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Risk Analysis of Wave Energy Converter System Using Failure Mode and Effect Analysis

Okoro, U. *[1], Adedipe, O.[2], Bori, I.[3], Usman, F.J.[4], and Diugwu, I.[5]
[1,2,3,4] Department of Mechanical Engineering, Federal University of Technology, Minna, PMB 65, Minna Nigeria
[5]Department of Project Management Technology, Federal University of Technology, Minna, PMB 65, Minna Nigeria
Corresponding author's email: u.g.okoro@futminna.edu.ng

Abstract

This study reports the development of the reliability analysis of a wave energy converter system. It covers the description of a generic wave energy converter with emphasis on the functions of components, the development of the reliability methodology based on Failure mode and effect analysis (FMEA). The highlight of the study is the evaluation, by a team of experts, of the functional failures of the selected components based on risk factors of the probability of occurrence, the severity of consequence and detectability. These evaluations form the basis for the calculation of the Risk Priority Number (RPN): an index representing the risk-held in each of the identified functional failures. The analysis revealed five critical components, namely hydraulic fluid (1000), filter (900), valves (800) and oil reservoir (560) and pressure line (700), whose failure holds about 80% of the total risk exposure of the system. The result of the study can serve as decision support towards - product improvement for emerging technologies as well as towards maintenance prioritisation (management) for existing technologies.

Keywords: *Reliability, Wave Energy Converter, Decision support, Maintenance management*

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1. Introduction

There are many reasons why engineers use risk analysis in design. Probably the most compelling of all is for continuous product development (PD). Technology evolves leading to the development of new materials and new processes which, in turn, are reviewed not only in the context of how they can improve the quality and reliability of new and existing products but also understanding how they can perform against known and emerging hazards and threats. This is the "continual improvement philosophy." Other reasons for which risk analysis may be applied in engineering practices include but not restricted to desire for improve competitive positioning, optimize maintenance and minimize operating expenditure, improve warranty and reduce service cost (Cabanes *et al.*, 2017).

On the other hand, the world continues to experience increasing demand for energy with a preference for non-fossil fuel-based options. Efforts have been geared towards a form of devices that will harness the abundant free Ocean energy. Ocean energy resources include Ocean surface waves, tidal currents, tidal range, deep ocean currents, thermal gradients, and changes in salinity. The Ocean energy converters are technologies employed to harness the renewable energy inherent in these resources into a useful form - typically, electric power (Mofor *et al.*, 2014). These technologies include wave energy converters (WEC), tidal stream converters, deep ocean current devices, etc. Wave energy technology operates on a simple principle that harvest ecologically non-intrusive energy directly from ocean currents (Okoro and Kolios, 2016; Kenny *et al.*, 2017; Do *et al.*, 2018; European Commission, 2018; Kara, 2018). Besides the simplicity of operation, wave energy technology also has other endearing qualities which other renewable sources do not have. Some of these qualities are security and diversity of supply, intermittent but predictable and limited social and environmental impacts (Mehmood *et al.*, 2012). These have triggered growing interest in wave power technology over the years from policy makers, industries and academia and (Mofor *et al.*, 2014). In addition, many researchers reported that the aggregate global annual potential of different ocean energy resources is significantly in excess of the global annual electricity demand. As a result, many countries around the globe aim to utilise ocean energy sources of power generation (Melikoglu, 2018). However, these emergent ocean wave energy technologies are all under development and consequently there is no database developed so far for information on their operating reliabilities (Magagna and Uihlein, 2015; IRENA, 2018; Pisacane *et al.*, 2018; Watson *et al.*, 2019). Reliability of wave energy converter is extremely difficult to assess due to very limited field experience and confidentiality issues - relating to the emerging stage of development of the sector. Many reports have shared views of major stakeholders on why the situation had persisted with most pointing to "early development threshold" which constrains developers to use more reliable data from the accumulated experience in similar technologies such as wind turbines (Hill *et al.*, 2009; Myrent *et al.*, 2013; Dao and Crabtree, 2019) instead. Others cited the harsh marine environment and restricted accessibility for maintenance as some of the factors. Some of the popular databases for renewable energy technologies as found in Europe and America are Onshore and Offshore Wissenschaftliches Mess- und Evaluierungs Program (WMEP), Landwirtschaftskammer Schleswig-Holstein (LWK), Technical Research Centre of Finland, Sandia National Laboratory (SNL) Crew Database, DNV-KEMA, and GL Garrad Hassan.

With the objective to understand and increase the reliability of wave energy converters, this study aims at developing a reliability methodology based on FMEA methodology with inputs from experts' tacit knowledge and existing literature. The result of the study is targeted at further exposing potential functional failures in the operation of wave energy technologies with the aim to stir up ideas/recommendations for control (Ratnayake, 2012) and leading to a reduction in uncertainties of the business models.

2. Materials and methods

2.1 Material

The material of the study is a wave energy converter presented in Okoro et al. (2015). The components are identified as follows: Double rod-double acting cylinder (1), Shut-off valve (2), Flexible connection (3), Pressure gauge (4), Gas accumulator (5), Position directional control valve (6), Switch (7), In-line Filter (8), Solenoid operated variable flow control valve (9), Variable flow control valve (10), Directional Control Valve (11), Pressure relief valve (12), Hydraulic motor (13), Generator (14), Reservoir (15), Load pressure control valve (16), Check valve (17), Oil tank (18), Hydraulic pump (19), Directional control valve (20), Double pilot operated check valve (21), and Non-Compensate flow valve (22). A typical WEC system has the arrangement shown in Fig. 1.

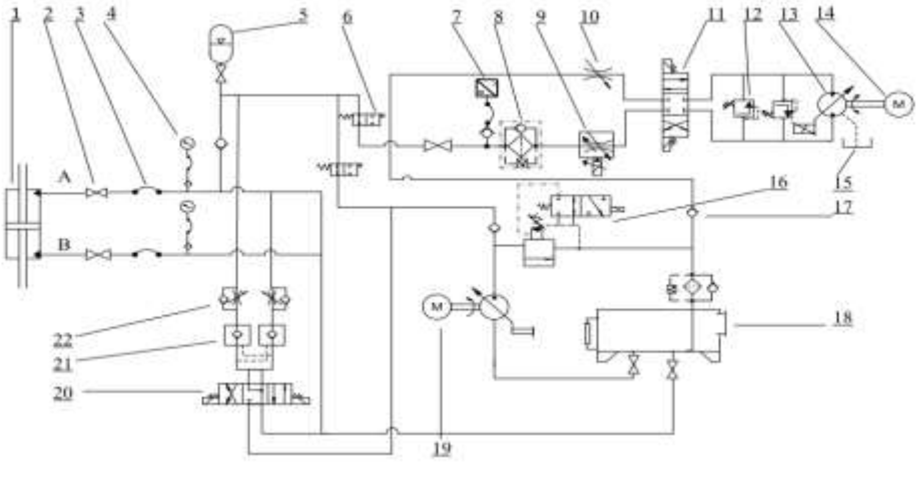
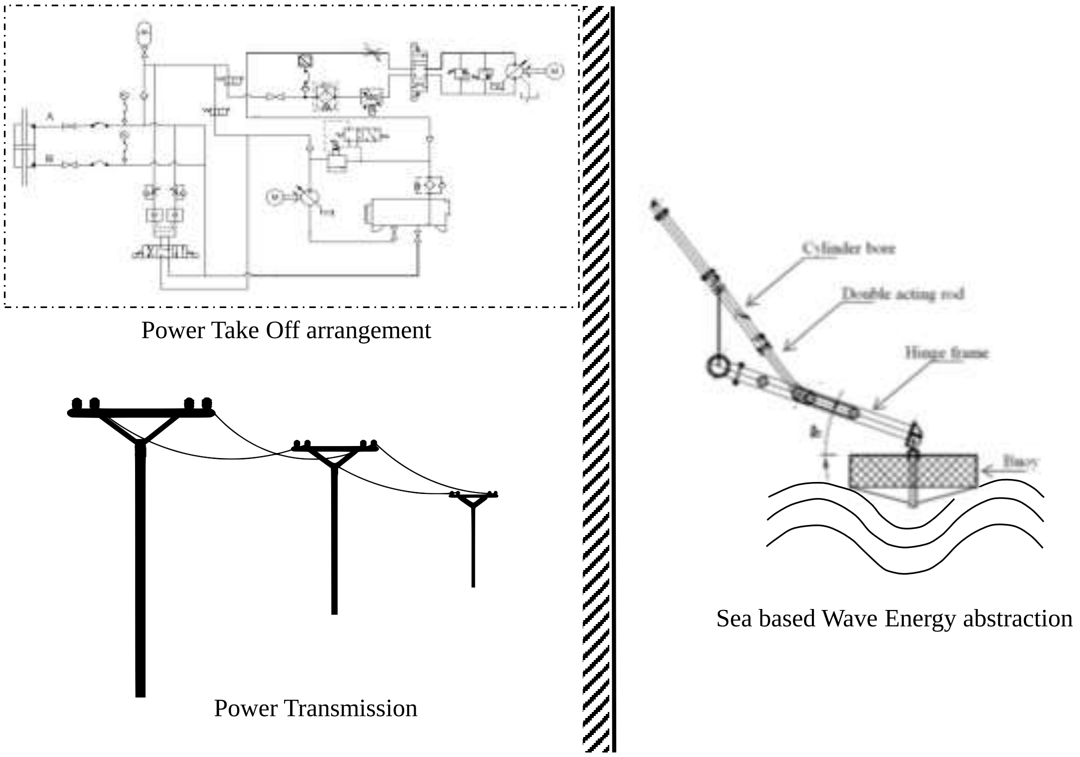


Fig. 1: Schematic diagram of Hydraulic PTO based on ISO 1219

2.1.1 Description of working of wave energy converter system

A systematic way to establish the working of a WEC is through functional analysis. Internal functional analysis can actually identify the functions accomplished by the components of the system. These functions as identified for a WEC system can be summarized under three categories, namely wave power intake, power take-off (PTO) and power transmission as shown in Fig. 2. However, the scope of the work presented in this paper is limited to the power intake and take-off of the WEC system.



Power Take Off arrangement

Power Transmission

Sea based Wave Energy abstraction

Fig. 2: Categories of the function of WEC

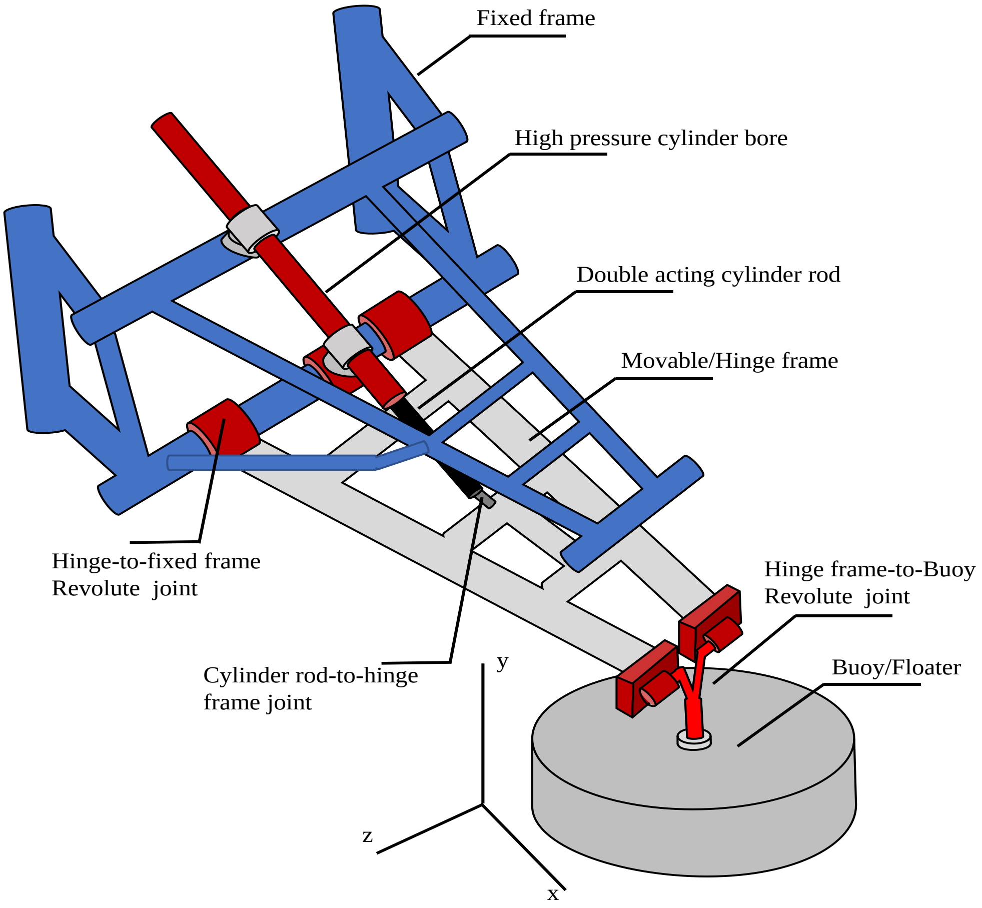


Fig. 3: Floater-link mechanism for power intake

2.1.2 Wave power intake

The wave power intake sub-system comprising of the ocean wave, floaters and links are responsible for absorbing energy from interaction with the ocean wave. An incoming ocean wave excites the floater. In response to the excitation force, the floater heaves and in the process generates waves. Energy absorption is enhanced when floater/link generates waves that interact destructively with the incoming waves of the ocean, as captured in the popular paradox “to create a wave means to destroy a wave.” To achieve this, the arrangement of floater-mechanisms must produce a heave motion strong enough to resist work done by the excitation force. The resulting equal and opposite reaction is transferred to a double-acting rod of the cylinder and does work on the fluid inside the chambers thus completing the power intake cycle. Fig. 3 shows the floater and link mechanism for power intake.

2.1.3 Power take-off cycle

The working of the power take-off cycle is explained with reference to Fig. 1. This can be summed up by the two-stroke action of the double-acting rod of the cylinder (component 1): the forward stroke of the double-acting rod must be partly resisted by the fluid to sustain the activities in power intake cycle while the remainder of the stroke force is responsible for energizing the fluid in the cylinder chamber. Once energized, the fluid is forced out through port A and through the High Pressure (HP) Line to the Hydraulic motor (component 14). In turn, differential pressure thus created in the cylinder sucks fluid in from the Low Pressure (LP) Line through port B. During downward stroke, the reverse happens; high energy fluid is forced out through port B to the HP line while intake from the LP line happens through port A. The switch over of port A to HP line and port B to LP line and vice versa (as the case may be) is controlled by the Directional control valve (component 20). Once out of the port, the HP fluid flows through HP lines to a Hydraulic motor where it drives a turbine to cause a rotary motion of a shaft linked to a generator. The generator drives an electrical machine that generates electricity. Often, a HP accumulator is used to create and maintain a fluid flow gradient. This completes the Power Take-Off cycle.

2.1.4 WEC components design intent

The arrangement of components in the WEC system is depicted in Fig. 4. Each component of the WEC system must consistently function according to the design intent to realize the objectives of the system. In this context, failure mode implied conditions that the system/subsystem/component behaves in a manner not intended by design. Table 1 shows the design intents of the components of the WEC system.

Table 1 Design functions of components of WEC

Components	**Symbol**	**Description of design intent**
Wave/floater	τ_{ext}	Excitation torque
Float/Arm	$\theta_{arm}; \omega_{arm}$	Displacement and velocity of the arm
Hinge frames	$\tau_{PTO}; X_c;\ \dot{X}_c$	PTO Torque; stroke (displacement) and velocity of double-acting-rod
Cylinder	$F_c; P_A; P_B$	Cylinder force, Exit and Inlet pressure
Hydraulic motor	$Q_A; Q_B, \tau_M$	Discharge and flow rate to/fro ports A and B, Motor torque
Generator	$\omega_G; P_{out}$	Input angular velocity, and Power out

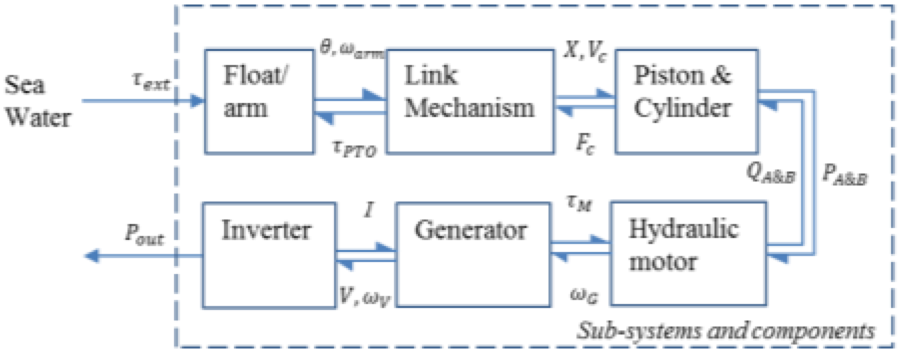


Fig. 4: Functional diagram of the WEC system showing the hierarchy of main sub-systems (Hansen Kramer and Vidal, 2013).

2.2 Method

Team selection: The selection of the FMEA team for risk analysis was based on the author's network of friends that included seven experts - 3 Directors of Renewable Energy institutes, 2 Power Take Off Engineers and 2 Researchers. Each of the selected stakeholders has more than 5 years of experience working in similar WEC projects.

Material and information sourcing: Information relevant for the FMEA analysis was sort from literature - textbooks, journals, FMEA reports on related systems, and standards (IMCA, 2002; International Standard Organisation, 2002; Arabian-Hoseynabadi et al., 2010; McDermott et al., 2011). This is in addition to inputs from the team of experts. The highlight of the material and information sourcing is the development of the FMEA analysis sheet. This follows an indebt study to identify the generic components, functions and functional failures of the WEC system. The final copy of the FMEA sheet has a structure shown in Table 2 (without the scores). From the author's point of view, the experiences of the team are enough to serve as validation for the identified component's functions and failures. Such practice has been used in Quchi (2004).

FMEA sheet evaluation: The evaluation process was challenged by the fact that the FMEA team members were spread across different geographical locations at the time of the analysis. These included Asia, Europe, and Nigeria. To overcome this challenge, the team adopted video conferencing and sharing application –WebEx, for communications. The FMEA sheet and preference scale were sent to each team member for evaluation, along with documents relevant for the FMEA analysis in time enough to allow for proper acquaintance with the peculiarities of the WEC system used for the case study. These documents include a hydraulic circuit diagram of the WEC system, the manufacturer's technical design specifications of the various components of the WEC system, failure data of the components (as used in related systems), user manuals, FMEA reports of related systems (Dinmohammadi and Shafiee, 2013). After these documents had been sent, a time was agreed for harmonisation of individual evaluations. Fig. 5 shows the methodology for a typical FMEA study.

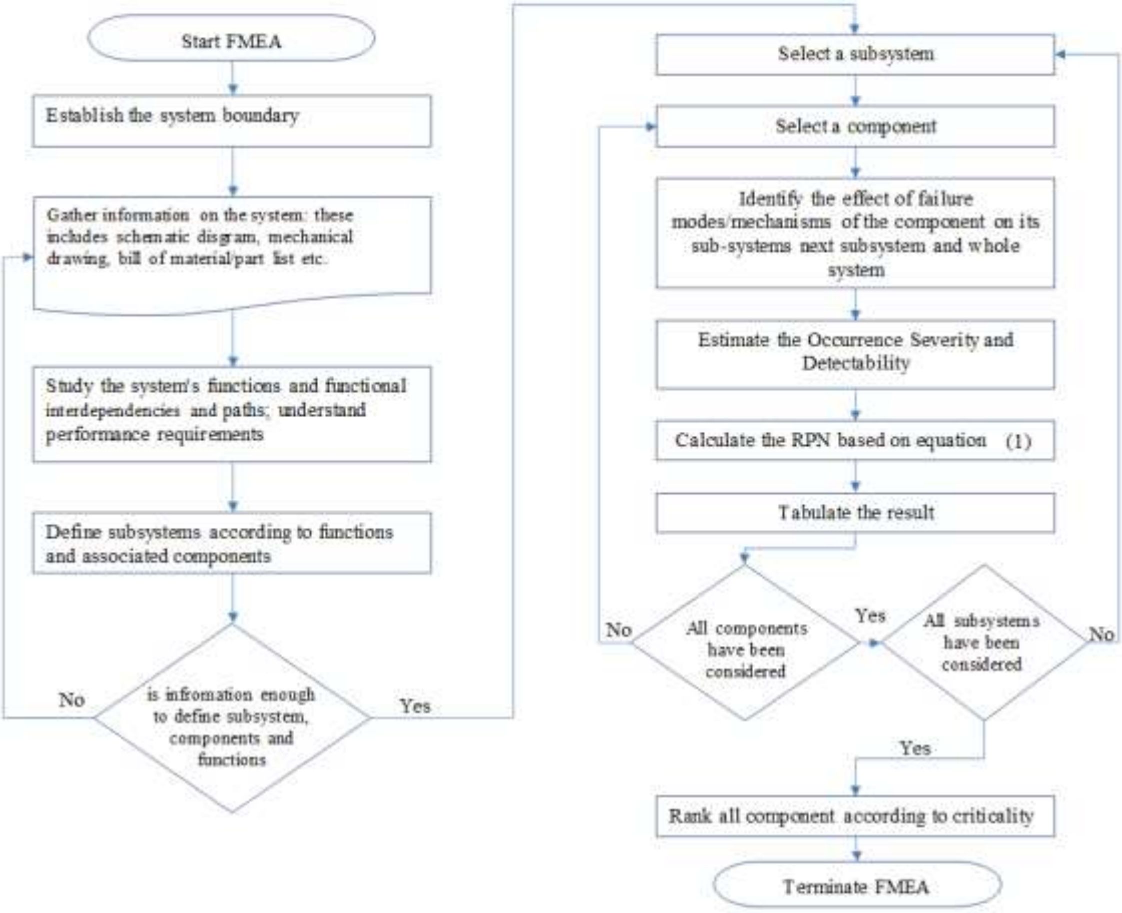


Fig. 5: Methodology of FMEA

Score elicitation and harmonisation: Each member of the team evaluated the risk of realising the functional failures independently based on the three factors: Occurrence, Severity, and Detectability. A way to capture such subjective expert opinion's risk performance perception is through score elicitation (Hasselbalch *et al.*, 2005), guided by the preference scale of Fig. 6. As it is normal, in such multiple experts' evaluation, to have different (often conflicting) experts opinions/scores for a given functional failure under the factors, the paper adopted a harmonisation scheme that gives preference to scores from experts whose area of expertise relates most to the component under consideration. The scheme also provided the opportunity for the evaluators to shed more light on the preference of scores in conflicting zones.

In the context of this study, Severity (S) is defined as a rating corresponding to seriousness of an effect of a potential failure expressed as a number in a scale of 1 to 10 where 1 implies no effect; 5 - moderate effect; 8 - serious effect; and 10 - hazardous effect. Occurrence (O) expresses how often the causes of failure mode/mechanisms are experienced in the system/structure prior to maintenance interventions. Like in the case of severity, it is expressed as a number in an ordinal scale of 1 to 10 where 1 signifies fairly unlikely, 5 - occasionally, 8 - fairly certain and 10 - certain. Detectability (D) refers to the likelihood that the potential failure mode/mechanism will be spotted in time enough to allow for control measures to be put in place. It is rated on a scale of 1 to 10 where 1 signifies that the failure will be detected, 5 - might detect, 8 – highly likely not to be detected, and 10 - almost certain not to be detected in time enough to allow for control action to be implemented.

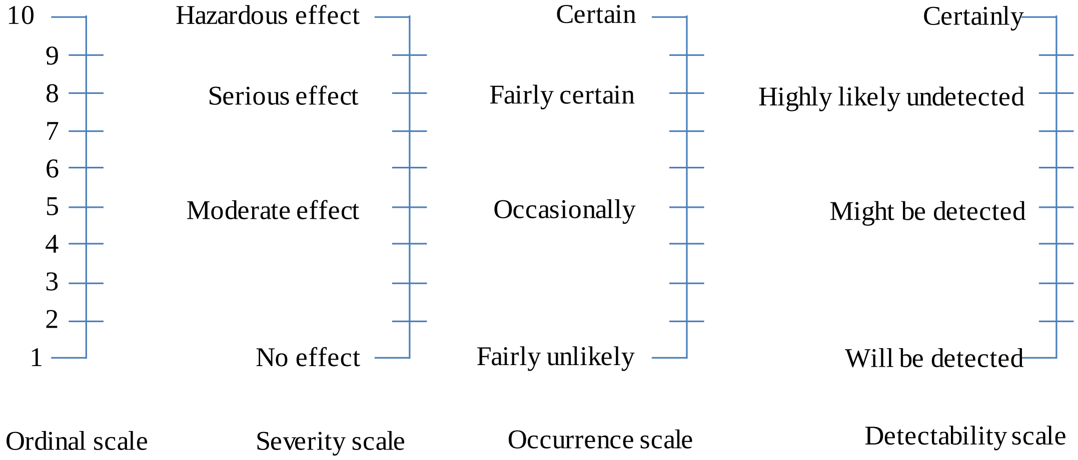


Fig. 6: Preference scales

Ranking of failure mode/mechanism: Ranking of failure modes/mechanisms was based on the risk priority number (RPN): a number indicating the level of significance of the failure mode/mechanism. RPN is a quantitative measure of inherent risk in a failure mode/mechanism and it is calculated using Equation (1).

$$RPN = O \times S \times D \quad (1)$$

Interpretation of the RPN score is such that the higher the value, the more critical the failure mode/mechanism is.

3. Results and discussion

3.1 FMEA record sheet

The FMEA record sheet (Table 2) is the first of the result series of FMEA study. The analysis results in the decomposition of the WEC system into 5 sub-systems and 16 main components. Each of these components performs at least one of the six functions defined in Table 1. A total of 10 failure modes are identified. Consequences for such functional failure are considered from the point of view of the effect on the next up and below functions in the hierarchy (Fig. 4) and on the overall objective of the system as noted in Stamatis (2003). The harmonised scores representing the experts' opinions on the occurrence, severity, and detectability of the consequences are entered under O, S, and D columns respectively as presented in Table 2. The last column of Table 2 contains the

RPN as derived from Equation (1). It expresses the risk-held in each of the failure modes.

Table 2: Failure mode and effect analysis of a prototype wave energy converter record sheet

Components		**Function**	**Failure mode and consequences**	**O**	**S**	**D**	**RPN**
Power intake mechanism	Connection joint	Motion transfer between Floater and Hydraulic cylinder	Loss of motion. *Causes*: No/Low cylinder force and/or pressure. Floater fails in function. *Effect*: **Motor** -Loss of output	3	4	3	36
	Floater			2	4	2	16
	Hinge frame			5	7	3	105
Hydraulic Cylinder	Double-acting Rod	Energize fluid through the action of the reciprocating motion of the double-acting rod	Loss of cylinder force. *Causes*: (*i*) Failed Piston rod – seizure, fatigue, buckling; (*ii*) Barrel – leakages (*iii*) Failed seals: *Effects*: **Motor** - Overheating, lubricant spill, wear. **Power intake mechanism** -loss of absorption	4	7	4	112
	Barrel			2	8	3	48
	Seals			2	9	8	144
Pipeline-fluid subsystem	Pressure Lines;	Maintains fluid flow between cylinder outlet motor and cylinder inlet at desired fluid flow parameters.	Loss of flow. Causes:(*i*) Cylinder failure (*ii*) leakage in the flow line, (*iii*) faulty accumulator and/or valves (*iv*) Fluid failure -Contamination *Effect*: **Line** -blockage, burst, high fluid temperature and loss of flow control. **Valves** – abrasion, **Environment - p**ollution from lubricant spill, objectionable noise. M**otor** -overlabour, pressure pulsation and transient local pressure spike, vibration, loosened connections and joints, misalignment, overheating, increase in the rate of wear, low motor efficiency, low generator output, no discharge at the cylinder or motor, Drop in the electricity generation capacity.	7	10	10	700
	Valves			10	10	8	800
	Accumulators			5	9	5	225
	Filter			10	9	10	900
	Hydraulic fluid.			10	10	10	1000
	Oil reservoir	Receptacle for expended fluid from hydraulic motor. Heat exchanger	Loss of fluid, no/low heat exchange efficiency. Causes: **Motor** -defective leading to overheating and loss of lubrication; contamination of fluid leading to corrosion.	7	10	8	560
Hydraulic motor	Shaft	Converts hydraulic energy of the fluid to rotational energy	Loss of conversion. Causes: (*i*) Defective motor: irregular shaft torque, (*ii*) low fluid flow energy. *Effect*: No power generation; High temperature; Vibration and noise	2	8	5	80
Electric generator	Circuit winding;	Generate power through actions of rotating shaft across lines of flux of an electromagnet	Loss of electric power generation. Causes: (*i*) Generator is defective -open circuit at winding, an abnormal connection in the stator windings (Gellermann, 2012) (*ii*) Rotor dynamic eccentricity; (*iii*) Broken rotor bars; (*iv*) Cracked end rings Effects: **Generator**: torque pulsations, no conversion efficiency	2	9	8	144
	Rotor and rotor bars;			2	7	7	98
	End rings			4	8	7	224

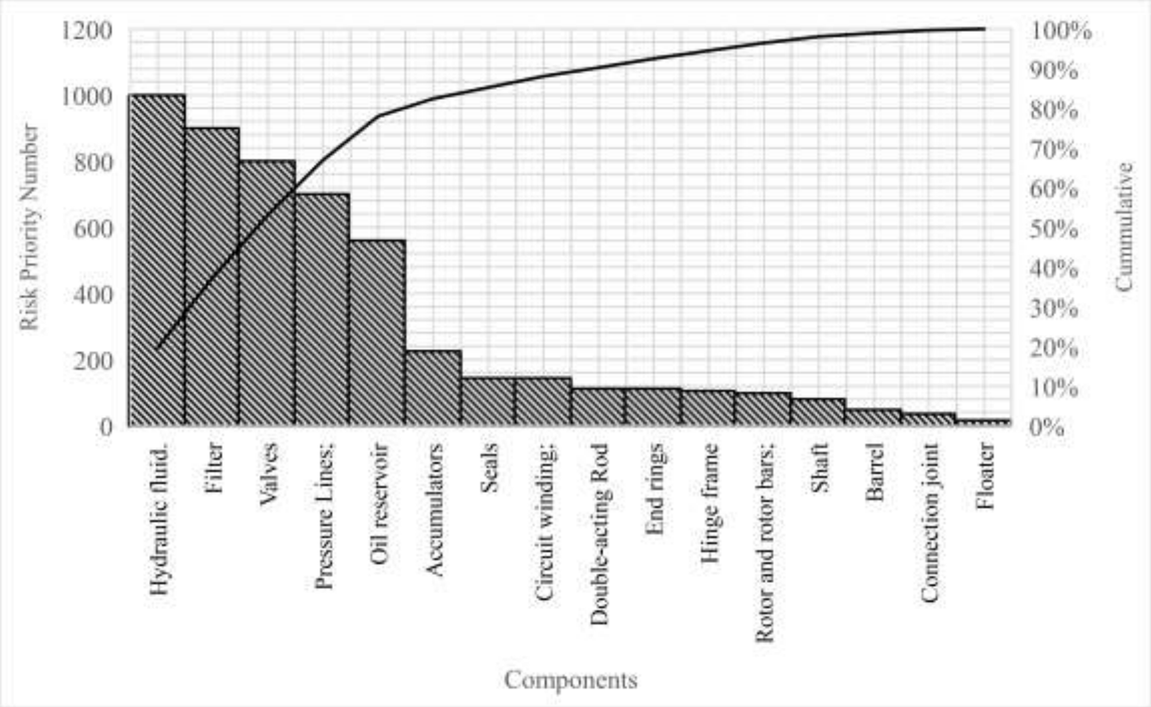


Fig. 7: Pareto Plot of RPN for components of a WEC system

3.2 Failure mode prioritisation

Fig. 7 presents the RPNs of the failure modes in descending order of magnitude in the form of bar charts. The chart has on the left-hand axis the RPN and on the right-hand axis the cumulative percentages. The value of the RPN is the same as the height of the bar - which represents the components. The cumulative axis expresses the cumulative sum of RPN as a percentage of the sum total of all the RPNs highlighting a pattern of accumulation of RPN across the system. The analysis assumes that the sum of RPN models the total risk content of the system whereas RPN is level of risk realisable as a result of action or inaction leading to functional failures of the components. As can be seen from Fig. 7, the first five high-ranking failures are shared amongst hydraulic fluid (1000), filter (900), valves (800), pressure line (700) and oil reservoir (560), respectively. A line drawn from the middle of the fifth bar (oil reservoir) to join the cumulative RPN curve and traced to the percentage cumulative RPN axis will meet the axis at 80% mark. This is interpreted as the sum of the risk-held in the components to the left of oil reservoir (comprising of the oil reservoir, pressure line, valves, filter, and hydraulic fluid) constituting about 80% of the total risk of the system (Arvanitoyannis and Varzakas, 2007; Micha, 2014). In other words, the inference is that just 5 out of 16 components making up the WEC system holds about 80% of the risk. This information has a lot of implications in terms of product development and maintenance management of existing devices.

On product development, developers often would like to design out some of the parameters contributing to high-risk values. These might involve the deployment of sensors into the candidate areas/components to increase detectability, provision of redundancy to reduce the severity, or choice of another material to reduce the occurrence. The experiences derived from such practice will go a long way in advising future designers on ways to improve the reliability of the emerging technology.

On maintenance management of existing systems, maintenance managers are often faced with situations involving choice such as budget fluctuation/shortage. In such a situation, the maintenance team might want to delay some scheduled maintenances. The outcome of such a study will aid the maintenance team to visualise how delay can affect the overall system's operation and make an informed decision. In this context, the information contained in Fig. 7 suggests that when faced with maintenance challenges such as "budget deficit", the 5-top RPN ranking components have to be given priority over the rest of the components because they constitute 80% of the total risk.

The chart also shows a pattern of a functional relationship between the hydraulic fluid and the rest of high-ranking RPNs i.e. the filter removes contaminants from the hydraulic fluid, valves control the direction of the hydraulic fluid, the reservoir is a receptacle for the hydraulic fluid. Therefore, the failure of the other four may have a common cause in the failure of the hydraulic oil. Such insights are useful in suggesting design improvements or identification of areas that barriers are needed. The analysis had relied on the experience of the team of experts to account for the influence of the different operational conditions of the components on the failure prioritization. This is targeted at reducing inconsistency i.e. increasing repeatability of the FMEA.

4. Conclusions

The problem of lack of failure data for proper reliability analysis of emerging ocean-based renewable energy technologies such as wave energy converters still persists to date. However, recent reports from academia and industries have shown that it is possible to derive failures data of ocean-based energy devices from risk and reliability studies to drive proper research and development efforts. This work concerns the aspect reliability analysis of a generic wave energy converter based on FMEA. The highlights of the result are (i) the identification of 16 potential functional failures and consequences from main components of the system, and (ii) prioritisation of the failure modes based on risk factors of occurrence, severity, and detectability. The top 5 prioritised failure modes that are shown to hold 80% of the total risk inherent in the system are hydraulic fluid, filter, valves, pressure line and oil reservoir. Further observation shows a pattern that linked other 4 high-ranking RPN components to failure of hydraulic fluid, suggesting that the hydraulic fluid might be the primary cause of other failures after all. Such results and analysis are relevant to design engineers who desire to improve the reliabilities of emerging systems such as the WEC system, as well as maintenance engineers who are constantly seeking ways to optimise maintenance and reduce operational expenditure.

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