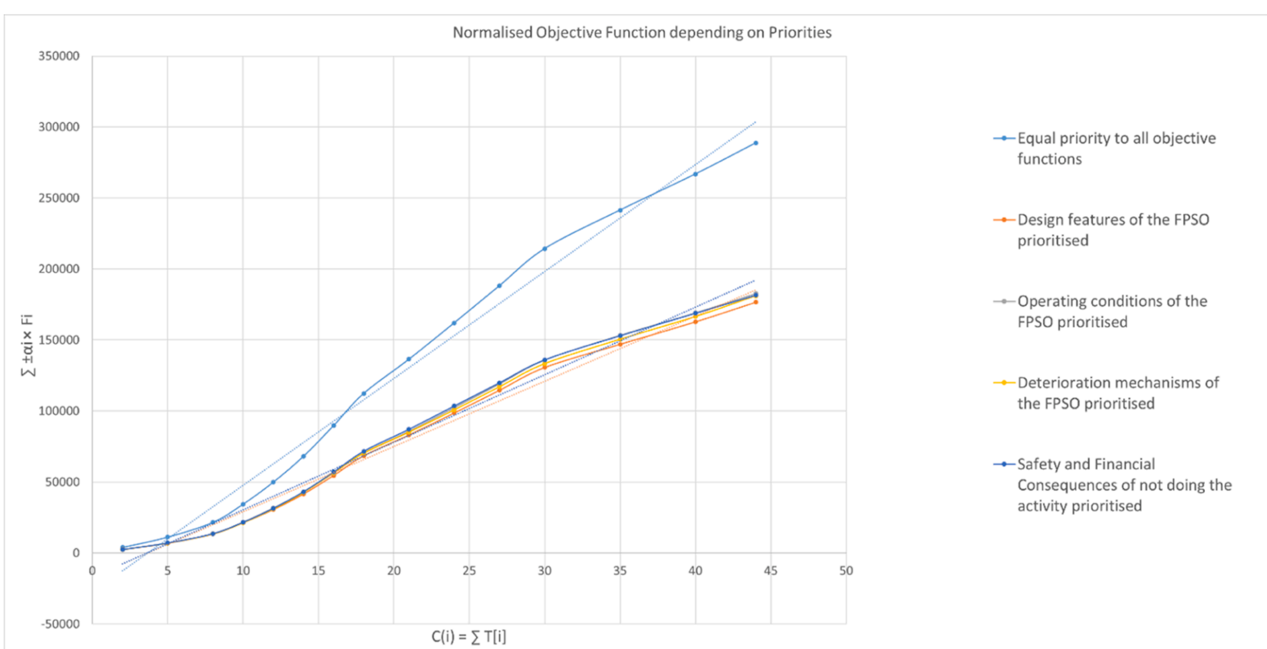


Fig. 17. Overall objective optimisation depending on Priorities.

It could be concluded that there exists scope for further research work that would incorporate impact of time required to carry out activities and the site constraints of available beds offshore, into the maintenance plan and its impact on asset condition enhancement due to the maintenance execution, to achieve the optimal maintenance system formulation.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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