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Application of a Revised-FMEA Approach for Reliability Evaluation of Vertical Axis Underwater Current Power Turbine Blade: A Case of a Novel UCPT in Nigeria

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The Underwater Current Power Turbine (UCPT) is a novel vertical axis underwater current power turbine designed to operate even in very low flow of less than 0.5m/s and multidirectional conditions developed at the Center for Maritime and Offshore Studies of Federal University of Petroleum Resources, Effurun, Nigeria. The prototyped concept was deployed for testing in river Ethiope of Nigeria between 2018 and 2020. During the test phase, several components were examined and data gathered. Based on the data collected and expert judgment, the turbine blades were identified as the most critical component of the power turbine. Usually, prior to the actual product development in engineering, analyses on prototype performance and reliability are often carried out. In this work, the theory of conditional probability is incorporated into a revised FMEA, in an attempt to decrease subjectivity when analyzing the most crucial and risk-prone components of the UCPT. The use of interval probability is applied to manage the uncertainties. With this approach, the failure risk of the UCPT vanes is accessed more objectively and precisely, and the best comparison of risks between products and processes across all system levels is facilitated.

1. INTRODUCTION

A recent study has attempted to uncover the potential of the Nigerian offshore environment for proper utilization (Agbakwuru and Idubor, 2019). Other literatures have also discussed the wave, wind, current, and swell obtainable in the region (Ewans et al., 2004; Agbakwuru and Idubor, 2019). It is largely found that the Nigerian ocean current is averagely about 0.30 m/s. The wave is mild and lacks large storms. This study attempts to seek the possibility of energy generation from the flow of ocean waters and extends to the review of the different kinds of turbines for use in mild conditions afore-described.

Existing literature has it that, Darrius vertical axis turbine can be used in low-speed flow to the limit of 0.5m/s (Agbakwuru and Umar, 2019). Unfortunately, studies and data collected from several locations in the West African offshore show an average speed of 0.3m/s. Based on this development; a concerted effort has been made to review the design of the Darrius Current Turbine technology. The consequence of such development is the development of a novel passive-to-active bladed turbine for use in water speed of less than 0.5 m/s which is well discussed in Agbakwuru and Umar (2019) and is now known and referred to as the F-UCPT (where 'F' represents the Federal University of Petroleum Resources, Effurun). The common benefit of the vertical axis turbine is the ease of installation. Further advantage is that most rotating and electricity generating units within the system are located on the topside (above water).

The prototype test results of the work of

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Agbakwuru and Umar (2019) are very interesting. There is presently a drive to scale up the system for a hybrid system, which will consist of a solar and marine unit. This is considered a great contribution to a Blue Economy. The technology will not only serve shipping, underwater mining, and oil/gas industries (Agbakwuru and Akaawase, 2017), but also offshore aquaculture which would require a good amount of electricity for sustainable mechanization. The main goal of this research is to further the development of the vertical axis underwater current turbine for low water flows, so as to enable its better reliability assessment and engineering design. As it is well known, the importance of ascertaining any engineering system's performance and reliability for optimization cannot be over-emphasized.

1.1. The System and its Performance

Good knowledge of any system's performance does not only create room for concept advancement. It also assists during the characteristics chart establishment. In describing the performance, most often, the core components are considered. Core components in the sense that they can influence the functionality of the entire system. In this case, attention has been paid to the following; geometry and submerged weight of blades, water flow velocity, and direction, and freeness of mating parts of the Underwater Current Power Turbine (UCPT).

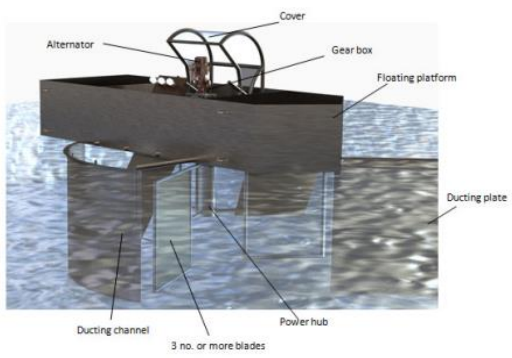

Figure 1: Modelled F-UCPT concept

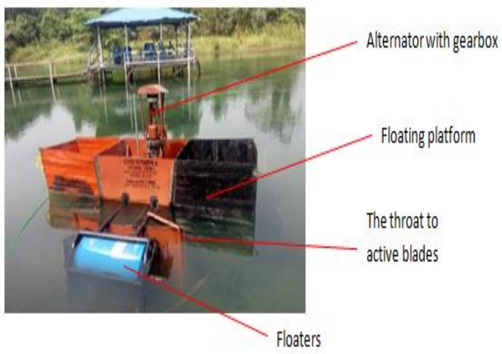

Figure 2: Prototyped F-UCPT

1.2. Operational Principle

F-UCPT has a passive and active side, on the active side water is stopped from flowing through the bladed region thereby harvesting the energy from the water current. On the passive side, the blades open allowing water to flow through the bladed region. It is important to mention that both events are mutually inclusive. Agbakwuru and Umar (2019) have explained the operational principle in detail. Refer to Figure 3 for the diagrammatic description.

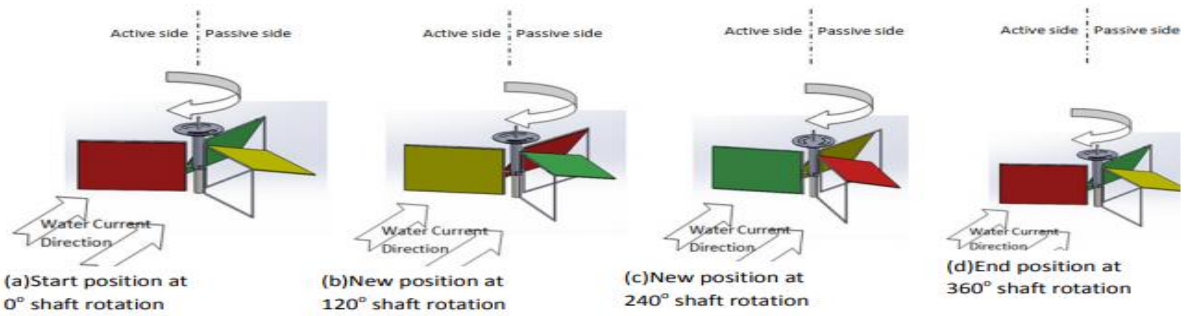

Figure 3: The operational principle of F-UCPT (sourced: Agbakwuru & Umar, 2019)

1.3 Reliability Study Review

Failure Modes and Effects Analysis (FMEA) is an engineering technique that uses risk priority number (RPN) to rank failure modes (Akaawase and Abam, 2018). RPN itself is the product of three ranked ratings, occurrence, severity, and detection (Carlson, et. al., 2012). Whereas, the occurrence (O) rating is assigned to the cause of the failure mode to reflect the probability of the cause and the immediate failure mode; the severity (*S*) rating is assigned to the end effect of the failure mode to reflect the seriousness of the end effect, and detection rating (*D*) is assigned to the cause of the failure mode to reflect the difficulty of detecting the cause or failure mode. Integer numbers between 1 and 10 quantify these ratings as shown in Table 1.

Traditionally, by comparing RPNs with each other, engineering decisions can be made. Failure modes with higher RPNs are considered to have a higher risk, and corrective actions are then taken to reduce the RPNs (Jakuba, 1987). In this way, the system reliability is improved. This concept has been adopted widely over the years by industries such as banking, automobiles and construction firms, etc. (Hill et al., 2008). Despite the wide implementation of FMEA in the industry, controversies have always been around it. For example, the criteria for quantifying the three ratings are mostly subjective, and they are described qualitatively in natural language based on the experience of teams. Different combinations of *O*, *S,* and *D* can produce identical values of RPN when they may in actual sense indicate different risks. As presented in Table 1, one can see that RPNs are not evenly distributed from 1 to 1000. Many "gaps" exist in the distribution. In fact, there are only 120 values existing in the range. This has a great effect on the interval mean. The traditional FMEA has been improved (Reder et al., 2016) but it is still difficult to address the issues of the degree of subjectivity in RPNs. Since the risk information provided by RPNs is always difficult. A comprehensive and realistic consideration of the possible end effects of FMEA is still hard. To solve the aforementioned problem, an expected cost approach is utilized to evaluate risks in this work.

The expected cost is a universal way of measuring risk, and it is obtained in a more objective way, thus reducing subjectivity (Jianmin and James, 1996). Moreover, the inclusion of cost as an evaluating factor gives the opportunity to balance the costs of corrective actions with expected revenues. This allows an optimized resource allocation and economical evaluation of changes.

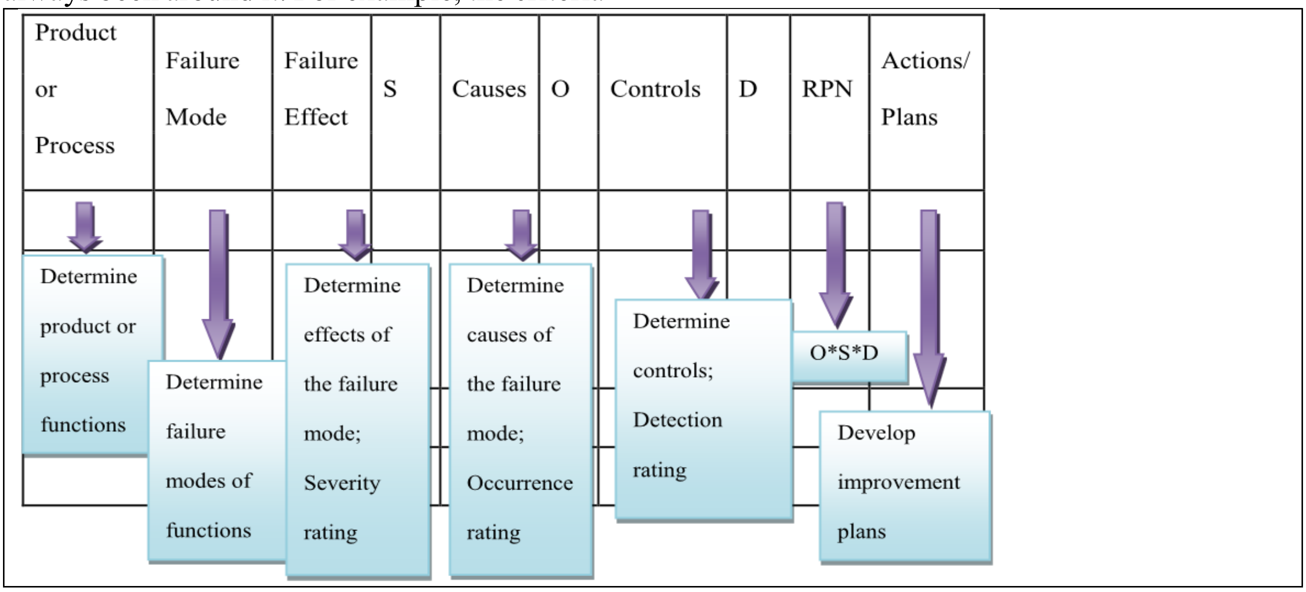

Figure 4: A Typical FMEA Table (source: Subburaman, 2010)

Table 1: Ratings for Occurrence (Based on Potential Failure Mode and Effects Analysis (FMEA) 4th Edition, 2008 Manual)

Rank	Probability of occurrence	Failure probability
10	Extremely high: failure almost inevitable	>1 in 2
9	Very high	1 in 3
8	Repeated failures	1 in 8
7	High	1 in 20
6	Moderately high	1 in 80
5	Moderate	1 in 400
4	Relatively low	1 in 2000
3	Low	1 in 15000
2	Remote	1 in 150000
1	Nearly impossible	<1 in 1500000

Table 2: Ratings for Severity
Adapted from Potential Failure Mode and Effects Analysis (FMEA) 4th Edition, 2008 Manual.

Rank	Effect	Severity of effect
10	Hazardous	Failure is hazardous, and occurs without warning. It suspends the operation of the system and/or involves noncompliance with government regulations.
9	Serious	Failure involves hazardous outcomes and/or non-compliance with government regulations or standards.
8	Extreme	The product is inoperable with loss of primary function. The system is inoper-able.
7	Major	Product performance is severely affected but still functions.
6	Significant	Product performance is degraded. Comfort or convince functions may not op-erate.
5	Moderate	Moderate effect on product performance. The product requires repair.
4	Low	Small effect on product performance. The product does not require repair.
3	Minor	Minor effect on product or system performance.
2	Very minor	Very minor effect on product or system performance.
1	None	No effect.

Rather than using Tables 1 and 2, we will be replacing them with expected costs. While the detection rating will be allowed to reflect failure scenarios as probabilities of either being successful or unsuccessful. This treatment makes the new methodology more realistic as the results obtained by this method are more objective and accurate, and they can be compared with each other across all system levels. Moreover, decision-making can be based on the balance between the costs of corrective actions and expected revenues.

2. METHODOLOGY

To examine the reliability using the modified FMEA, expected cost is used to conduct risk evaluation through the expression (Agung et al, 2015):

$$Risk = P_f C \tag{1}$$

where: P_f is the probability of failure and C is the failure cost.

For us to ascertain the level of risk, a cause-effect chain structure will be generated and then probabilities of root causes will be established, and conditional probabilities of intermediate effects and failure costs are determined. The cause-effect chain structure of the F-UCPT vanes under a corrosive environment is developed in Table 4. The content of Table 4 can be presented in a tree form (see Figure 5)

Table 3: Ratings for Detection
Adapted from Potential Failure Mode and Effects Analysis (FMEA) 4th Edition, 2008 Manual."

Rank	Detection	Likelihood of detection by the design control
10	Absolute uncertainty	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode, or there is no design control.
9	Very remote	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode.
8	Remote	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode.
7	Very low	Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode.
6	Low	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode
5	Moderate	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode.
4	Moderately high	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode.
3	High	High chance the design control will detect a potential cause/mechanism and subsequent failure mode.
2	Very high	Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode.
1	Almost certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode.

Table 4: The cause-effect chain for F-UCPT blades

<table>
<tr><td rowspan="5">C_R
Corrosive environment</td><td rowspan="5">E_{11}
Blade corrosion</td><td rowspan="2">E_{121}
Local stress concentration</td><td>D_{121}
Detected</td><td>$\bar{E}_{131}$
System shut-down</td><td></td></tr>
<tr><td>$\bar{D}_{121}$
Undetected</td><td>$\bar{E}_{131}$
Fatigue</td><td>$\bar{\bar{E}}_{141}$ Vane fracture</td></tr>
<tr><td rowspan="2">E_{122}
Strength reduction</td><td>D_{122}
Detected</td><td>E_{132}
System shut-down</td><td></td></tr>
<tr><td>$\bar{D}_{122}$
Undetected</td><td>$\bar{E}_{132}$
Fatigue</td><td>$\bar{\bar{E}}_{142}$ vane fracture</td></tr>
<tr><td>E_{123}
Propagated cracks</td><td colspan="2">E_{133}
vane fracture</td><td></td></tr>
</table>

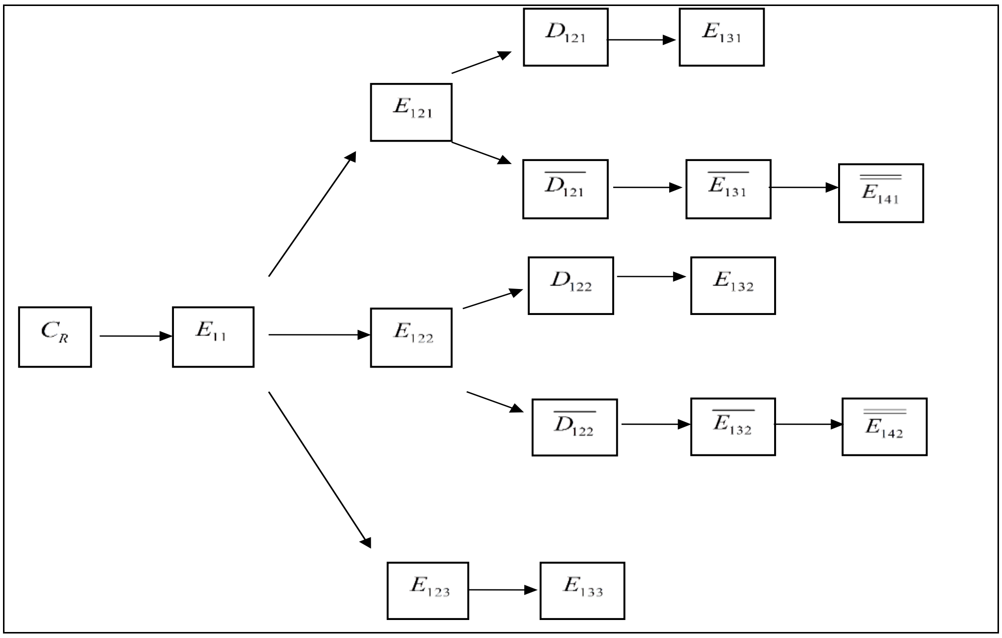

Figure 5: A Cause-Effect Chain Structure of Hydrokinetic Turbine vanes

Where: C_R is the root cause, E_{11} is the immediate effect, E_{121}, E_{122}, E_{123} are subsequent effects, D_{122}, D_{121} are detections, $\overline{D}_{122}$ are undetected, $\overline{E}_{131}$ is the outcome of undetected events, $\overline{\overline{E}}$, $\overline{\overline{E}}_{142}$ are the end effects. Equation 1 can be solved if the probabilities are determined. To get the probabilities, the theory of conditional probability is engaged. The theory suggests that for two events A and B with P (A) > 0, the conditional probability of B given A is as follows:

$$P(B|A) = \frac{P(A \cap B)}{P(A)} \qquad (2)$$

Where $A \cap B$ means event A and B both occurred, $P(A \cap B)$ means the joint probability of A and B. The Equation 2 can also be written as:

$$P(A \cap B) = P(B|A)P(A) \qquad (3)$$

In Equation 3, the probability of event A and B happening at the same time is the product of the conditional probability of event B, given A and the occurrence probability of event A. From the expression of Equations 2 and 3, we can calculate the probability of failure easily while the failure cost is acquired from historical data. With this information, the risk of root cause R (C_R) is computed. In Figure 1, there are six paths in the structure, treating each path separately you will have;

1st Path: $C_R \rightarrow E_{11} \rightarrow E_{121} \rightarrow D_{121} \rightarrow E_{131}$

$$R_1(C_R) = P(C_R)P(E_{11} \mid C_R)P(E_{121}|C_R, E_{11})P(D_{121})P(E_{131} \mid C_R, E_{11}, E_{121}, D_{121})C_1$$
(4)

2nd Path: $C_R \rightarrow E_{11} \rightarrow E_{121} \rightarrow \overline{D}_{121} \rightarrow \overline{E}_{131} \rightarrow \overline{\overline{E}}_{141}$ (5)

$$R_2(C_R) = P(C_R)P(E_{11}|C_R)P(E_{121}|C_R, E_{11})P(\overline{D}_{121})P\left(\overline{E_{131}}\middle|C_R, E_{11}, D_{11}, E_{121}, \overline{D}_{121}\right)$$
$$P(\overline{\overline{E}}_{141} \mid C_R, E_{11}, E_{121}, \overline{D}_{121}, \overline{E}_{131})C_2$$

3rd Path: $C_R \rightarrow E_{11} \rightarrow E_{122} \rightarrow D_{122} \rightarrow E_{132}$ (6)

$$R_3(C_R) = P(C_R)P(E_{11} \mid C_R)P(E_{122} \mid C_R, E_{11})P(D_{122})P(E_{132} \mid C_R, E_{11}, E_{122}, D_{122})C_3$$

4[th]Path: $C_R \rightarrow E_{11} \rightarrow E_{122} \rightarrow \overline{D}_{11} \rightarrow \overline{E}_{12} \rightarrow \overline{\overline{E}}_{13}$ (7)

$$R_4(C_R) = P(C_R)P(E_{11}|C_R)P(C_R)P(E_{122}|C_R, E_{11})P(\overline{D}_{122})P(\overline{E_{132}}|C_R, E_{11}, E_{122}, \overline{D}_{122})$$
$$P(\overline{\overline{E}}_{142} \mid C_R, E_{11}, E_{122}, \overline{D}_{122}, \overline{E}_{132})C_4$$

5[th]Path: $C_R \rightarrow E_{11} \rightarrow E_{123} \rightarrow E_{133}$

$$R_5(C_R) = P(C_R)P(E_{11} \mid C_R)P(E_{123} \mid C_R, E_{11})P(E_{133} \mid C_R, E_{11}, E_{123})C_5 \quad (8)$$

Thus, the total risk of root cause becomes:

$$R \quad (C_R) = R_1(C_R) + R_2(C_R) + R_3(C_R) + R_4(C_R) + R_5(C_R) \quad (9)$$

Where:

$R_1(C_R)$ is the risk of root cause for the first chain, $P \quad (C_R)$ is the occurrence probability of the root cause, $P(E_{21} \mid C_R)$ is the conditional probability of effect E_{21} given the occurrence of the root cause C_R. To obtain the total risk of root cost (C_R); probability and failure cost need to be collected from the cause-effect chain structure. Next, the following cost is determined.

$$C_l = (T_{dt} + T_{dl} + T_f)R_l \times N \quad (10)$$

Where: C_l is the labor cost, R_l is the labor rate, T_{dt} is the detection time, T_{dl} is the delay time and T_f is the fixing time.

$$C_o = (T_{dt} + T_{dl} + T_f)R_o \quad (11)$$

Where: C_o is the opportunity cost, R_o is the hourly opportunity cost.

$$C_m = C_p \times N_p \quad (12)$$

Where: C_p is the cost of parts, N_p is the number of parts and C_m is the cost of materials. From the probability intervals introduced to cater for uncertainties, lower the and upper bound of the total expected cost of the root is obtained as follows:

Upper bound:

$$R(C_R)' = R_1(C_R)' + R_2(C_R)' + \cdots R_n(C_R)'$$

(13)

Lower bound:

$$R(C_R)^0 = R_1(C_R)^0 + R_2(C_R)^0 + \cdots R_n(C_R)^0$$

(14)

Thus, the expected cost of root cause $R(C_R)$ becomes:

$$R(C_R)' < R(C_R) \quad < R(C_R)^0 \quad (15)$$

3. RESULTS AND DISCUSSION

The results obtained and the discussions therein are discussed below:

Table 8: Failure Scenarios of Hydrokinetic Turbine Blades

Tremendous change in flow velocity (0.1-0.2)	Overspeed rotation of Vanes (0.6-0.7)	Varying loads on vane (0.95)	Detected (0.95-0.99)	System shut-down	
			Undetected (0.01-0.05)	Fatigue (0.6-0.7)	Vane fracture (0.8-0.9)
C_R Corrosive environment (0.6-0.8)	E_{11} Vane corrosion (0.63)	E_{121} Local stress concentration (0.5-0.8)	D_{121} Detected (0.95-0.99)	E_{131} System shut-down	
			$\overline{D_{121}}$ Undetected (0.01-0.05)	$\overline{E_{131}}$ Fatigue (0.6-0.7)	E_{141} Vane fracture (0.8-0.9)
		E_{122} Strength reduction (0.8-0.9)	D_{122} Detected (0.96-0.99)	E_{132} System shut-down	
			$\overline{D_{122}}$ Undetected (0.02-0.06)	$\overline{E_{132}}$ Fatigue (0.6-0.7)	E_{142} Vane fracture (0.8-0.9)
		E_{123} Propagated cracks (0.4-0.6)	E_{133} Vane fracture(0.5-0.7)		
Presence of trivial debris (0.5-0.6)	Impact on Vanes (0.01-0.02)	Small deformation (0.5-0.1)	Reduced efficiency (0.5-0.7)		
Presence of moderate debris (0.1-0.2)	Debris piling on Vanes (0.4-0.6)	Increasing loads on system (0.5-0.7)	System shut-down (0.6-0.8)		
Presence of huge debris (0.01-0.02)	Impact on Vanes (0.7-0.8)	Vane fracture (0.6-0.8)			

Table 9: Probability Values

$P(C_R)$	0.6 – 0.7	$P(D_{122})$	0.96 – 0.99
$P(E_{11} \mid C_R)$	0.63	$P(\overline{D_{122}})$	0.02 – 0.06
$P(E_{121} \mid C_R, E_{11})$	0.5 – 0.8	$P(\overline{E_{131}} \mid C_R, E_{11}, E_{122}, \bar{D}_{121})$	0.6 – 0.7
$P(E_{122} \mid C_R, E_{11})$	0.8 – 0.9	$P(\bar{\bar{E}}_{131} \mid C_R, E_{11}, E_{121}, \bar{D}_{121}, \bar{E}_{131})$	0.8 – 0.9
$P(E_{123} \mid C_R, E_{11})$	0.4 – 0.6	$P(\overline{E_{132}} \mid C_R, E_{11}, E_{122}, \bar{D}_{122})$	0.6 – 0.7
$P(D_{121})$	0.95 – 0.99	$P(\bar{\bar{E}}_{142} \mid C_R, E_{11}, E_{122}, \bar{D}_{122}, \bar{E}_{132})$	0.8 – 0.9
$P(\overline{D_{121}})$	0.01 – 0.05	$P(E_{133} \mid C_R, E_{11}, E_{123})$	0.5 – 0.7

Based on the prototyping experience gathered at river Ethiope in Abraka, Delta State; the following data was generated for hourly opportunity cost; labor rate, and cost. The content of Table 8 is derived from the prototype data, ranked with respect to potential failure. Applying equations 4 to 9 to the data in Table 8, the results presented in Table 9 were obtained.

Using equations 10 through 15, while weighing potential loss (time, cost) in an event of a failure which is a function of the complexity of the entire F-UCPT system; the expected cost and the results in Tables 10 and 11 were gotten.

Calculating risk in terms of expected cost: ₦250, 000 ≤ $R(C_R)$ ≤ ₦345, 000.

Table 10. Loss Time of the Two Failures (in Hours)

Parameters	Blades fracture	System shutdown
Detection time	4	1
Fixing time	3	1
Delay time	5	2
Total time	12	4

Table 11. Costs of the Two Failures (in Naira)

Parameters	Vanes fracture	System shutdown
Labor cost	13000	5
Material cost	250000	1
Opportunity cost	65000	25
Total cost	328000	31

The results presented in Table 8 through Table 11 show that the system blades are reliable given the data available for the analysis. The interest in this presentation is the reform in the use of FMEA. This in the authors' opinion is an improvement to the existing art.

4. CONCLUSION

The methodology adopted in this work employs expected cost as the tool to evaluate risks such that the subjectivity in risk results is minimized and the comparison of risks is easily and fairly facilitated. Again as indicated, the blade is the F-UCPT's component exposed to the largest risk. In this presentation, given the available data, it can be deduced that the F-UCPT is as well reliable.

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