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Operational failure prevention methodology for offshore systems using multiple criteria decision-making process

Keywords

AHP, modiefied FMEA, offshore operational reliability.

Abstract

A framework for decision analysis, which has been applied on an operational offshore system and is based on a multiple criteria decision making (MCDM) process, is presented in this paper. This provides a generic methodology for the evaluation of alternatives and implementation of operational and design improvements based on the experience gained from past failures. The Failure Modes and Effects Analysis (FMEA) method is modified and used as a significant criterion together with Analytic Hierarchy Process (AHP) in order to enhance the decision making process. The mathematical model of AHP identifies and combines the weight of changes, as well as the results of modified FMEA. This combination takes into account possible interactions among the causes of failure by integrating several elements, enhancing the FMEA method. Next, the paper describes a decision model that incorporates also decision maker's subjective assessments and is suitably applied to an autonomously operating floating structure. This decision making technique, enables the manipulation of both qualitative assessments and quantitative metrics in order to improve final judgments and, in general, advance the operation of the complex floating system.

1. Introduction

Environmental issues and globalization increases competition among manufacturers who increase their effort and research in order to develop high quality, cost competitive and environmental friendly systems. Along with equipment's increasing size and complexity also cost increased significantly, therefore many manufacturers around the world adopt new methods in order to improve design and ensure safety and the efficiency of operation processes and maintenance. They consider very important to reduce maintenance costs and improve operational efficiency. Additionally it is necessary to improve the adaptability and the reliability through research and development of new components and utilization of multi criteria decision-making processes.

The multi-criteria decision making (MCDM) methods are more valuable when decision-makers face complex problems with multiple conflicting and subjective criteria [1]. One of these methods is the analytic hierarchy process (AHP), which is designed to solve complex decision-making problems when there are multiple objectives or criteria to consider [2], [3].

Failure Mode and Effects Analysis (FMEA) is an important evaluation methodology, because it facilitates the identification of potential problems in the design stages or process by examining the effects of lower level failures. Additionally it is a procedure in product development and in their operation management for analysis of potential failure modes within a system. It is used as a reliability evaluation technique to determine the effect of system and equipment failures [4]. Failures are classified according to their impact on mission success and personnel/equipment safety. When used during the design stage the aim is to avoid future failures. Next it can be applied in process control, before and during ongoing operation of the process. The use of FMEA begins, ideally, at the earliest conceptual stages of design and continues throughout the lifetime of the product or service [5], [6], [7].

However, traditional FMEA has been criticized as having several drawbacks because it concentrates on the analysis of existing systems rather than proposing ways of achieving excellence in designing a system. These drawbacks are addressed in several papers. Also FMEA method is focused on the delivery of quality products (services) to its users [8], [9].

The financial impact of various possible problems in the processes is not directly considered, and therefore, it was necessary to create a method which would identify and prioritize those failures that have the biggest (financial) impact on the operation. In this way, alternatives may be evaluated on the basis of maximum financial gain. It is evident that risk priority number (RPN) values and the expected cost result in different priorities to identical failure modes, which must be taken into account in decision making. Another separate problem when using RPN values lies in the fact that failure detection value does not accurately measure the contribution to the risk [10].

In complex systems it is well established that both qualitative and quantitative judgments are required. In this context several algorithms have been developed. The analytic hierarchy process (AHP) is in our case used to produce an overall decision. Using a modified FMEA, identified in the literature as g-analysis, produces quantitative inputs, which are combined with subjective inputs in an AHP process. In AHP the final decision is reached through pair-wise comparisons. The model proposed in this paper offers a flexible and intelligent approach for appropriate improvements in an offshore platform. Multiple criteria decision making has been applied to maintenance problems and FMEA has provided feedback for new design processes [11]. Further on FMEA has been suitably applied in offshore structures reliability improvement [12]

2. Methodology

2.1. Analytic hierarchy process

AHP was developed at the Wharton School of Business by Thomas Saaty, and allows decision makers to model complex problems in a hierarchical structure showing the relationships of the goal, objectives (criteria), sub-objectives, and alternatives. Also uncertainties and other influencing factors can be included [13], [14] [15].

AHP is built on a solid yet simple theoretical foundation. The basic 'model' is a hierarchical chart of components depicted in boxes. The top box of chart represents the goal of the decision problem, and splitting in lower levels boxes represents an objective contributing to the goal. Each box can then be further decomposed into lower level boxes, which represent sub-objectives. And so on. Finally, boxes corresponding to the lowest level sub-objectives are broken down into alternative boxes, where each alternative box represents how much the alternative contributes to that sub-objective. By adding up the priorities of the boxes for the alternatives, we determine how much the alternatives contribute to the objectives. Thus AHP is based on three basic principles: decomposition, comparative judgments, and hierarchic composition or synthesis of priorities [1], [16].

When decomposition is applied to a complex structure, then hierarchically clusters, sub-clusters, sub-sub clusters are created. Then the principle of comparative judgments is applied to conduct pairwise comparisons of all combinations of criteria in a cluster with respect to the parent of the cluster. These pairwise comparisons are used to derive 'local' priorities of the objectives in a cluster with respect to their parent. The principle of hierarchic composition or synthesis is applied to multiply the local priorities of objectives or criteria in a cluster by the 'global' priority of the parent objectives, producing global priorities throughout the hierarchy and then adding the global priorities for the lowest level alternatives.

All theories are based on axioms; and originally AHP was based on three relatively simple axioms. The first axiom, the reciprocal axiom, requires that, if a parent criterion $PC(A_A,A_B)$ is a paired comparison of alternatives A and B with respect to their parent, criterion C, representing how many times more the alternative A possesses a property than does alternative B, then $PC(A_B,A_A) = 1/ PC(A_A,A_B)$. The second, or homogeneity axiom, states that the elements being compared should not differ too much, otherwise there will probably be larger errors in judgment. When constructing a hierarchy of objectives, one should attempt to arrange criteria in a cluster so that they do not differ by more than an order of magnitude. The AHP uses judgments to estimate dominance in making comparisons. The scale of relative importance ranges from 1 to 9, or about an order of magnitude, using Saaty's (1980) predefined ratio scale as listed in *Table 1*. The numerical and graphical modes of Expert Choice accommodate almost two orders of magnitude, allowing a relaxation of this axiom. Judgments beyond an order of magnitude generally result in a decrease in accuracy and increase in inconsistency.

Table 1. Fundamental Scale of Absolute Numbers [1], [17].

Intensity of importance	Value description	Explanation
1	Criterion i and criterion j are of equal importance.	Two activities contribute equally to the objective.
3	Criterion i is weakly more important than criterion j.	Experience and judgment slightly favor one activity over another
5	Criterion i is strongly more important than criterion j.	Experience and judgment strongly favor one activity over another.
7	Criterion i is very strongly more important than criterion j.	An activity is strongly favored and its dominance demonstrated in practice.
9	Criterion i is absolutely more important than criterion j.	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between the two adjacent values.	When a compromise in judgment is needed.

The third axiom states that judgments about, or the priorities of, the criteria in a hierarchy do not depend on lower level criteria. This axiom is required in order that the principle of hierarchic composition correctly applied. While the first two axioms are always consonant with real world applications, the third axiom requires careful examination, as it is not uncommon to be violated. Thus, while the preference for alternatives is almost always dependent on higher level criteria, the objectives and the importance of the objectives might or might not be dependent on lower level criteria, alternatives.

AHP allows for the application of data, experience, insight, and intuition in a logical and thorough way, the ranking, the resource allocation and the benchmarking. Also, AHP enables decision-makers to derive ratio scale priorities or weights as opposed to arbitrarily assigning them. In this way, AHP not only supports decision-makers by enabling them to structure complexity and exercise judgment, but also allows them to incorporate both objective and subjective considerations in the decision process [1].

2.2. Modified FMEA and g-analysis

The failures that occur in a structure or in the individual components of a system need to be recorded and assessed in order to perform a reliable evaluation. The use of AHP in combination with FMEA provides an enchase evaluation method. But the combination of these methods needs a modification of FMEA to achieve direct insert values of RPN result to AHP, because the data from individuals RPN numbers and the total RPN normally take values between 1 and 1000. In this case for inserting that data to AHP it must be reduced to a value between 0 and 1. This is done by using a logarithmic function to the result of a normal RPN [18].

The principle of the FMEA remains the same to find RPN for a given component or overall system. The modifications that apply to FMEA achieve to prepare the values after the first calculation of the cause of the failure occurring and with a second calculation relating the RPN, the data is entered into the AHP. The analysis at this stage modifies the normal FMEA. The individual RPN is modified to an overall average RPN for all failure effects. Also a new column is added to the FMEA table for the probability of the cause of the failure to occur. This is called the probability product and is assessed on a scale of 1 to 10. The probability product results are given by using the formula (1):

$$\text{Prob. } product = \frac{\text{Prob. } of\ cause}{10} * \text{Prob. } of\ the\ effect \qquad (1)$$

A new modified RPN (the *rpn* in table) is given by multiply the Probability product with *Detection rate* and *Severity*, which allows *rpn* to be given for each failure effect that takes account of the Probability of the cause.

$$rpn = Sever. * Detect.\ rate * \text{Prob. } product \qquad (2)$$

The average of these modified rpn_{av} (the summary of *rpn* divided by components) is used in the following formula (3) of g-analysis and the result is inserted directly into AHP as criterion.

$$g = 1 - \left[\frac{\log_2(rpn_{av}+1)}{10}\right] \qquad (3)$$

To perform the solution of formula *g*, use the value of rpn_{av} with a base of logarithm ~2 in the second part of the formula. By this $\log_2(rpn_{av}+1)$ the value range of the output is reduced from the average in a range between 1 and 10, and then divided by 10

gives the requisite value in a range between 0 and 1. The addition of 1 to rpn_{av} value prevents the case where a log of 0 must be calculated.
The insertion of result *(g)* is done to AHP as a criterion. Next the assessing is done as in a normal model with the weighting of its importance being decided through the use of pair-wise comparisons. Therefore, in case the qualitative data are considered very important then g will have a high weighting; if not the weighting should be lower.

3. AHP and FMEA for floating structure

The components and the systems on a floating offshore structure are numerous, complex and they must comply with a reliable operation and should be economically viable. Also the prevention of conflict with other sea space users, the forecast to avoid hazardous situations like releases from leaks of liquids used in those systems and the positive or negative impacts on marine habitat etc., must be considered with the same attention. These considerations need to combine both quantitative and qualitative judgments which are applied and combined in the AHP [19], [20].

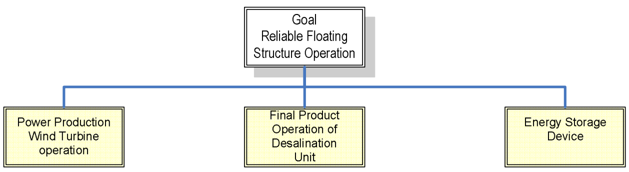

Figure 1. AHP goal Reliable Floating Structure Operation

The construction of the hierarchy for the offshore floating structure fig. 1 was made in respect to the main factors influencing the reliable operation of the structure. The main components which relate for a reliable operation are:

- The power production unit, consisting of a wind turbine power generator and a photovoltaic system.
- The final production, which depends on the available power supply in order to operate the desalination system that produces potable water.
- The energy storage devices for safe supply of critical equipment and as a power supply for short time to handle wind speed variations.

The power supply to the desalination plant comes mainly from the wind (and Photovoltaic systems for the exploitation of solar energy). Thus no energy from the shore power network or any other type of generator diesel is used. This means that although we have a power source without a fixed frequency and voltage, the electrical system components, create a circuit suitable for stable operation of all equipment, despite significant differences in wind speed. The wind turbine produces and distributes, through advanced electrical and electronic components of energy conversion, the power required to drive the reverse osmosis sea water desalination [21].
The goal for the framework model is to demonstrate the influence of the criteria of the given alternatives. To illustrate the difference from inserting the results of modified evaluation technique FMEA and the influence of each criterion in each section of floating structure, and thus the influence of the different criteria in the reliable operation. The criteria, sub-criteria and alternatives can be also split into more criteria and alternatives.
The following shortened version refers to the evaluation with use of FMEA to a floating desalination unit. The initial step was to identify the components of the system that was to be analyzed. The evaluation and the ranking follow the normal FMEA technique with judgments to the severity of each effect, the probability of each cause, the detection rate and the probability of each effect. According to the aforementioned method one more column entered for the calculation of Probability product and the column *rpn* supplemented with modified RPN with respect to probability product which are shown in *Figure 1*. The detection rate ranking is 10 in accordance to the automated operation. The data presented in *Table 2* is based on recorded failures of five years operation of the system.
The research advises to consider the possible inter-dependence between the failure cause and current control pattern, and the inner dependence between current control method and failure cause. However, the use of AHP method as assessment method may effectively improve the arisen defects from the use of FMEA only as evaluation method. The synthesis of both qualitative and quantitative judgments produces an enhanced decision making tool. It is also proved that by improving the priority of RPN, not only the risk of individual failure modes is improved, but the overall risks reduced effectively. Therefore the method is more effective than traditional RPN method.

4. AHP Synthesis and alternatives

Concerning the construction of hierarchy in the following version shown in *Figure 2* regarding the operation and potable water production of the desalination unit, the goal was assessed using the following criteria:

Table 2: FMEA and modified *rpn*. (adopt by authors)

System part	Function	Failure mode	S (Severity rating)	Cause(s) of failure	O (Occurrence rating)	Occurrence/Probability of effect	Detection method/ Current controls	D (Detection rating)	Probability Product	modified *rpn* (Risk priority
Air compressor	supply air to open air motivated valves	air compressor no rotation or no air supply	9	electrical or mechanical failure	5	10	PSA	10	5	450
PSA (Pressure Air Switch)	observe air pressure supply to valves and EPFD	fail to observe the pressure decrease	7	defective PS	1	10	observe from control panel	10	1	70
Sea Water inlet valve	supply sea water	no open/ no sea water supply	8	no air supply to open valvestack valve from corrosion	1	10	FI1,PS1	10	1	80
(FWF): Sea water inlet filter before feed pump	clean & supply sea water	no water across filter	4	dirty filter	3	10	FI1,PS1	10	3	120
Sea water feed pump (SWFP)	supply sea water	feed pump no rotation or no water supply	8	electrical or mechanical failure	2	10	FI1,PS2	10	2	160
Sand Filter (SF)	clean & supply sea water	no water across filter	3	dirty filter	0	1	FI1,PS1	10	0	0
PT: Compares pressure before sand filter and after filter 1,2	observe press before and after filters	fail to observe the press difference	8	defect PT	0	1	FI1 PS1	10	0	0
Filter 1	remove dirty after SF	no water across filter	3	dirty filter	2	1	PT, PS1,FI1	10	0,2	6
VA1 : Valve after No1 filter	supply sea water to HPP	no open	5	no air supply to open valve	0	1	PT, PS1,FI1	10	0	0
Filter 2	remove dirty after SF	no water across filter	3	dirty filter	3	1	PT, PS1,FI1	10	0,3	9
VA2: Valve After No2 filter	supply sea water to HPP	no open	5	no air supply to open valve	0	1	PT, PS1,FI1	10	0	0
FI1: inlet water flow indicator	observe flow rate	fail to observe flow rate	3	defect, dirty FI1	0	1	PS1	10	0	0
PS1 : Activate by water pressure before HHP	observe pressure before HPP	fail to observe the pressure increase	8	defective PS1	2	10	PS2, FI2	10	2	160
TI1: feed water temperature	observe water tempreture	fail to react water temp rise	9	defective TI1	0	1	observe in control panel	10	0	0
NI1: inlet water conductivity meter	observe water salinity	fail to react water salinity	7	defective NI1	0	1	observe in control panel	10	0	0
High Pressure Pump (HPP)	supply sea water to RO	HPP pump no rotation	8	electrical or pump failure/ belt broken	5	10	PS2	10	5	400
Excessive Press Fluctuation (EPF) DUMPER	reduce fluctuation to system press after reciprocating HPP	no open	4	stack valve from corrosion	0	1	PS2	10	0	0
PS2: control operating pressure	observe RO operating pressure	fail to observe the pressure rise	6	defective PS	0	1	PS4, FI3, PS3	10	0	0
Reverse Osmosis (RO)	clean sea water to potable	mebrane fail	9	ruins or dirty membranes	8	9	PS3, PS4, NI2, FI3	10	7,2	648
PS4: discharge brine press	observe brine press	fail to observe pressure fluctuation	8	defective PS	0	10	PS3	10	0	0
MV2: closed at normal operation, opens when ERD fail	closed to supply brine in press to work ERD	no closed	9	motor failure	1	10	PS3, PS4	10	1	90
VA3: this valve open for feed water the Energy Recovery Device	supply sea water ERD for feed RO	no open	5	no air supply to open valve	0	10	FI2	10	0	0
Energy Recovery Device (ERD)	use the dump press energy of brine disharge from RO to Increase the feed	no rotation	7	mechanical failure to ceramic rotating impeller	0	10	FI2	10	0	0
MV1: Opens and control press when working ERD	control press when working ERD	no open	7	motor failure	0	5	PS3, PS4	10	0	0
FI2: flow indicator after REC	observe flow rate	fail to observe flow rate	5	dirty FI2 defective FI2	0	1	observed of control panel	10	0	0
Boosters pump (BPP)	increase the press of water supplied from ERD	BPP pump no rotation	7	electrical or mechanicalfailure	5	10	PS2	10	5	350
FI3: flow indicator at pure water line	observe flow rate	fail to observe flow rate	6	dirty FI3 defective FI3	0	1	PS3, observe control panel	10	0	0
PS3: Permeate water press stop plant above 3 bar	observe potable water press	fail to observe pressure rise	9	defective PS3	0	5	FI3, PS4, observe of Control panel	10	0	0
TI2: permeate water temperature	observe temperatur of permeate water	fail to observe temperature rise	9	defective TI3	1	1	observe from control panel	10	0,1	9
NI2: inlet water conductivity meter	observe water salinity	fail to observe water salinity rise	9	defective NI2, dirty NI2	1	1	observe from control panel	10	0,1	9
									Total rpn	2561

- Safety. Relates to the operation, the location and the maintenance program safety. Concerns accessibility, usability, maintenance program and the relationship with safety issues.
- Environmental. Will the construction be environmental friendly? The rise of national concerns for the environment and quality of life indicates the compatibility of the system with strictly environmental standards.
- Economy. Will the structure be economically viable?
- FMEA. *g*, where the assessment is entered directly unlike with the other criteria which are posed in pair-wise comparisons that are made at a later stage

The sub criteria which are required to perform this framework of AHP, and entered in the model are:

Safety, sub criteria:

- Location/ accessibility include i.e. the location of foundation, the interaction with other sea users, which include the waters near the coast where other ships are likely to run around, the personnel accessibility, and the logistics.
- Maintenance frequency, concerning the technical requirements, the survey program, the repairs, for the efficiency operation of the structure.
- Leakage, it relates to the leakage preventing satisfaction in accordance with the requirements.

Environment, sub criteria:

- Impact of Operation in relation with environment, like the operational program, the disposal of produced products, the selection of location of foundation and the disturbance of residents or other disturbing factors.
- Human factor, concerning the habitability, the usability, the ergonomics, the working conditions, which are affected by the movement of the floating structure since waves and can cause injury to persons and damage systems, etc.
- Lifetime utility, in respect through the operational lifetime of the structure.

Economy, sub criteria:

- Life cycle cost, is the cost of the total system over its projected life. This figure includes construction cost, general and administrative (G&A), personnel, maintenance cost, spare parts and related costs.
- Availability, which represents the services periods, downtime periods, mean times between failures etc.
- Performance, according to available funds and the expectations from the system operating conditions.

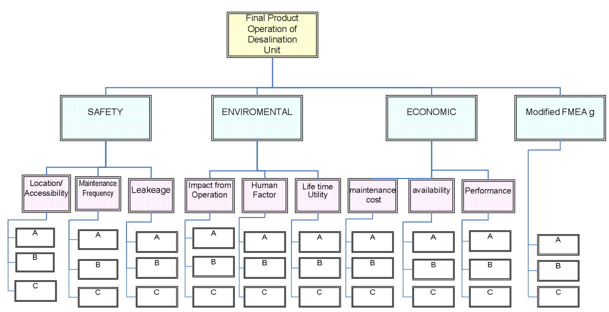

Figure 2. AHP Synthesis and alternatives

The proposed alternatives provide an overview of the operational decision between:

A. To increase (maximize) the productivity, in our case 25%. This could be achieved by the installation of the system to a higher energy potential location, probably with accessibility difficulties, bigger loads to wind turbine, and the adaptation of an operation algorithm to maximize available energy utilization, which however leads to more start-stop of desalination system, more charge-discharge cycles in energy storage device, and increase in the frequency of repairs.

B. Maximization of the life time and minimization of costs. This requires to function in a manner, which includes smoother operation, less start stops, fewer discharge cycles and reducing maintenance cost, with more repairs instead of replacements. This may reduce productivity by 25%.

C. The conservation of current operational conditions, according to the variation of citizens needs in the region of system installation.

Each judgment is made with respect to the alternatives while taking into account past failures and requirements of system operation with grate care, because they are factors that will influence the decisions and the actions that have to be made for reliable operation.

The analytic hierarchy process (AHP) mathematical solver, runs to synthesize the results and normalize the values. The g value which was added to the AHP at this stage allows the software to take it into account when synthesizing the results.

The compositions of the representative model illustrate the alternative B as the best with total value 0.4059 *Table 3*. The alternative B represents the reducing of productivity as the proposed favorable alternative.

In the same table illustrated that the second favorable alternative is current operation, where safety and environmental considerations take higher value.

The last one is the alternative A, where the operational handling maximizes productivity.

Such results could be enhanced by more detailed study of the measured failure rates in individual subassemblies, further operational research like the introduction of more options and further judgments that may change the current results.

5. Conclusions

The decisions to renewable energy structures development comprise considerations for environmental protection and management. Even

Table 3. The results for choose the best alternative.

	alternative	A	B	C	TOTALS		
SAFETY	location accesibility	0,0058	0,0499	0,0506	0,1063	0,2131	1
	maintenance frequency	0,0051	0,0346	0,0173	0,0570		
	leakege	0,0028	0,0350	0,0121	0,0498		
ENVIROMENT	impact from operation	0,0660	0,0133	0,0312	0,1105	0,3477	
	Human Factor	0,0099	0,1066	0,0454	0,1619		
	life time Utility	0,0058	0,0501	0,0194	0,0753		
ECONOMIC	maintenance cost	0,0065	0,0346	0,0717	0,1128	0,2491	
	Availiability	0,0484	0,0059	0,0147	0,0690		
	Performance	0,0450	0,0059	0,0164	0,0673		
	FMEA g analysis	0,0571	0,0701	0,0628	0,1900		
	TOTAL	0,2525	0,4059	0,3416	1,0000	1,0000	

more the attitudes and judgements for the project, in long-term provide help and assist social and economic growth.

The important in decision making process is to produce answers that are valid in practice. The AHP is a useful way to deal with complex decisions that involve dependence and feedback analyzed in the context of benefits, opportunities, costs and risks.

The methodology application to project development and operation, evaluates the efficient allocation of resources, reduces the energy consumption, and provides a mechanism to achieve effective usability and efficiency. Also it embodies adequately and readily considerations in a single tool to assist the overall assessment.

In this paper the failures that are gathered and evaluated by the FMEA method are analyzed. First the calculation of probability of the cause of the failure occurring was done and then RPN data was prepared for entry into the AHP. The results of the modified *rpn* were entered directly in AHP process to be compared with other criteria that have been arranged in a hierarchical tree. The use of the AHP as it has been applied literally to hundreds of examples both real and hypothetical, will allow a fully documented and transparent decision to be made with full accountability. The results and the information synthesized to determine relative rankings of alternatives and both quantitative and qualitative criteria are compared by using judgments to derive weights and priorities.

The case study is concentrated on implementation of the model at the desalination system of the structure, and after performing the analysis the subsequent evaluation ensures if the current decision can be robust. In future work the implementation of this model can compare the whole system with more alternatives. Also the applications of a sensitivity analysis could enchance the AHP results and provide further advice to decision makers.

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