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A NEW METHOD FOR FAILURE MODES AND EFFECTS ANALYSIS AND ITS  
APPLICATION IN A HYDROKINETIC TURBINE SYSTEM

by

LIANG XIE

A THESIS

Presented to the Faculty of the Graduate School of the  
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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Approved by

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## ABSTRACT

The traditional failure modes and effects analysis (FMEA) is a conceptual design methodology for dealing with potential failures. FMEA uses the risk priority number (RPN), which is the product of three ranked factors to prioritize risks of different failure modes. The three factors are occurrence, severity, and detection. However, the RPN may not be able to provide consistent evaluation of risks for the following reasons: the RPN has a high degree of subjectivity, it is difficult to compare different RPNs, and possible failures may be overlooked in the traditional FMEA method.

The objective of this research is to develop a new FMEA methodology that can overcome the aforementioned drawbacks. The expected cost is adopted to evaluate risks. This will not only reduce the subjectivity in RPNs, but also provide a consistent basis for risk analysis. In addition, the cause-effect chain structures are used in the new methodology. Such structures are constructed based upon failure scenarios, which can include all possible end effects (failures) given a root cause. Consequently, the results of the risk analysis will be more reliable and accurate.

In the new methodology, the occurrence and severity ratings are replaced by expected costs. The detection rating is reflected in failure scenarios by the probabilities of either successful or unsuccessful detections of causes or effects. This treatment makes the new methodology more realistic. The new methodology also uses interval variables to accommodate uncertainties due to insufficient data.

The new methodology is evaluated and applied to a hydrokinetic turbine system. This turbine is horizontal axis turbine, and it is under development at Missouri S&T.

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# 1. INTRODUCTION

## 1.1. OVERVIEW OF FAILURE MODES AND EFFECTS ANALYSIS

Failure Modes and Effects Analysis (FMEA) is an engineering technique using risk priority number (RPN) to prioritize failure modes. RPN is the product of three ranked ratings, occurrence, severity and detection. It is calculated as  $RPN = O \times S \times D$ . Occurrence ( $O$ ) rating is assigned to the cause of the failure mode to reflect the probability of the cause and the immediate failure mode, 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. These ratings are quantified by integer numbers between 1 and 10. RPNs are compared with each other, and failure modes with higher RPNs are considered to have higher risk, and corrective actions are taken to reduce their RPNs. In this way the system reliability is improved.

FMEA was firstly used by contractors for NASA in early 1960s. In 1967, civil aviation industry started to use FMEA and related techniques [1], and a standard for performing FMEA was published. The use of FMEA in automotive industry began from mid 1970s [2]. It was adopted by the Ford Motor Company for safety and regulatory consideration. And Toyota conducted the FMEA technique on the catalytic converter which was used in the 1975 Toyota models. Critical failure modes to the durability of the catalytic converter and their risks were studied and prioritized in this case study. Since then, the implementation of FMEA started to spread all over industry.

A bank performed process FMEA on its ATM system [3], and according to the RPNs, “machine jams” and “heavy computer network traffic” were considered to have the first and second highest risks, so that they could be treated with priority.

In [4], FMEA was performed on salmon processing. Fish receiving, casing/marking, blood removal, evisceration, filet-making cooling/freezing, and distribution were identified as the processes with the highest RPN values. After corrective actions were taken, a second calculation of RPN values was carried out resulting in substantially lower values.

FMEA was conducted on the study of wafer biscuit production lines in a food company. It was used as a tool to assure products quality and as a mean to improve operational performance of the production cycle. [5]

However, despite the wide implementation of FMEA in industry, controversies have always been around. For example, the criteria for quantifying the three ratings are mostly subjective, and they are described qualitatively in natural language based upon the experience of teams; completely different combinations of *O*, *S*, and *D* can produce identical values of RPN when they may indicate totally different risks. RPNs are not evenly distributed from 1 to 1000, many “holes” exist in the distribution, and actually only 120 values exist among the range, the mean of which are far from the mean of the interval. *O*, *S*, and *D* are considered to be equally important in the calculation of RPN. In fact the weight of one factor may be different from the other two.

Numerous FMEA approaches have been made to overcome the shortcomings mentioned above, among which the fuzzy logic approach is one of the most popular approaches.

The  $O$ ,  $S$ , and  $D$  ratings are all described in linguistic terms, and somewhat subjective and imprecise. Fuzzy mathematics was considered to be a promising tool for directly manipulating such linguistic terms in order to analyze risks associated with failure modes [6-9].

The methodology of the fuzzy RPNs was proposed in [10]. The  $O$ ,  $S$  and  $D$  ratings are fuzzified and evaluated in a fuzzy inference system built on a consistent base of IF-THEN rules. Then the fuzzy output is defuzzified so that the crisp value of the RPN can be obtained and used for a more accurate ranking of the potential risks. It shows that in this method exactly same RPN can only be generated with exactly same  $O$ ,  $S$  and  $D$  ratings.

Gargama and Chaturvedi proposed two methods in [11]. One of them computes fuzzy RPNs by fuzzy extension principle. This method scores  $O$ ,  $S$ ,  $D$  ratings linguistically for each failure mode and translate them into fuzzy numbers. The RPN is calculated by fuzzy arithmetic as a fuzzy number as well. These fuzzy RPNs are then defuzzified using the centroid method and ranked in a descending order.

Similar fuzzy logic approaches can be found in [12-16] and so on. All of these papers follow the general approach when utilizing fuzzy logic, and what distinguishes them is normally the application area or the specifics of fuzzy inference system.

Beside the aforementioned approaches which are aimed at overcoming drawbacks of RPNs, some other modified methods have been proposed too.

In [17], Bevilacqua et al. proposed a modified method which uses a special RPN composed of a weighted sum of six parameters to evaluate risks, and conducted Monte Carlo simulation to randomly generated several sets of possible weights. Ashen proposed

a cost-oriented approach to improve the method of FMEA from an economic perspective in [18], which considers the failure costs associated with both externally detected faults and internally detected faults to fully cover a financial risk assessment. In [19], artificial neural networks were used by Seo, and the life cycle cost of a product during conceptual design was approximated by implementing the networks. A model for estimating reliability life cycle costs was proposed by Jiang [20]. However, this method is mainly applied to remanufactured products instead of new products. In [21], a robust design method, which includes the effects of uncertainty while evaluating the economic benefits of design changes, was proposed by Roser.

Other approaches aimed at better representation of failures were made by many researchers as well. For example, in [22], Lee proposed employing Bayes probabilistic networks which trace causal chains and their probabilities. The method can not only enhance the way failure is represented in the traditional FMEA but also increase the accuracy of risk analysis. He and Adamyan [23] proposed an approach which combined FMEA and Petri nets to analyze multiple failure effects and their impacts on reliability and quality of product and process design. These approaches provide reliable failure representation and probability estimates, but they do not incorporate cost into the risk prioritization.

Using the expected cost to prioritize risks has proven its validity and objectivity. It was firstly brought up in [24] and has been adopted by many researchers.

Rhee proposed an approach, called life cost-based FMEA with Monte Carlo simulation in [25]. This approach evaluated risk in terms of life cycle cost, which was measured by the loss time. Monte Carlo simulations were applied to the analysis to take

the uncertainty of parameters. In Rhee's another approach [26], a systematic use of empirical data for applying life cost-based FMEA was proposed. According to this approach, information such as availability of system, down time of system, failure frequency, and loss time can all be derived from empirical data. And Monte Carlo simulation needs to be applied as well to account for uncertainty of parameters.

In [27] and [28], Kmenta proposed an approach named scenario-based FMEA. The author explained why the result of the risk analysis could be more reliable if FMEA was organized around failure scenario instead of failure mode and how the analysis process could be facilitated. The rationality behind failure scenarios are discussed too. The expected cost was then proposed to be adopted as the tool to evaluate risks. And detailed comparison between expected cost and RPN were given in their work.

However, in Kmenta's work, detection ratings were assumed to be constant, the rationality behind which needs to be examined. In the approach presented in this thesis, besides the adoption of the expected cost as a tool to evaluate risks, cause-effect chain structures are used too. Such structure is constructed based upon failure scenarios with an identical root cause. Moreover, unlike the approach proposed by Kmenta, detection is included in the structure and contributes to risk evaluation too.

All of the above approaches provide insight into how the traditional FMEA can be improved by various ways. But it is still difficult to address the following issues: the degree of subjectivity in RPNs is significant, comparison of risk information provided by RPNs is difficult and a comprehensive and realistic consideration of possible end effects is still hard.

This research is motivated by the needs to prioritize risks with higher objectivity and accuracy and facilitate comparison of risks between products or processes.

## **1.2. RESEARCH OBJECTIVE**

In this work, a new FMEA approach is proposed to improve the traditional FMEA method so that failure risk can be prioritized more objectively and precisely, and comparison of risks between products or processes across all system levels can be easily facilitated.

To accomplish this objective, the expected cost is utilized in this method to evaluate risks. The expected cost is a universal measurement of risks, and it can be obtained in a much more objective way. This reduces subjectivity in the results to minimum. And by using the expected cost, the results of risk analysis from different system levels can be compared easily. Moreover, with the inclusion of cost as an evaluating factor, it gives the opportunity to balance the costs of corrective actions with expected revenues. This allows an optimized resource allocation and economical evaluation of changes.

What's more, the cause-effect chain structures which are based upon failure scenarios are employed in the new methodology as well. Failure scenario can take all possible end effects into consideration, and so such a cause-effect chain structure can provide a much more reliable and accurate result of risk analysis. At the meantime, by constructing such structures, the calculation of expected cost becomes quite straightforward.



In the new methodology, the occurrence and severity ratings are replaced by the expected costs. The detection rating is reflected in failure scenarios by the probabilities of either successful or unsuccessful detections of causes or effects. This treatment makes the new methodology more realistic.

This method overcomes the aforementioned drawbacks and proves its advantages over the traditional FMEA. 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.

### **1.3. THESIS OUTLINE**

In Section 2, the methodology and limitations of the traditional FMEA are discussed first. Then an extensive review on different approaches that have been made to improve the traditional FMEA and hydrokinetic energy conversion systems is conducted, followed by the background introduction of a hydrokinetic system being developed at Missouri S&T.

In Section 3, the objective of the proposed FMEA approach is introduced first. Then the overview and implementation of the method are illustrated, including all the major components of the method and steps that should be carried out when applying the method. Last, a simple example is used to demonstrate how to apply the method to a problem in reality.

Section 4 mainly consists of application of the proposed method to a hydrokinetic system. The process of the application is illustrated from the first step. Two case studies

are then carried out in this section in order to compare the results and prioritize the one with higher risk.

Section 5 contains the conclusions drawn from the application of the method in Section 4 and some insight into future work. A general introduction to the methodology of the new method is presented in this section first. Then the advantages of the new method over the traditional FMEA are discussed. Future work that can be done to improve the new method is proposed in this section too.

## **2. LITERATURE REVIEW**

### **2.1. INTRODUCTION TO TRADITIONAL FMEA**

Failure Modes and Effects Analysis (FMEA) is one of the widely-used engineering analysis techniques. It is performed to identify, prioritize and eliminate known and potential failures, problems and errors in systems, products or processes before they reach customers [29]. It provides a systematic method of examining all the possible ways in which a failure could occur.

The FMEA is performed in several steps. The first step is describing the product or process on which FMEA is conducted. Then functions of the product or process are defined so that potential failure modes could be identified. Once all possible failure modes are obtained, occurrence rating is assigned to the cause of the failure mode to reflect the probability of the cause and the immediate failure mode, severity rating is assigned to the end effect of the failure mode to reflect the seriousness of the end effect, and detection rating is assigned to the cause of the failure mode to reflect the difficulty of detecting the cause or failure mode. All of the three ratings are quantified by integer values ranging from 1 to 10 and then multiplied together to obtain the risk priority number (RPN), which is used to determine the risk priority of a failure mode.

Failure modes with higher RPNs are considered to have higher risk of malfunction during operation so that corrective actions are taken to reduce the RPNs of these failure modes prior to others. If the RPNs are not reduced as expected, new corrective actions will be designed until the purpose is satisfied. The flowchart describing FMEA procedure is shown in Figure 2.1.

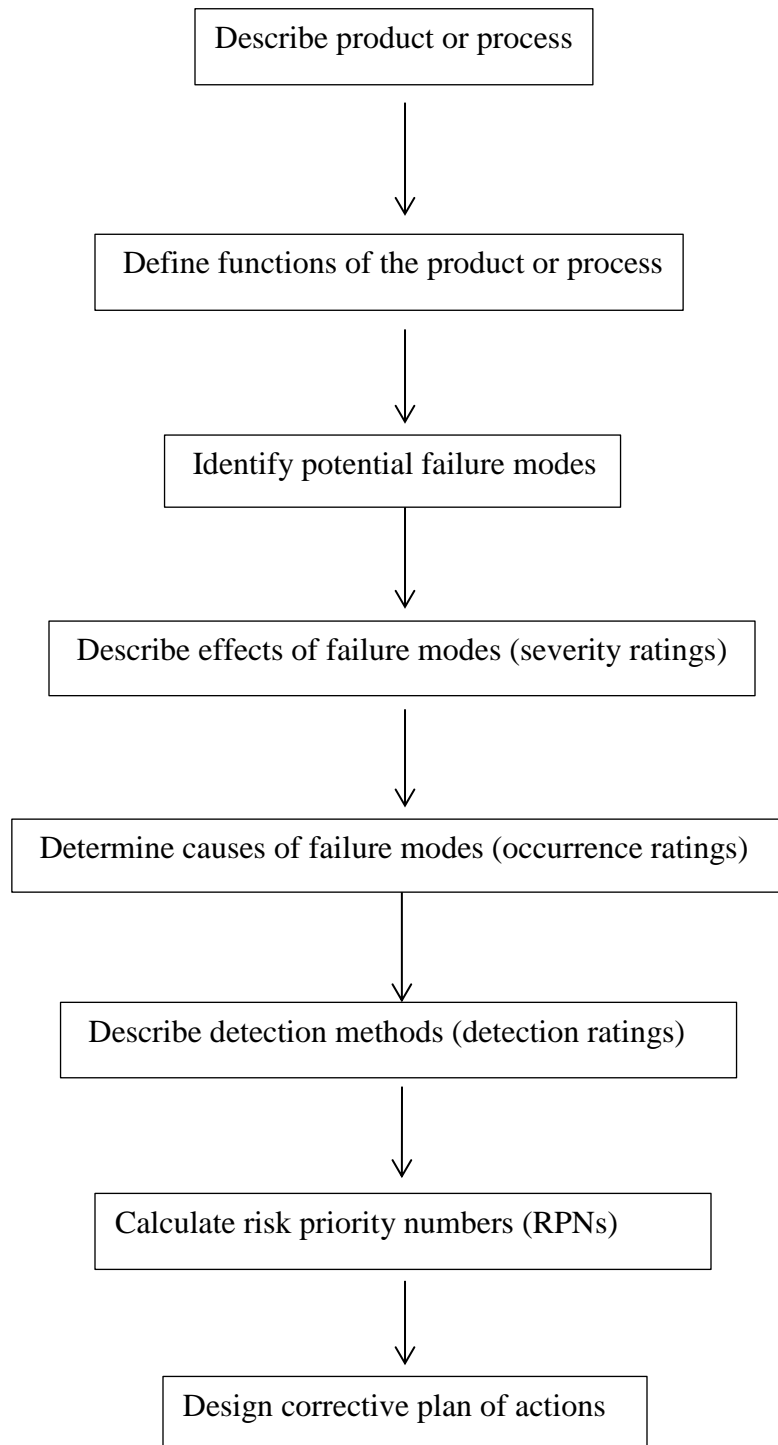


Figure 2.1. Flowchart Describing the Procedure of FMEA

As aforementioned, risk priority number (RPN) is used in FMEA to prioritize failure modes. It is calculated by the following equation.

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

In Equation (1),  $O$  stands for occurrence rating,  $S$  stands for severity rating and  $D$  stands for detection rating. All of the three ratings are quantified by integer values ranging from 1 to 10. Details of the three ratings are provided in Table 2.1 through Table 2.3.

Table 2.1. Ratings for Occurrence [30]

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 2.2. Ratings for Severity [30]

Rank	Effect	Severity of effect
10	Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations.
9	Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards.
8	Extreme	Product is inoperable with loss of primary function. The system is inoperable.
7	Major	Product performance is severely affected but functions. The system may not operate.
6	Significant	Product performance is degraded. Comfort or convince functions may not operate.
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.

Table 2.3. Ratings for Detection [30]

Rank	Detection	Likelihood of detection by 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.

A good FMEA table satisfies the following requirements:

- Identifying known and potential failure modes
- Identifying the causes and effects of each failure mode
- Prioritizing the identified failure modes according to the risk priority number (RPN)
- Providing corrective actions

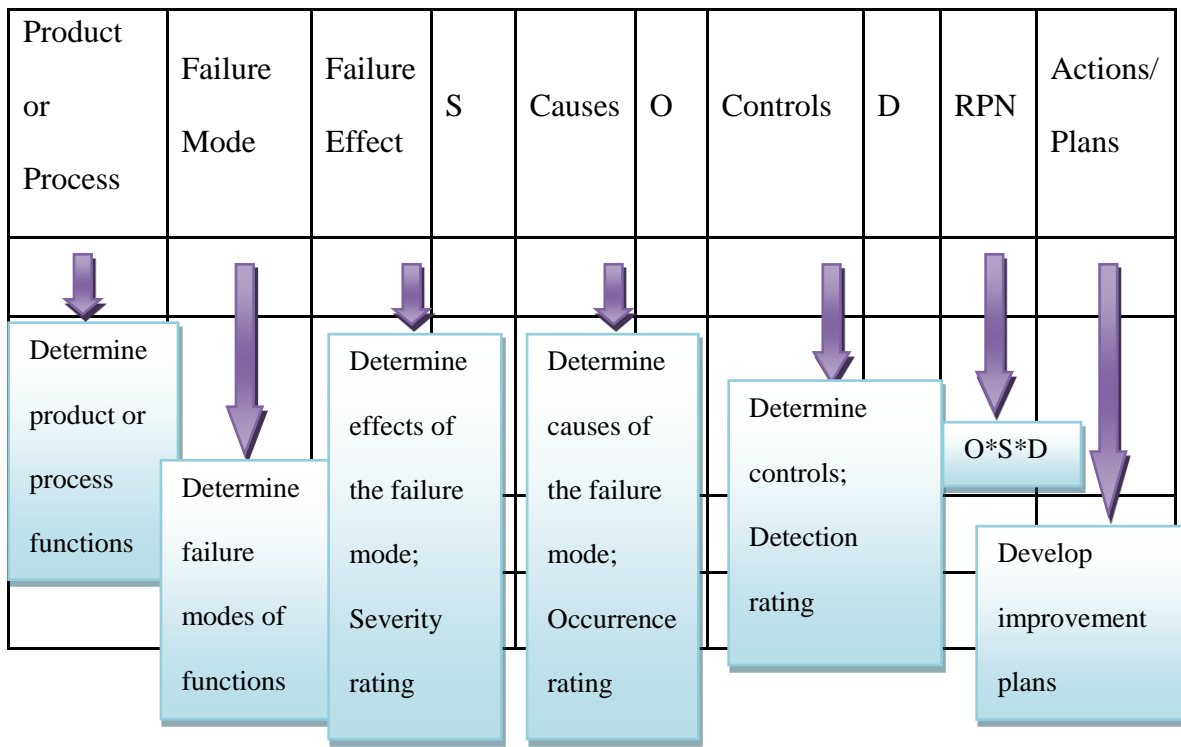
A typical FMEA table is given in Table 2.4.

Because FMEA is easy to use and understand, it's been widely adopted since last century. FMEA was firstly used by contractors for NASA in early 1960s, then it began to be adopted by industry too. In 1967, civil aviation industry started to use FMEA and related techniques [1], and a standard for performing FMEA was published. The use of FMEA in automotive industry began from mid 1970s [2]. It was adopted by the Ford Motor Company for safety and regulatory consideration. And Toyota conducted the FMEA technique on the catalytic converter which was used in the 1975 Toyota models. Critical failure modes to the durability of the catalytic converter and their risks were studied and prioritized through this case study. Since then, the implementation of FMEA started to spread all over industry.

A bank performed process FMEA on its ATM system [3]. According to the RPNs, "machine jams" and "heavy computer network traffic" were considered to have the first and second highest risks.



Table 2.4. A Typical FMEA Table



In [4], FMEA was performed on salmon processing. Fish receiving, casing/marking, blood removal, evisceration, filet-making cooling/freezing, and distribution were identified as the processes with the highest RPN values. After corrective actions were taken, a second calculation of RPN values was carried out resulting in substantially lower values.

However, despite the contribution the traditional FMEA has made to industry all over the world, its shortcomings have never been ignored and have been criticized for many reasons. In next section, more details about the limitations of the traditional FMEA will be discussed.

## 2.2. LIMITATIONS OF TRADITIONAL FMEA

As previously mentioned, the traditional FMEA has proved to be one of the most important early failure-preventive engineering techniques. However, many issues still need to be addressed for further enhancement of this method.

The most criticized shortcoming of FMEA is the determination methodology utilized in producing RPNs. As is known now, RPN is the key factor in FMEA. It is the ultimate tool used by FMEA to evaluate the risk of failure modes. However, as the product of three integer values, *O* (occurrence), *S* (severity) and *D* (detection), the validity and rationality of RPN and the result it yields are always questioned for the following reasons:

- Completely different combinations of *O*, *S*, and *D* can produce identical value of RPN when they can be meaning totally different risks. For example, two different events with the *O*, *S* and *D* ratings of 8, 5, 2 and 2, 4, 10 have the same RPN values while they represent totally different risks.
- RPNs are not evenly distributed from 1 to 1000, which is shown in Table 2.5. Many “holes” exist in the distribution. This introduces much difficulty in interpreting the meaning of the differences between different RPNs. For example, does the difference between RPNs 1 and 2 have the same meaning as the difference between 900 and 1000?
- *O*, *S*, and *D* are considered to be equally important in the calculation of RPN, which may not be true from the perspective of many practitioners, who believe that *S* (severity) is the most important factor.

Table 2.5. RPN Scale Characteristics [31]

Interval	No. of values	%
1-200	67	55.8
201-400	26	21.7
401-600	17	14.2
601-800	7	5.8
801-1000	3	2.5

- *O*, *S*, and *D* are converted differently. The conversion of *O* may follow a linear fashion while that of *D* doesn't. For example, *O* (occurrence) value of 1 and 2 may represent the occurrence probability of 0.1 and 0.2, respectively, following a linear function,  $Y=10*X$ . But detection value cannot be converted in this way.
- Due to the determination methodology of RPN, small variation in one of the *O*, *S*, and *D* ratings can generate vastly different RPNs. For example, if *O* and *S* are both 10, and *D* is 1 or 2, the RPNs are 100 and 200 respectively. Although the detection rating is only changed by 1, the change of RPN is 100.
- The three risk factors are difficult to be quantified precisely and objectively, because the *O*, *S*, and *D* values are often quantified based on the experience of the team members who conduct the analysis, which means different evaluation results can be obtained when the same failure mode is analyzed by different FMEA teams. So the RPN is considered to be of high degree of subjectivity when

estimating the values of the three factors, especially the values of  $S$  (severity) and  $D$  (detection).

For these reasons, it is concluded that RPNs used in the traditional FMEA may not offer a consistent evaluation of risks. In another word, the RPN is seriously limited in terms of its ability to compare, scale and integrate risk information[28]. Considering this, researchers have made many different approaches to improve the traditional FMEA method, which will be discussed in next section.

### **2.3. IMPROVEMENTS ON TRADITIONAL FMEA**

As discussed above, the result of the traditional FMEA method, RPNs, may not be able to offer a consistent evaluation of risks. Moreover, the irrationality and subjectivity of RPNs are criticized too. For the purpose of making FMEA a more reliable tool to conduct risk prioritization, numerous approaches have been made by far. One of the most popular approaches proposed to improve the traditional FMEA is to include other factors such as costs in the risk evaluation process.

The purpose of performing FMEA is to identify and determine the risk priorities of failure modes so that appropriate corrective actions can be taken to prevent potential failures from happening. As is known, risk contains two basic elements: chance and consequence. Chance is easy to understand, which may represent possibility, uncertainty or probability. Meanwhile, consequence often means cost, injury or hazard, so cost can properly serve as an accepted measure of consequences. Moreover, it is also an objective means to evaluate the real effects of failures, which makes it a legitimate factor that can be included to evaluate risks and reduce subjectivity as well. Also, with the inclusion of

cost as an evaluating factor, it gives the opportunity to balance the costs of corrective actions with expected revenues, allowing an optimized resource allocation and evaluation of changes [31].

Ashen proposed a cost-oriented approach to improve the method of FMEA from an economic perspective in [18], which considers the failure costs associated with both externally detected faults and internally detected faults to fully cover a financial risk assessment. A case study using the new method with an automotive supplier, proved it to be more advantageous than conventional FMEA. However, comprehensive and accurate information on the cost of failures is required to implement this approach.

Rhee proposed an approach, called life cost-based FMEA with Monte Carlo simulation in [25]. This approach evaluated risk in terms of life cycle cost, which was measured by loss time. Monte Carlo simulations were applied to the analysis to take the uncertainty of parameters, such as detection time, delay time and fix time into consideration instead of using point estimation of those parameters. This method showed its advantage over RPN and life cost-based point estimation by enabling designers pick the best design in terms of cost.

In Rhee's another approach [26], a systematic use of empirical data for applying life cost-based FMEA was proposed. According to this approach, availability of the system can be derived from empirical data, by which downtime and failure frequency can both be obtained. In addition, with the use of empirical data, loss time can be estimated too, by which failure cost can be acquired. And this approach applies Monte Carlo simulation to the analysis to account for the uncertainty of parameters aforementioned as well.

In [32], Rhee applied the proposed method to a linear particle collider. The concept “expected cost” was adopted, and the two components of expected cost, probability of failure and failure cost, were analyzed more precisely in this work. The author used empirical data to obtain the probability of failure so that the uncertainty and subjectivity which were introduced by estimation could be minimized. Furthermore, in this work the author also provided the break-down of the failure cost, which included labor cost, material cost and opportunity cost as well. It proved that this approach helped engineers with not only design improvements but also concept selection. This overcomes the drawback of the traditional FMEA, which does not consider both risk and lifecycle cost during concept selection. However, the author also admitted the difficulty of extracting useful empirical data efficiently, since a huge amount of irrelevant data existed.

Using expected cost to prioritize risks has proven its validity and necessity and has been adopted by many researchers since firstly brought up by [24]. But there is still space for improvement. Another approach which was proposed from a different angle follows next.

As known, the traditional FMEA is basically an analysis technique organized around failure modes, the description of which can be easily mistaken with failure causes and failure effects sometimes. Failure modes can be as simple as negative statements of function, but when engineers try to describe a failure mode, they often focus on the description of what went wrong, which leads to a statement describing an effect or a cause rather than a failure mode [33].

However, the term failure mode can be less confusing and the process of risk analysis can be facilitated if a failure scenario is generated beforehand, because in a

failure scenario, the failure mode becomes an arbitrary link. In this way, if the failure mode has a cause, and the cause also has its own cause, they will all be added together in the form of a chain; similarly, if the failure mode has a subsequent effect, and this effect has its own subsequent effect, they can also be added to the chain too. So this cause-effect chain can be lengthened whenever new causes and effects are identified. In this way, the simple chain composed of causes and effects now represents a failure scenario. It can be foreseen that risk analysis based on failure scenarios will provide much more reliable and accurate results than the analysis based on a traditional FMEA table, since the possibilities of all kinds of failures given a root cause are all under consideration in failure scenarios while in a traditional FMEA table only the most serious effect is considered.

In sum, the necessity of constructing such failure scenarios lies in the fact that a traditional FMEA table always overlooks different failures that might happen. Take the occurrence of oil leak in a car engine for instance. Suppose oil leak has an effect, for example, engine malfunction. In a traditional FMEA table, such as Figure 2.1, a simple chain will be constructed with occurrence rating assigned to the cause, severity rating assigned to the engine malfunction and detection rating assigned to the detection difficulty of oil leak before engine malfunction is realized. After that, the three ratings are multiplied together to obtain the RPN of this failure mode. Then the risk priority is determined by the RPN. It is not reasonable to completely deny the reliability of this result. However, if a failure scenario rather than a failure mode is considered in this case, totally different results can be obtained. The failure scenarios constructed for this case are shown in Figure 2.2.

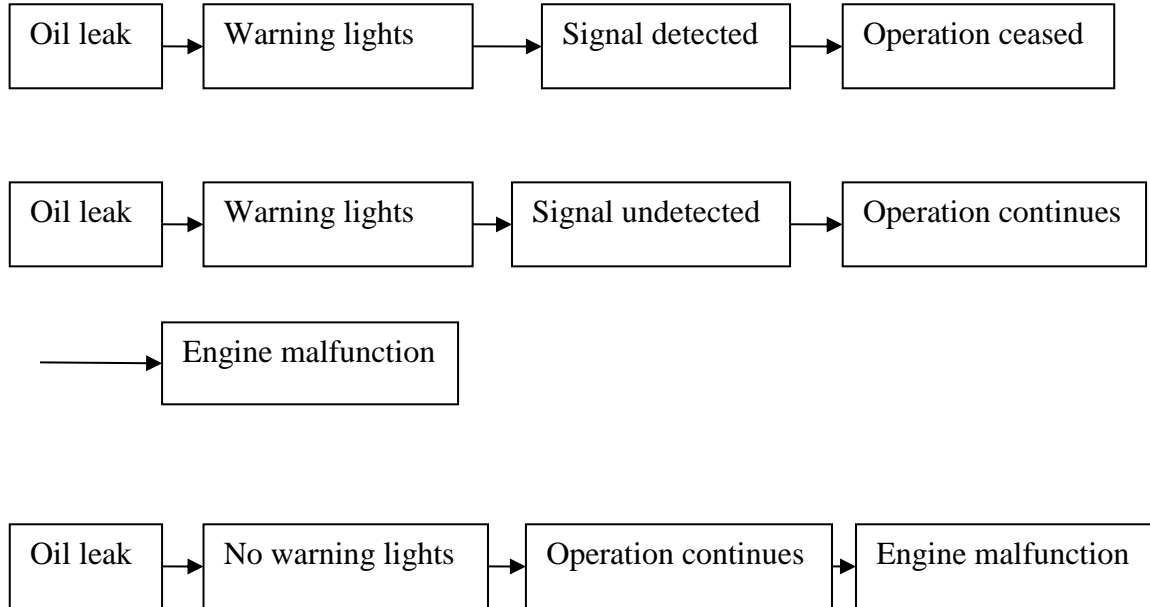


Figure 2.2. An Example of Failure Scenarios [27]

It can be seen from the figure that unlike a traditional FMEA table, three chains instead of only one are constructed. Each of the cause-effect chains represents an individual failure scenario, so the risk analysis should be conducted in every chain now, which implies the possibility that a more reliable result of risk evaluation could be obtained. Moreover, by constructing such chains, “operation ceased” as a new end effect or failure in addition to “engine malfunction” is identified.

In [27], the idea of scenario-based FMEA was first brought up by Kmenta. The author explained why the result of risk analysis could be more reliable if FMEA was organized around failure scenario instead of failure mode. Moreover, the expected cost was proposed to be adopted as the tool to evaluate risks. The advantages of expected cost over RPN were discussed too. But only cursory explanation was given in this work. In



[28], more details were given on the advantages of failure scenario over failure mode and the rationality behind failure scenarios. In addition, detailed comparison between the RPN and expected cost was given in this work too.

Many different approaches have been made to improve FMEA. And some of them proved to be applicable in eliminating the shortcomings of the traditional FMEA, but some still need to be further examined. In this work, a modified approach based on Kmenta's method and the idea of Bayesian network FMEA [22] is made. And it is applied to a hydrokinetic energy conversion system being developed at Missouri S&T.

#### **2.4. HYDROKINETIC ENERGY CONVERSION SYSTEMS**

Hydrokinetic energy is an emerging field of renewable energy. Compared to hydroelectric energy, which is the most widely used renewable energy around the world, hydrokinetic energy is still in the developmental phase.

Hydrokinetic energy is described as the energy that can be generated from flowing water in rivers or oceans. Unlike the conventional hydropower generation, hydrokinetic energy is generated by extracting kinetic energy from flowing water rather than potential energy from falling water [34].

An illustration of the hydrokinetic turbine blades and transmission shaft assembly is shown in Figure 2.3.

In a typical hydrokinetic turbine, the rotor of the hydrokinetic turbine is immersed in the river or ocean. The kinetic energy of flowing water is then harnessed by the system to rotate the rotor blades. Through the transmission shaft and gear box, the energy is then

transmitted to a generator that is coupled to the rotor. As long as the rotor blades are rotated by the flowing water, the generator will generate electric power continuously.

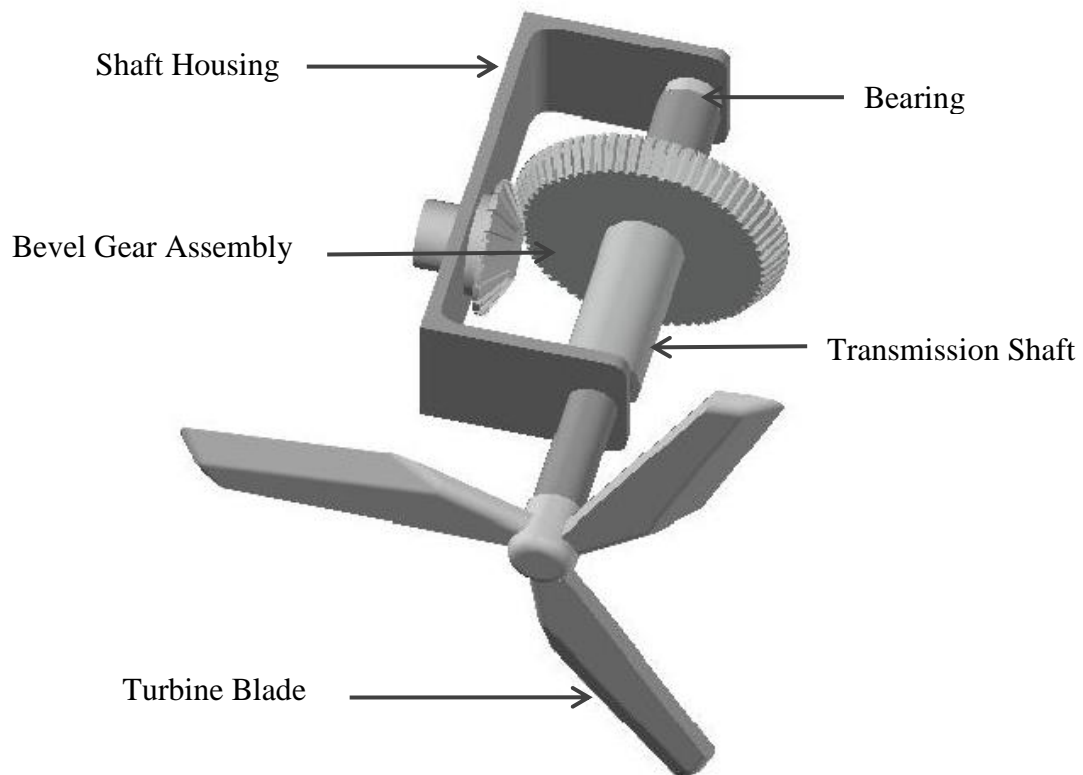


Figure 2.3. Assembly of Hydrokinetic Turbine Blades [35]

Hydrokinetic systems have many advantages over other hydropower systems. Since a hydrokinetic turbine harnesses the kinetic energy of flowing water instead of potential energy of water fall, it doesn't require the construction of dams or reservoirs,

which saves a lot of work and labor cost and incurs very little impact on environment, so it is much more environment-friendly compared with other power sources [36, 37].

Moreover, a hydrokinetic turbine system is usually smaller in size compared with solar or wind energy system, which makes it easier to be moved and reallocated. Therefore, it is more adapted to the natural environment change. The initial cost of a hydrokinetic turbine is relatively small too [38, 39].

By studying the process of energy generation from other fields, such as tidal energy, marine current energy and most importantly wind energy, a good understanding of how hydrokinetic energy conversion system works can be obtained, because they basically work on the same principle. The kinetic energy of the streaming fluid is utilized to rotate an electromechanical energy converter and subsequently generate electricity. [40]

Currently, turbine systems, which are conceived as major choices for the conversion of hydrokinetic energy, generally fall into three categories: horizontal axis, vertical axis and cross flow turbines [41]. But the first two types, horizontal axis and vertical axis turbines, however, are most widely used.

**2.4.1. Horizontal Axis Hydrokinetic Turbine.** Horizontal axis turbines usually have axes parallel to the incoming water flow. The kinetic energy of the flowing water will rotate the turbine blades and then electric power will be generated continuously. Various arrangements of axial turbines including inclined axis turbines and straight axis turbines can be found in Figure 2.4. Generally speaking, an inclined axis turbine is mostly considered to be used for small river energy conversion, while straight axis turbines are the prime choices for tidal energy conversion.

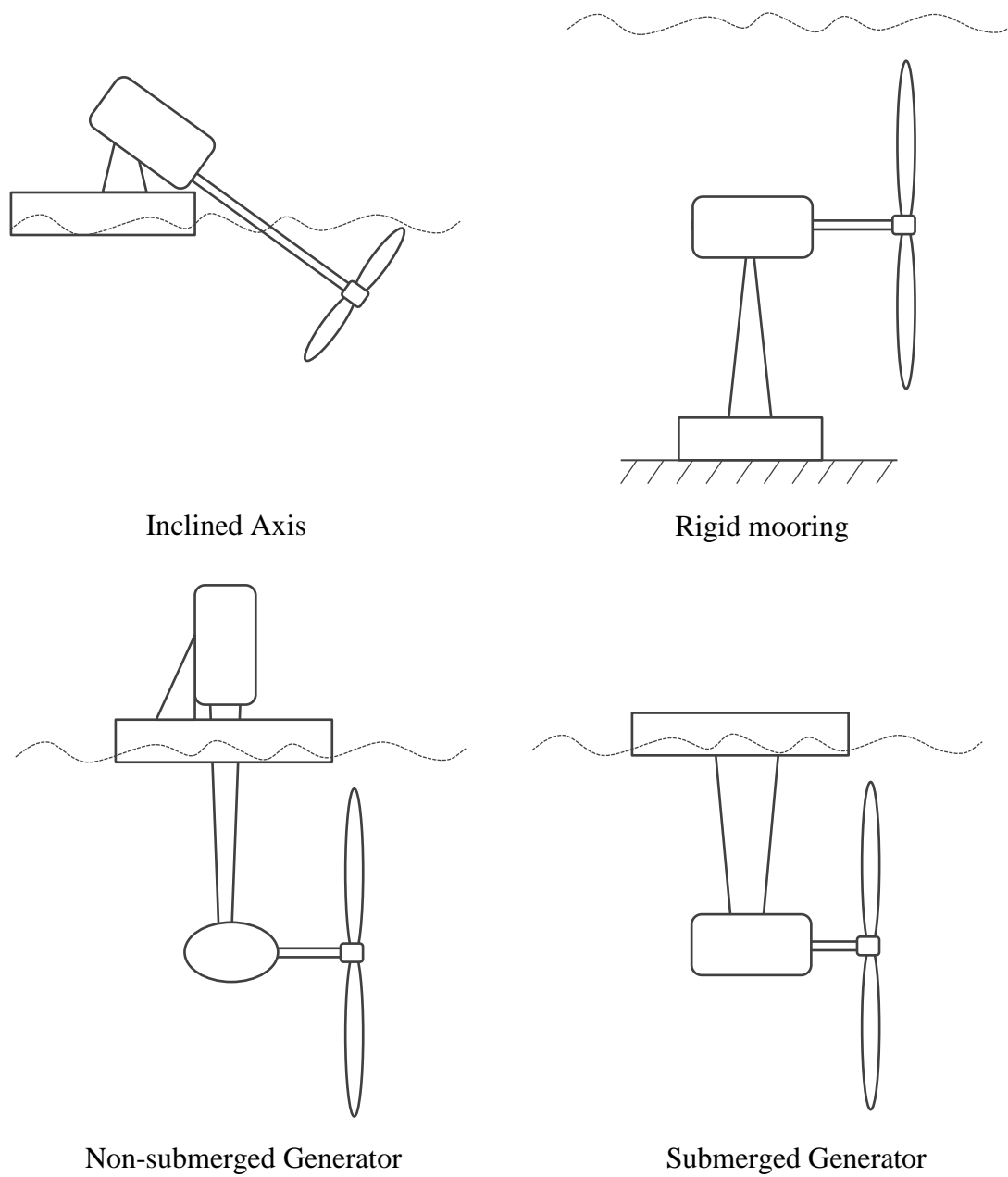


Figure 2.4. Types of Horizontal Axis Hydrokinetic Turbine [41]

**2.4.2. Vertical Axis Hydrokinetic Turbine.** In the vertical axis domain, various arrangements of turbines are shown in Figure 2.5. Darrieus turbines are the prominent choices for vertical axis turbines, especially the two straight bladed turbines in the figure. The applications of them are quite common and easy to find, however, the use of Darrieus turbines with curved or parabolic blades cannot be found yet. Gorlov and Savonius turbines are shown in the figure too, which may consist of straight or skewed blades.

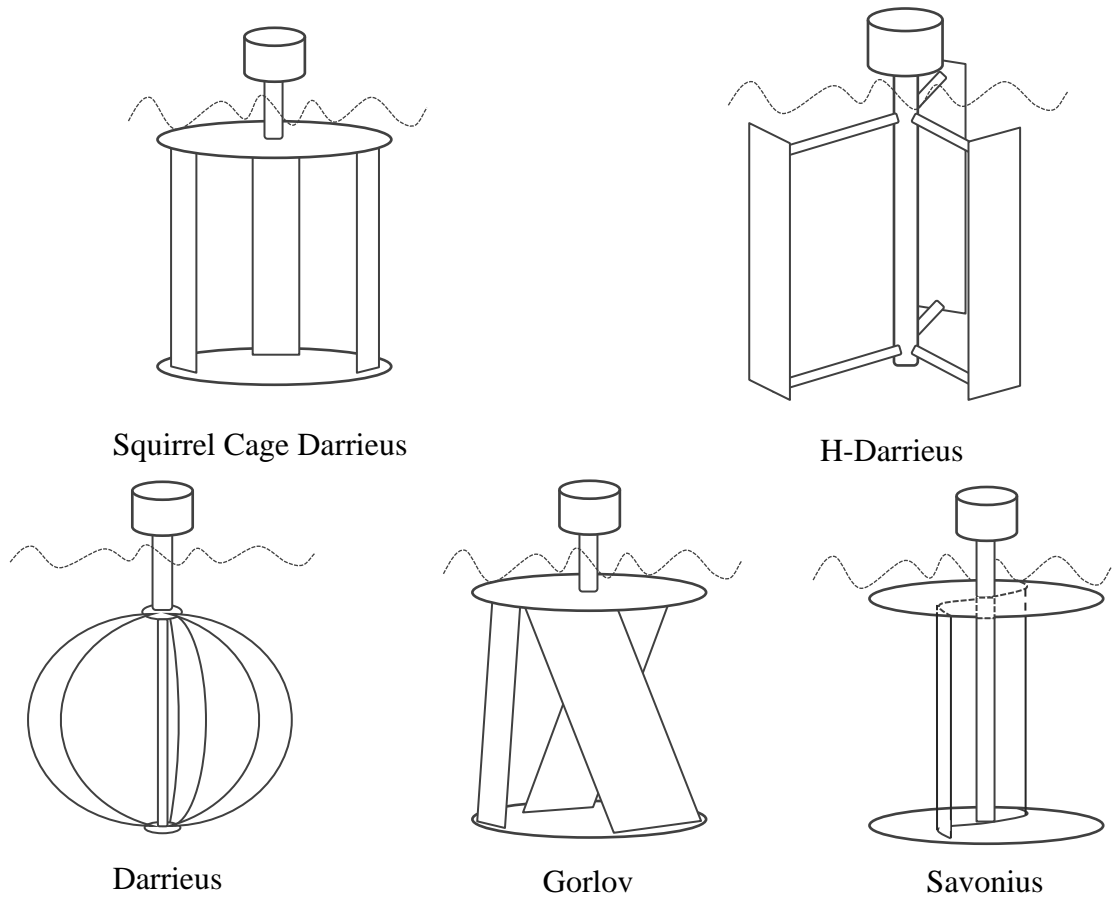


Figure 2.5. Types of Vertical Axis Hydrokinetic Turbine [41]

**2.4.3. Challenges and Prospects.** Although the advantages of hydrokinetic are obvious, the challenges it faces are significant too. Because the concept of hydrokinetic energy is relatively new, not much work has been done towards the development of hydrokinetic turbines and they are not widely deployed for commercial use yet. So data regarding underwater installation, material issues, etc. is limited, which puts a lot of obstructions on the way to develop a cost-effective hydrokinetic system.

However, the future of hydrokinetic system is still promising. Study shows that the US rivers hydrokinetic power potential is estimated to be 12,500 MW per year [42]. As the electricity consumption around the globe increases every year, if hydrokinetic energy is proved to be cost-effective, utilizing this promising power source will help address the pending energy crisis the world faces [43].

In Section 2.5, a hydrokinetic system being developed at Missouri University of Science and Technology will be introduced.

## **2.5. HYDROKINETIC TURBINE BEING DEVELOPED**

The turbine developed in Mechanical Engineering Department at Missouri S&T is a horizontal axis turbine shown in Figure 2.6.

According to [44] and [45], for wind turbine systems, failure modes of turbine blades have the highest RPNs, and they should be given more consideration at the design stage.

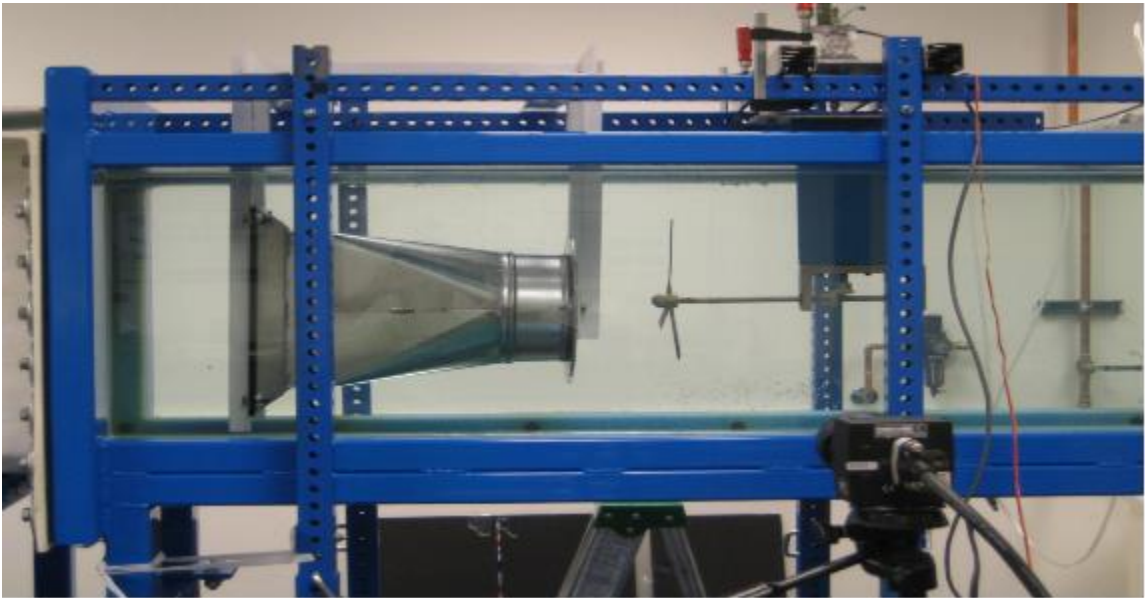


Figure 2.6. Hydrokinetic Turbine at Missouri S&T

Since hydrokinetic turbine and wind turbine are similar from design and operation point of view, and they basically work on the same principle, it is assumed that for hydrokinetic systems, turbines blades are also have the failure modes with the highest RPNs and priority should be given to them for corrective actions.

The turbine blades can be seen in Figure 2.7 and Figure 2.8. The blades are made from composite materials, because composite materials are lightweight, durable and water resistant compared with metals. More importantly, composite materials make it possible to embed sensors inside the blades during manufacturing process so that the structure health can be monitored when the system is in operation.



Figure 2.7. Front View of the Turbine Blades



Figure 2.8. Side View of the Turbine Blades



Figure 2.7 and Figure 2.8 show front and side view of the turbine blades of the hydrokinetic system, respectively. Each of the three composite blades is about 0.3 m in length and embedded with a fiber optic strain gage and acoustic transducer.

The fiber optic strain gage senses the degradation of the blade structure over time due to cyclic loading and transient environmental factors. A power and electronics module inside the blade conditions the fiber optic strain gage signal into an acoustic signal that is transmitted by the acoustic transducer. The acoustic waves propagate through the water to a receiver that is located near the shore or on the system foundation. The received acoustic signal can then be broadcast above water long distances by radio waves to the monitoring station. The broadcast signal can be interpreted at the monitoring station, yielding real-time strain data from the blade [46].

The proposed modified FMEA approach will be applied to the turbine blades introduced above, details of which will be given in Section 4.

In the next section, details on the motivation to propose the new method and how it works will be discussed.

### 3. IMPROVED FMEA METHODOLOGY

#### 3.1. OBJECTIVE OF THE NEW APPROACH

As discussed in previous chapter, although the traditional FMEA is a good tool for preventing potential failures, the methodology has many drawbacks, especially the way of determining the risk priority numbers.

The objective of this research is to develop a new FMEA approach to improve the traditional FMEA method so that failure risks can be prioritized more objectively and precisely in terms of cost.

In the new method, the expected cost instead of RPN is used to conduct risk evaluation by the following equation.

$$Risk = P_f C \quad (2)$$

where  $P_f$  means the probability of failure, and  $C$  means the failure cost.

From the perspective of many engineers, risk contains two elements: 1) chance: possibility, uncertainty, probability, etc., and 2) consequence: cost, hazard, injury, etc. The chance describes the possibility of undesired event, and the consequence is intended to quantify the loss caused by the failure. Since a probability is a universal measure of chance and a cost is also a universal measure of consequence, the expected cost as the product of failure probability and failure cost can serve as a legitimate way to evaluate risk. In addition, the results obtained in this way can minimize subjectivity since the probability of failure and failure cost can be usually obtained from available historical data.

From Equation, it is observed that expected cost is composed of two elements, the probability of failure  $P_f$  and the failure cost  $C$ . If  $P_f$  and  $C$  both increase, the risk will increase; if  $P_f$  and  $C$  both decrease, the risk will decrease; however, if  $P_f$  increases and  $C$  decreases, or,  $P_f$  decreases and  $C$  increases, the change of risk cannot be determined.

Prior to any risk calculation, the cause-effect chain structures should be constructed first. Such structures are constructed based upon failure scenarios [27] and Bayes Belief Networks [22].

In a cause-effect chain structure, all possible end effects given a root cause are under consideration, and this makes the results of risk analysis more reliable and accurate. In addition, detections are included in the structure as well, which is unlike the approach proposed by Kmenta in [28], where the probability of detection is assumed to be constant. In this approach, the detection is included in the cause-effect chain structure and is reflected as the probability of successful or unsuccessful detection when calculating the probability of end effects. This makes the results more realistic.

By adopting expected cost and cause-effect chain structures, the new method overcomes the drawbacks of the traditional FMEA in the following areas.

- When calculating RPNs, there is no standard scale for the  $O$  (occurrence),  $S$  (severity), and  $D$  (detection) ratings, and they vary based on scope, applications and so on [28]. The ratings are not based upon strictly objective elements but most on the experience of the team members who conduct the analysis, and so the results yielded by RPNs are inevitably considered to be of high subjectivity.

- Since the magnitudes of RPNs are not meaningful, the comparison of RPNs between different products or processes is difficult and sometimes impossible. Different products or processes have different criteria based on which the *O*, *S* and *D* ratings are quantified, so the failure mode of one product with higher RPN does not necessarily have higher risk than the failure mode of another product.
- Even within a single FMEA, comparison of RPNs is not straightforward, because the traditional method is unable to represent the distance between each RPN value. As known, RPN is the product of three ordinal values: *O*, *S* and *D*. Ordinal values are often used to rank industries, such as quality of hotels, theaters and restaurants etc. The magnitudes of RPNs are not meaningful, and they can only represent the rank in a group of items [47]. So the distance between the values cannot be measured, for example, if one RPN is twice another one, you can only make an appropriate assumption that the failure mode with the higher RPN has “higher” risk than the other failure mode. You cannot state that its risk is twice that of the other one.
- Furthermore, the traditional FMEA tends to overlook different end effects that might actually happen, since in a traditional FMEA table, only the most serious end effects of failure modes are considered and then severity ratings are assigned to them. But in reality, when the cause of a failure mode happens, it is very likely that other different end effects can happen too.

In the next section, an overview of the proposed methodology will be discussed.

### 3.2. OVERVIEW OF THE NEW APPROACH

As discussed in Section 3.1, the cause-effect chain structures should be constructed first to conduct the risk analysis. A cause-effect chain structure is mainly based upon failure scenarios. Once given a root cause, this structure is expected to include as many failure scenarios as possible to make the risk evaluation more accurate and reliable. An example of the cause-effect chain structure for demonstration is shown in Figure 3.1.

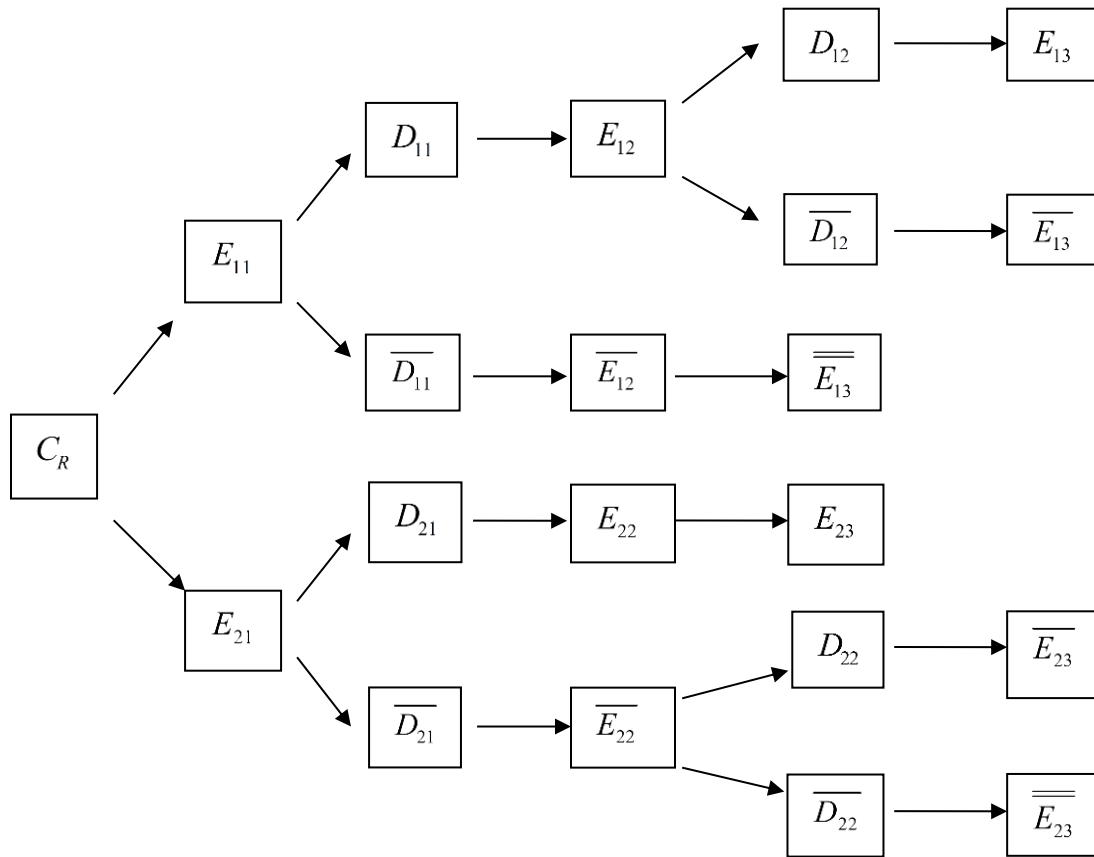


Figure 3.1. A Cause-Effect Chain Structure for Demonstration

Each chain is composed of three basic elements: root cause  $C_R$ , detection  $D$  and effect  $E$ , which includes immediate effects, intermediate effects and end effects. The end effect in each chain is often represented by failure cost  $C$  when calculating the risk in terms of cost.

The subscription of symbols in such a structure is explained in Table 3.1 below. There are six cause-effect chains in this structure. Since every chain can be interpreted in a similar fashion, only the first two chains are used to explain the methodology of the new FMEA approach.

Table 3.1. Meanings of Symbols in a Cause-Effect Chain Structure

Symbols	Meanings
$C_R$	Root cause in a cause-effect chain structure
$E$	Effect of cause in a cause-effect chain structure
$E_{ij}$	The $j$ -th intermediate effect in the chain initiated by the $i$ -th immediate effect of root cause $C_R$ without unsuccessful detection ahead
$\overline{E_{ij}}$	The $j$ -th intermediate effect in the chain initiated by the $i$ -th immediate effect of root cause $C_R$ with one unsuccessful detection ahead

Table 3.1. Meanings of Symbols in the Cause-Effect Chain Structure (cont.)

$\overline{\overline{E_{ij}}}$	The $j$ -th intermediate effect in the chain initiated by the $i$ -th immediate effect of root cause $C_R$ with two unsuccessful detections ahead
$D$	Detection implemented in a cause-effect structure
$D_{ij}$	Successful detection of intermediate effect $E_{ij}$
$\overline{D_{ij}}$	Unsuccessful detection of intermediate effect $E_{ij}$
$C$	Failure cost of end effect in each failure scenario
$C_i$	The failure cost in the $i$ -th chain of the structure

In the first chain, root cause  $C_R$  has an immediate effect  $E_{11}$ . Detection is then implemented to detect the occurrence of  $E_{11}$ . If it is detected, effect  $E_{12}$  happens. On the other hand, if it goes undetected, another effect  $\overline{E_{12}}$  happens. Then effect  $\overline{E_{12}}$  is under detection again, which yields two different end effects depending on whether it is detected or not.  $E_{13}$  means the end effect if  $E_{12}$  is detected successfully, and it is represented by failure cost  $C_1$ .  $\overline{E_{13}}$  is the end effect if  $E_{12}$  is not detected at all, and it is represented by failure cost  $C_2$ . It can be expected that  $C_2$  will be much larger than  $C_1$ .

Using the same method, FMEA teams will be able to construct different cause-effect structures for different root causes. Then the expected cost of every root cause will

be compared with each other. The one with the highest expected cost will be the root cause with the highest risk so that corrective actions can be taken prior to others.

It should be pointed out that the structure shown in Figure 3.1 is merely an illustrative case used to demonstrate the methodology. The number of immediate effects, intermediate effects and detections are all changeable. For example, root cause  $C_R$  may have one or more immediate effects in the structure above, while in the case above it has two immediate effects,  $E_{11}$  and  $E_{21}$ . Similarly, one immediate effect may have one or more subsequent effects too. The number of detections in a cause-effect chain is also changeable. For example,  $D_{11}$  and  $D_{12}$  are implemented in the first cause-effect chain, but under certain circumstances it might be impossible to identify the occurrence of effect  $E_{12}$ . This means that  $D_{12}$  will not exist any longer. On the other hand, there might be more detections along the chain too, for example,  $D_{13}$ .

In sum, different root causes can have totally different cause-effect structures. However, the routine of constructing such a structure is universal. One just needs to examine from root cause to end effects and identify every intermediate effect  $E$  and detection technique in between.

### **3.3. IMPLEMENTATION OF THE NEW APPROACH**

Once a complete chain structure is constructed, the next step is collecting information from historical data or other sources to calculate the risk of root causes. Sometimes it can be extremely difficult to acquire useful information. If this happens, making appropriate assumptions is acceptable.



Equation (2) indicates that in order to calculate the risk, the probability of failure  $P_f$  and failure cost  $C$  should be obtained first.

To acquire the probability of failure, information such as the occurrence probability of root cause  $C_R$ , conditional probability of immediate effect and intermediate effect  $E$  are needed.

According to the theory of conditional probability, for two events  $A$  and  $B$  with  $P(A) > 0$ , the conditional probability for  $B$  given  $A$  is

$$P(B|A) = \frac{P(A \cap B)}{P(A)} \quad (3)$$

where  $A \cap B$  means events  $A$  and  $B$  both happen, and  $P(A \cap B)$  means the joint probability of  $A$  and  $B$ .

The equation above can be also written as

$$P(A \cap B) = P(B|A)P(A) \quad (4)$$

It means that 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  $A$ .

Moreover, considering another event  $C$ , the conditional probability of which given the occurrence of  $A$  and  $B$  is given as

$$P(C|A \cap B) = \frac{P(A \cap B \cap C)}{P(A \cap B)} \quad (5)$$

Equation (4) can be written as

$$P(A \cap B \cap C) = P(C|A \cap B)P(A \cap B) \quad (6)$$

By the theory provided by Equation (4) and (6), once occurrence probability of root cause  $C_R$ , conditional probability of immediate effect and intermediate effect  $E$  are all obtained, the probability of failure can be calculated easily. Moreover, a cause-effect chain structure makes the calculation straightforward.

The failure cost can usually be acquired by historical data. After all the information is collected, the risk of root cause  $R(C_R)$  can be now calculated.

For the structure in Figure 3.1, the equations that calculate the risk of root cause  $C_R$  are shown below. There exist six paths in the structure, each path is evaluated individually then all the results are added together to represent the total risk of root cause.

For path 1:  $C_R \rightarrow E_{11} \rightarrow D_{11} \rightarrow E_{12} \rightarrow D_{12} \rightarrow E_{13}$

$$\begin{aligned} R_1(C_R) &= P(C_R)P(E_{11}|C_R)P(D_{11})P(E_{12}|C_R, E_{11}, D_{11})P(D_{12}) \\ &P(E_{13}|C_R, E_{11}, D_{11}, E_{12}, D_{12})C_1 \end{aligned} \quad (7)$$

For path 2:  $C_R \rightarrow E_{11} \rightarrow D_{11} \rightarrow E_{12} \rightarrow \overline{D_{12}} \rightarrow \overline{E_{13}}$

$$\begin{aligned} R_2(C_R) &= P(C_R)P(E_{11}|C_R)P(D_{11})P(E_{12}|C_R, E_{11}, D_{11})P(\overline{D_{12}}) \\ &P(\overline{E_{13}}|C_R, E_{11}, D_{11}, E_{12}, \overline{D_{12}})C_2 \end{aligned} \quad (8)$$

For path 3:  $C_R \rightarrow E_{11} \rightarrow \overline{D_{11}} \rightarrow \overline{E_{12}} \rightarrow \overline{\overline{E_{13}}}$

$$R_3(C_R) = P(C_R)P(E_{11}|C_R)P(\overline{D_{11}})P(\overline{\overline{E_{13}}}|C_R, E_{11}, \overline{D_{11}})C_3 \quad (9)$$

For path 4:  $C_R \rightarrow E_{21} \rightarrow D_{21} \rightarrow E_{22} \rightarrow E_{23}$

$$R_4(C_R) = P(C_R)P(E_{21}|C_R)P(D_{21})P(E_{23}|C_R, E_{21}, D_{21})C_4 \quad (10)$$

For path 5:  $C_R \rightarrow E_{21} \rightarrow \overline{D_{21}} \rightarrow \overline{E_{22}} \rightarrow D_{22} \rightarrow \overline{E_{23}}$

$$R_5(C_R) = P(C_R)P(E_{21}|C_R)P(\overline{D_{21}})P(\overline{E_{22}}|C_R, E_{21}, \overline{D_{21}})P(D_{22})P(\overline{E_{23}}|C_R, E_{21}, \overline{D_{21}}, \overline{E_{22}}, D_{22})C_5 \quad (11)$$

For path 6:  $C_R \rightarrow E_{21} \rightarrow \overline{D_{21}} \rightarrow \overline{E_{22}} \rightarrow \overline{D_{22}} \rightarrow \overline{\overline{E_{23}}}$

$$R_6(C_R) = P(C_R)P(E_{21}|C_R)P(\overline{D_{21}})P(\overline{E_{22}}|C_R, E_{21}, \overline{D_{21}})P(\overline{D_{22}})P(\overline{\overline{E_{23}}}|C_R, E_{21}, \overline{D_{21}}, \overline{E_{22}}, \overline{D_{22}})C_6 \quad (12)$$

The total risk of root cause is given by

$$R(C_R) = R_1(C_R) + R_2(C_R) + R_3(C_R) + R_4(C_R) + R_5(C_R) + R_6(C_R) \quad (13)$$

In Equation (7),  $R_1(C_R)$  means the risk of root cause for the first chain.  $P(C_R)$

means the occurrence probability of root cause,  $P(E_{11}|C_R)$  means the conditional

probability of effect  $E_{11}$  given the occurrence of root cause  $C_R$ . Moreover, since

detection is also considered when constructing the cause-effect chain structure,  $P(D_{11})$  in the equation means the probability of successful detection. The other elements in the equations can be explained in a similar way.

Equations (7) through (12) calculate the risk of root cause in each path. Equation (13) adds them together to calculate the total risk in terms of expected cost.

In next section, a simple example will be given to demonstrate the new FMEA methodology.

### **3.4. AN EXAMPLE FOR DEMONSTRATION**

In Section 2.3, an example was used to show the difference between a failure scenario and a failure mode, the same example is adopted here to demonstrate how the new method is applied to evaluate the risk of root cause.

All of the failure scenarios initiated by a root cause are shown in Figure 2.2 in Section 2. Based upon the failure scenarios, a cause-effect chain structure is constructed as shown in Figure 3.2.

In the structure, oil leak is the root cause  $C_R$ , and the purpose of analysis is to find the total risk of  $C_R$  in terms of expected cost. As seen from the structure, “Oil leak” as a root cause has two immediate effects, “Warning lights on” and “No warning lights”, and each of them serves as a cause in their own chains.

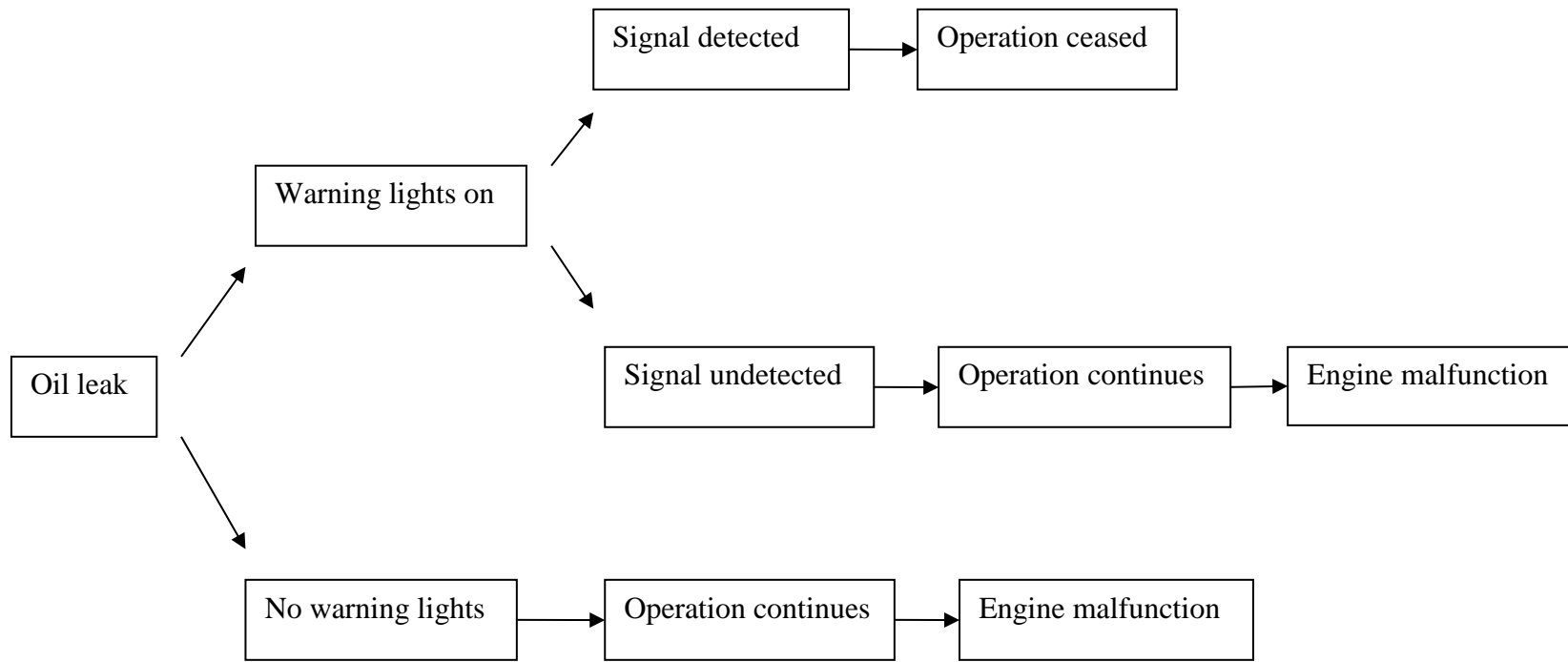


Figure 3.2. An Example of Cause-Effect Chain Structures [27]

If warning lights turn on, and the signal is detected, then the end effect will be “Operation ceased”, and this means that the driver will send the car to be examined.

On the other hand, if the signal is not detected, the driver will continue driving without noticing the oil leak, and this leads to the end effect “Engine malfunction”.

Besides these two failure scenarios, there is another possibility that warning lights never turn on after oil leak. If this happens, the driver will also continue driving without noticing oil leak in the engine, and so the end effect in this failure scenario is “Engine malfunction” too.

The simplified structure after substituting symbols into Figure 3.2 is shown below in Figure 3.3.

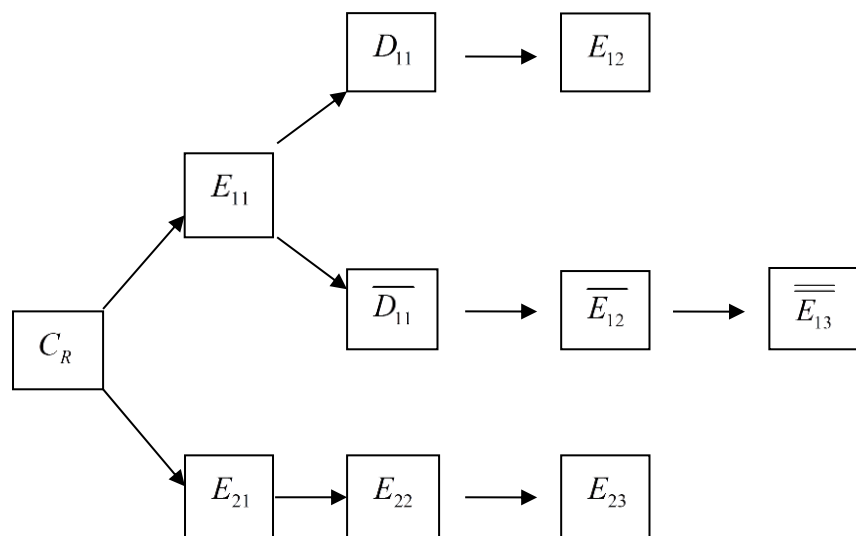


Figure 3.3. Simplified Structure after Substituting Symbols into Figure 3.2

In this case, for a root cause “Oil leak”, there exist three failure scenarios, in another word, three chains. To evaluate the risk, the risk of root cause in each chain should be analyzed separately first. Then add all the risk together in order to acquire the total risk of root cause for the whole structure. So the next step after the construction of such a structure will be collecting as much useful information from historical data as possible. Once the information about the occurrence probability of each element in the structure above and failure cost are both acquired, the risk of “Oil leak” in terms of cost can be calculated.

The equations used to calculate the risks are displayed below.

For path 1:  $C_R \rightarrow E_{11} \rightarrow D_{11} \rightarrow E_{12}$

$$R_1(C_R) = P(C_R)P(E_{11}|C_R)P(D_{11})P(E_{12}|C_R, E_{11}, D_{11})C_1 \quad (14)$$

For path 2:  $C_R \rightarrow E_{11} \rightarrow \overline{D_{11}} \rightarrow \overline{E_{12}} \rightarrow \overline{E_{13}}$

$$R_2(C_R) = P(C_R)P(E_{11}|C_R)P(\overline{D_{11}})P(\overline{E_{12}}|C_R, E_{11}, \overline{D_{11}})P(\overline{E_{13}}|C_R, E_{11}, \overline{D_{11}}, \overline{E_{12}})C_2 \quad (15)$$

For path 3:  $C_R \rightarrow E_{21} \rightarrow E_{22} \rightarrow E_{23}$

$$R_3(C_R) = P(C_R)P(E_{21}|C_R)P(E_{22}|C_R, E_{21})P(E_{23}|C_R, E_{21}, E_{22})C_3 \quad (16)$$

The total expected cost of root cause is given by

$$R(C_R) = R_1(C_R) + R_2(C_R) + R_3(C_R) \quad (17)$$

Now that all the equations used for calculating risks are obtained, the next step is collecting information on all of the elements in the equations, for example, the occurrence probability of root cause  $P(C_R)$ .

The information is provided in Table 3.2 and Table 3.3. The values may change for other cases, since the information can vary significantly under different circumstances, for example, age of the car, regular maintenance history of the car, and so on.

Table 3.2. Probability Values

$P(C_R)$	0.1	$P(E_{12}   C_R, E_{11}, D_{11})$	0.99
$P(D_{11})$	0.95	$P(\overline{E_{12}}   C_R, E_{11}, \overline{D_{11}})$	0.94
$P(\overline{D_{11}})$	0.05	$P(\overline{\overline{E_{13}}}   C_R, E_{11}, \overline{D_{11}}, E_{12})$	0.99
$P(E_{11}   C_R)$	0.97	$P(E_{22}   C_R, E_{21})$	0.99
$P(E_{21}   C_R)$	0.03	$P(E_{23}   C_R, E_{21}, E_{22})$	0.98

Table 3.3. Failure Costs (in Dollars)

$C_1$	500	$C_3$	3000
$C_2$	3000		



With the information provided by Table 3.2 and Table 3.3, the risk of root cause for each path can be calculated as follows.

$$R_1(C_R) = 0.1 \times 0.97 \times 0.95 \times 0.99 \times 500 = \$45.61425 \quad (18)$$

$$R_2(C_R) = 0.1 \times 0.97 \times 0.05 \times 0.94 \times 0.99 \times 3000 = \$13.54023 \quad (19)$$

$$R_3(C_R) = 0.1 \times 0.03 \times 0.99 \times 0.98 \times 3000 = \$8.7318 \quad (20)$$

The total expected cost of root cause is then given by

$$R(C_R) = 45.61425 + 13.54023 + 8.7318 = \$67.88628 \quad (21)$$

The total expected cost of root cause  $R(C_R)$  is about 68 dollars.

In the next section, the new FMEA method will be applied to the turbine blades of the aforementioned hydrokinetic system. The expected costs of two root causes are evaluated and compared to each other so that the root cause with higher expected cost can be identified and corrective actions are taken to reduce the expected cost.

#### 4. APPLICATION

In Section 3, a new FMEA approach was introduced. This approach uses the expected cost to evaluate the risk of root causes. In order to facilitate the process of risk analysis, a cause-effect chain structure which is based on failure scenarios is employed too. Failure scenarios can include all possible failures initiated by the same root cause, and this makes the result of the risk analysis more reliable and accurate. After constructing such a structure, information such as probabilities of root causes, conditional probabilities of intermediate effects and failure costs is collected from historical data and other sources. Then the risk of the root cause in terms of expected cost can be calculated easily.

The objective of this research task is to evaluate and apply the new FMEA method to the hydrokinetic turbine design. The system is still under development, data are not sufficient. But we still conduct the application using historical data and other sources.

Wind turbine and hydrokinetic turbine are quite similar to each other from both design and operation point of view, and thousands of wind turbines are in service right now, and data from wind turbines can serve as a source for the risk analysis on hydrokinetic turbines. However, the operation environment of hydrokinetic turbines is significantly different from that of wind turbines, and the data should be used selectively. At the meantime, data from hydrokinetic turbines that are deployed all over the world are collected as well when applying the new approach to the aforementioned hydrokinetic turbines.

In this section, details on how the new approach is applied to the hydrokinetic turbine system will be discussed. Since a turbine blade is the most critical component in the system, in this case study, we applied the new method to its design. Root causes and intermediate effects of turbine blades are examined to make sure all possible failure scenarios are considered.

#### **4.1. FAILURE SCENARIOS OF TURBINE BLADES**

Root causes that might happen when the turbine is in operation are considered and all the possible failure scenarios that are initiated by the root causes are shown in Table 4.1.

As can be observed from the first column in the table, there are in total six root causes. Each of them initiates a cause-effect chain structure. The second root cause, “Corrosive environment”, is used to demonstrate how to conduct the risk analysis. This root cause results in five different failure scenarios. Each scenario is analyzed separately, and then the results are aggregated together to obtain the total risk of this root cause.

#### **4.2. CONSTRUCTING CAUSE-EFFECT CHAIN STRUCTURES**

As discussed in Section 3, such a structure is composed of several cause-effect chains which are connected at the beginning by the same root cause, and each chain represents a failure scenario that is initiated by the root cause.

Table 4.1. Failure Scenarios of Hydrokinetic Turbine Blades

Tremendous change in flow velocity (0.1-0.2)	Overspeed rotation of blades (0.7-0.8)	Varying loads on blade (0.95)	Detected (0.95-0.99)	System shutdown	
			Undetected (0.01-0.05)	Fatigue(0.6-0.7)	Blade fracture (0.8-0.9)
$C_R$ Corrosive environment (0.6-0.8)	$E_{11}$ Blade corrosion (0.65)	$E_{121}$ Local stress concentration (0.5-0.7)	$D_{121}$ Detected (0.95-0.99)	$E_{131}$ System shutdown	
			$\overline{D}_{121}$ Undetected (0.01-0.05)	$\overline{E}_{131}$ Fatigue (0.6-0.7)	$\overline{\overline{E}}_{141}$ Blade fracture (0.8-0.9)
		$E_{122}$ Strength reduction (0.8-0.9)	$D_{122}$ Detected (0.95-0.99)	$E_{132}$ System shutdown	
			$\overline{D}_{122}$ Undetected (0.01-0.05)	$\overline{E}_{132}$ Fatigue (0.6-0.7)	$\overline{\overline{E}}_{142}$ Blade fracture (0.8-0.9)
		$E_{123}$ Propagated cracks(0.4-0.5)	$E_{133}$ Blade fracture(0.5-0.6)		
		Presence of trivial debris (0.5-0.6)	Impact on blades (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 blades (0.4-0.6)	Increasing loads on system (0.5-0.7)	System shutdown (0.6-0.8)		
Presence of huge debris (0.01-0.02)	Impact on blades (0.7-0.8)	Blade fracture (0.6-0.8)			

Since one root cause corresponds to one cause-effect chain structure, so in order to construct as many structures as possible, we need to figure out all the possible root causes first.

The cause-effect chain structure was constructed as shown in Figure 4.1.

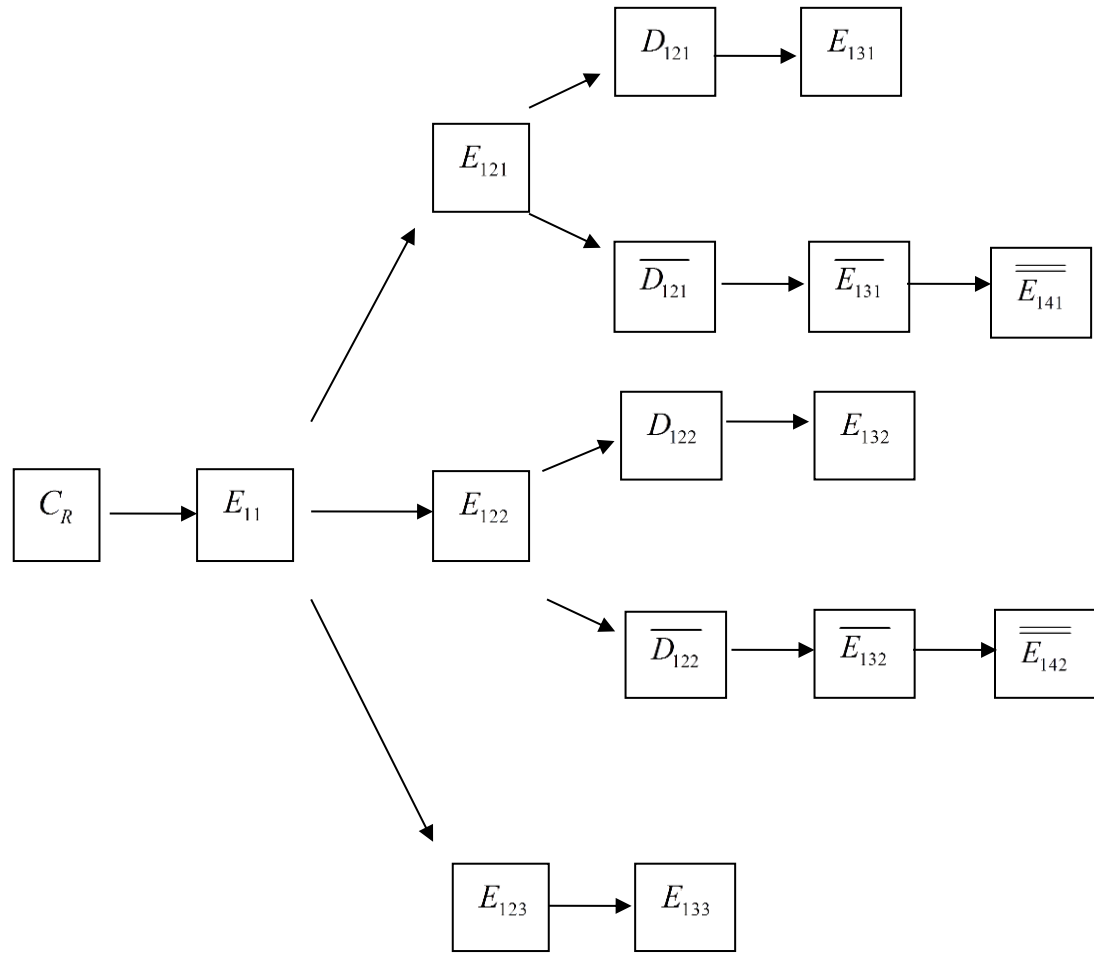


Figure 4.1. A Cause-Effect Chain Structure of Hydrokinetic Turbine Blades

It is shown in the structure that root cause  $C_R$  has only one immediate effect  $E_{11}$ , which is followed by three different subsequent effects  $E_{121}$ ,  $E_{122}$ , and  $E_{123}$ . Then  $E_{121}$  goes under detection.  $D_{121}$  means successful detection of  $E_{121}$  so that end effect  $E_{131}$  happens.  $\overline{D_{121}}$  means unsuccessful detection of  $E_{121}$  so that  $\overline{E_{131}}$  happens, which is followed by an end effect  $\overline{\overline{E_{141}}}$ . Similarly,  $E_{122}$  goes under detection too and leads to two different end effects  $E_{132}$  and  $\overline{\overline{E_{142}}}$ . Since there is no detection technique for effect  $E_{123}$ , the occurrence of  $E_{123}$  directly leads to end effect  $E_{133}$ .

As mentioned before, all of the end effects will be evaluated in terms of cost, and so failure costs  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$  and  $C_5$  are used to evaluate end effects  $E_{131}$ ,  $\overline{\overline{E_{141}}}$ ,  $E_{132}$ ,  $\overline{\overline{E_{142}}}$  and  $E_{133}$ , respectively.

Equation (22) through Equation (26) shown below calculate the risk of root cause for each chain.

For path 1:  $C_R \rightarrow E_{11} \rightarrow E_{121} \rightarrow D_{121} \rightarrow E_{131}$

$$R_1(C_R) = P(C_R)P(E_{11}|C_R)P(E_{121}|C_R, E_{11})P(D_{121})P(E_{131}|C_R, E_{11}, E_{121}, D_{121})C_1 \quad (22)$$

For path 2:  $C_R \rightarrow E_{11} \rightarrow E_{121} \rightarrow \overline{D_{121}} \rightarrow \overline{E_{131}} \rightarrow \overline{\overline{E_{141}}}$

$$R_2(C_R) = P(C_R)P(E_{11}|C_R)P(E_{121}|C_R, E_{11})P(\overline{D_{121}})P(\overline{E_{131}}|C_R, E_{11}, E_{121}, \overline{D_{121}})P(\overline{\overline{E_{141}}}|C_R, E_{11}, E_{121}, \overline{D_{121}}, \overline{E_{131}})C_2 \quad (23)$$

For path 3:  $C_R \rightarrow E_{11} \rightarrow E_{122} \rightarrow D_{122} \rightarrow E_{132}$

$$R_3(C_R) = P(C_R)P(E_{11}|C_R)P(E_{122}|C_R, E_{11})P(D_{122})P(E_{132}|C_R, E_{11}, E_{122}, D_{122})C_3 \quad (24)$$

For path 4:  $C_R \rightarrow E_{11} \rightarrow E_{122} \rightarrow \overline{D_{122}} \rightarrow \overline{E_{132}} \rightarrow \overline{E_{142}}$

$$R_4(C_R) = P(C_R)P(E_{11}|C_R)P(E_{122}|C_R, E_{11})P(\overline{D_{122}})P(\overline{E_{132}}|C_R, E_{11}, E_{122}, \overline{D_{122}})P(\overline{E_{142}}|C_R, E_{11}, E_{122}, \overline{D_{122}}, \overline{E_{132}})C_4 \quad (25)$$

For path 5:  $C_R \rightarrow E_{11} \rightarrow E_{123} \rightarrow E_{133}$

$$R_5(C_R) = P(C_R)P(E_{11}|C_R)P(E_{123}|C_R, E_{11})P(E_{133}|C_R, E_{11}, E_{123})C_5 \quad (26)$$

Equation (27) aggregates the results and acquires the total risk of root cause. The total expected cost of root cause is then given by

$$R(C_R) = R_1(C_R) + R_2(C_R) + R_3(C_R) + R_4(C_R) + R_5(C_R) \quad (27)$$

As can be observed from the equations, in order to obtain the total risk of root cause  $C_R$ , information such as probabilities and failure costs should be collected.

### 4.3. COLLECTING INFORMATION ON THE HYDROKINETIC TURBINE

Now the cause-effect chain structure is constructed, and how the risk is calculated is known as well. The next step is to collect information for each element in Equation (22) through Equation (26).

**4.3.1. Probabilities of Failures.** To obtain the probabilities of failures, information such as occurrence probabilities of root causes, conditional probabilities of intermediate effects, and probabilities of successful or unsuccessful detection should be estimated first.

The probability values involved in the equations above are all shown in Table 4.2. As mentioned before, since information on hydrokinetic turbines is quite limited, historical data on wind turbines are adopted too, which will inevitably introduce more uncertainties to the probability values assigned to root causes and intermediate effects. So interval probabilities are employed here. For example, the occurrence probability of root cause “Tremendous change in flow rate and direction” which is the first cell in the first column of Table 4.1 is assigned to be “[0.1-0.2]”, because different rivers or streams have different current flow situations, even within the same river, the flow situation changes too.

Interval probabilities can accommodate uncertainties due to insufficient data. When more data are available, these intervals can be modified to be more accurate so that the results are more accurate and reliable. Since some of the probabilities are in the form of intervals, it can be foreseen that expected costs will be in the form of intervals too. This means that the expected cost obtained by the new method can accommodate uncertainties too and allow for further modifications.



Table 4.2. Probability Values

$P(C_R)$	0.6-0.8	$P(D_{122})$	0.95-0.99
$P(E_{11} C_R)$	0.65	$P(\overline{D_{122}})$	0.01-0.05
$P(E_{121} C_R, E_{11})$	0.5-0.7	$P(\overline{E_{131}} C_R, E_{11}, E_{121}, \overline{D_{121}})$	0.6-0.7
$P(E_{122} C_R, E_{11})$	0.8-0.9	$P(\overline{\overline{E_{141}}} C_R, E_{11}, E_{121}, \overline{D_{121}}, \overline{E_{131}})$	0.8-0.9
$P(E_{123} C_R, E_{11})$	0.4-0.5	$P(\overline{E_{132}} C_R, E_{11}, E_{122}, \overline{D_{122}})$	0.6-0.7
$P(D_{121})$	0.95-0.99	$P(\overline{\overline{E_{142}}} C_R, E_{11}, E_{122}, \overline{D_{122}}, \overline{E_{132}})$	0.8-0.9
$P(\overline{D_{121}})$	0.01-0.05	$P(E_{133} C_R, E_{11}, E_{123})$	0.5-0.6

**4.3.2. Costs of Failures.** Once the probabilities of failures are available, the next step is to find the cost of failures.

Time is a factor to determine the cost of failure. In order to obtain the cost of failures, detection time  $T_{dt}$ , fixing time  $T_f$  and delay time  $T_{dl}$  should be acquired first.

Detection time means the time to realize and identify a certain type of failure that has occurred and diagnose the exact location and its root cause. Fixing time is the time to fix each individual component. Delay time is the time incurred for on-value activities such as waiting for response from technicians. The unit for all the time information is in hours.

The failure cost mainly includes three components: labor cost  $C_l$ , material cost  $C_m$  and opportunity cost  $C_o$ . The meanings of labor cost and material cost are explicit by their names. The opportunity cost is the cost that incurs when a failure inhibits the main function of the system and prevents any value creation.

The labor cost can be derived with the aforementioned time information using the following equation:

$$C_l = (T_{dt} + T_f + T_{dl}) \times R_l \times N \quad (28)$$

where  $R_l$  means labor rate, and  $N$  represents the number of operators that are assigned to fix problems.

The material cost can be obtained using the following equation:

$$C_m = C_p \times N_p \quad (29)$$

where  $C_p$  means the cost of part, and  $N_p$  represents the number of parts that need to be replaced.

The opportunity cost is calculated using the following equation:

$$C_o = (T_{dt} + T_f + T_{dl}) \times R_o \quad (30)$$

where  $R_o$  means hourly opportunity cost.

The labor cost and opportunity cost are dependent on time and once the time information is obtained through historical data, they can be estimated easily.

After examining the cause-effect chain structure in Figure 4.1, we noticed that there are two different types of failures, “Blade fracture” and “System shutdown”. For the first failure, “Blade fracture”, the cost will be the summation of labor cost, material cost and opportunity cost. However, for the second failure, “System shutdown”, the cost will be the summation of labor cost and opportunity cost only, because in this case blades do not need to be replaced yet. And it can also be foreseen that the labor cost and opportunity cost involved in the second failure will be less than that involved in the first one, because the time of maintenance after system shutdown will be less than the time of replacing fractured blades.

Table 4.3 shows the comparison of the time loss between the two different failures.

Table 4.3. Loss Time of the Two Failures (in Hours)

	Blades fracture	System shutdown
Detection time	5	1
Fixing time	4	2
Delay time	4	2
Total time	13	5

The labor rate in this analysis is assumed to be \$50 per hour. Suppose two operators are assigned to fix problems after either of the two failures happens. The labor cost for either of the two failures can be calculated with Equation (28).

From Equation (29) it can be seen that the material cost is independent of time, and it is only related to the cost of parts to be replaced and the quantity of the parts. Since this case study is focused upon turbine blades of the hydrokinetic system, the two failures are only related to turbine blades too. The manufacturing cost of the turbine blades is about \$2500.

The hourly opportunity cost is composed of the labor rate as well as the loss of electrical power that is generated from the hydrokinetic system per hour, considering the system will be shut down when failure happens. The turbine blades used for this case study are very small in size, and the length of blade is about 0.3 m. The power generated by the system is relatively small, and so the failure-resulted loss of electric power may be neglected.

After conducting sufficient research on other turbines that have been deployed, it is estimated that the hourly opportunity cost for this hydrokinetic system is about \$500, which is relatively low because of the small size of the system. According to

Equation (30), the opportunity cost when either of two failures happens can then be calculated.

The comparison of the costs between the two different failures is shown in Table 4.4.

Table 4.4. Costs of the Two Failures (in Dollars)

	Blade fracture	System shutdown
Labor cost	1300	500
Material cost	2500	100
Opportunity cost	6500	2500
Total cost	10300	3100

It should be pointed out that the hydrokinetic system in this case study is much smaller compared to those tested in reality, so the failure costs for this system can be significantly magnified when the system is scaled up. For example, if the blades are lengthened and widened, the material cost will be higher when failure happens. The opportunity cost will be higher too because the shutdown of a larger system means increased loss of electrical power that should have been generated.

#### **4.4. CALCULATING RISK IN TERMS OF EXPECTED COST**

Now that the probability values are obtained and shown in Table 4.2, and the failure costs are listed in Table 4.4. Plugging the values in the two tables into

Equation (22) through Equation (26) will yield the risk of root cause for each path.

Then Equation (27) adds all the risks together and yields the total risk of root cause

$R(C_R)$ .

As mentioned before, since some of the probability values are intervals, the total risk, which is in terms of expected cost, will be an interval too. So the lower bound and upper bound need be found, separately.

The lower bound for each path is calculated by the following Equation (31) through Equation (35).

$$R_1(C_R)^l = 0.6 \times 0.65 \times 0.5 \times 0.95 \times 3100 = \$547.275 \quad (31)$$

$$R_2(C_R)^l = 0.6 \times 0.5 \times 0.6 \times 0.01 \times 0.6 \times 0.8 \times 10300 = \$8.8992 \quad (32)$$

$$R_3(C_R)^l = 0.6 \times 0.65 \times 0.8 \times 0.95 \times 3100 = \$918.84 \quad (33)$$

$$R_4(C_R)^l = 0.6 \times 0.65 \times 0.8 \times 0.01 \times 0.6 \times 0.8 \times 10300 = \$15.42528 \quad (34)$$

$$R_5(C_R)^l = 0.6 \times 0.65 \times 0.4 \times 0.5 \times 3100 = \$241.8 \quad (35)$$

The lower bound of the total expected cost of root cause is given by

$$\begin{aligned} R(C_R)^l &= R_1(C_R)^l + R_2(C_R)^l + R_3(C_R)^l + R_4(C_R)^l + R_5(C_R)^l \\ &= 547.275 + 8.8992 + 918.84 + 15.42528 + 241.8 \\ &= \$1732.23948 \end{aligned} \quad (36)$$

The upper bound for each path is calculated by the following Equation (37) through Equation (41).

$$R_1(C_R)^u = 0.8 \times 0.65 \times 0.7 \times 0.99 \times 3100 = \$1117.116 \quad (37)$$

$$R_2(C_R)^u = 0.8 \times 0.65 \times 0.7 \times 0.05 \times 0.7 \times 0.9 \times 10300 = \$118.0998 \quad (38)$$

$$R_3(C_R)^u = 0.8 \times 0.65 \times 0.9 \times 0.99 \times 3100 = \$1436.292 \quad (39)$$

$$R_4(C_R)^u = 0.8 \times 0.65 \times 0.9 \times 0.05 \times 0.7 \times 0.9 \times 10300 = \$151.8426 \quad (40)$$

$$R_5(C_R)^u = 0.8 \times 0.65 \times 0.5 \times 0.6 \times 3100 = \$483.6 \quad (41)$$

The upper bound of the total expected cost of root cause is given by

$$\begin{aligned} R(C_R)^u &= R_1(C_R)^u + R_2(C_R)^u + R_3(C_R)^u + R_4(C_R)^u + R_5(C_R)^u \\ &= 1117.116 + 118.0998 + 1436.292 + 151.8426 + 483.6 \\ &= \$3306.9504 \end{aligned} \quad (42)$$

The expected cost of root cause  $R(C_R)$  is given by

$$\$1732 \leq R(C_R) \leq \$3307 \quad (43)$$

#### 4.5. ANOTHER CASE STUDY

For the purpose of comparing risks of different root causes, the first root cause in Table 4.1, “Tremendous change in flow velocity and direction” was used to conduct another case study. The cause-effect chain structure is shown in Figure 4.2.

The risk of  $C_R$  in each path is calculated by the following equations.

For path 1:  $C_R \rightarrow E_{11} \rightarrow E_{12} \rightarrow D_{12} \rightarrow E_{13}$

$$R_1(C_R) = P(C_R)P(E_{11}|C_R)P(E_{12}|C_R, E_{11})P(D_{12})P(E_{13}|C_R, E_{11}, E_{12}, D_{12})C_1 \quad (44)$$

For path 2:  $C_R \rightarrow E_{11} \rightarrow E_{12} \rightarrow \overline{D_{12}} \rightarrow \overline{E_{13}} \rightarrow \overline{\overline{E_{14}}}$

$$R_2(C_R) = P(C_R)P(E_{11}|C_R)P(E_{12}|C_R, E_{11})P(\overline{D_{12}})P(\overline{E_{13}}|C_R, E_{11}, E_{12}, \overline{D_{12}})P(\overline{\overline{E_{14}}}|C_R, E_{11}, E_{12}, \overline{D_{12}}, \overline{E_{13}})C_2 \quad (45)$$

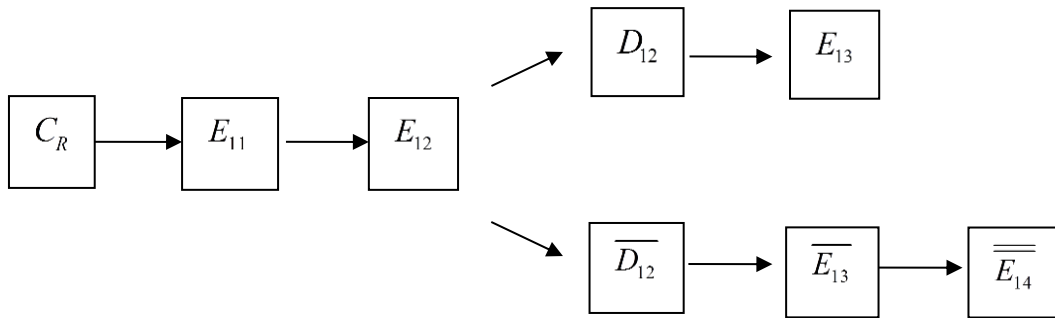


Figure 4.2. Another Cause-Effect Chain Structure of Hydrokinetic Turbine Blades

Next, information is collected and shown in Table 4.5 and Table 4.6 below.

Table 4.5. Probability Values

$P(C_R)$	0.1-0.2	$P(\overline{D_{12}})$	0.01-0.05
$P(E_{11} C_R)$	0.7-0.8	$P(\overline{E_{13}} C_R, E_{11}, E_{12}, \overline{D_{12}})$	0.6-0.7
$P(E_{12} C_R, E_{11})$	0.95	$P(\overline{\overline{E_{14}}} C_R, E_{11}, E_{12}, \overline{D_{12}}, \overline{E_{13}})$	0.8-0.9
$P(D_{12})$	0.95-0.99		



Table 4.6. Loss Time of the Two Failures (in Hours)

	System shutdown	Blade fracture
Detection time	3	5
Fixing time	2	4
Delay time	4	4
Total time	9	13

As discussed in Section 4.4, the labor rate is estimated to be \$50 per hour, the hourly opportunity cost is about \$500, and the material cost for the turbine blades is \$2500. With Equations (23), (24) and (25), and Table 4.6, the costs of the two failures are calculated and shown in Table 4.7.

Table 4.7. Costs of the Two Failures (in Dollars)

	System shutdown	Blade fracture
Labor cost	900	1300
Material cost	200	2500
Opportunity cost	4500	6500
Total failure cost	5600	10300

The probability values are shown in Table 4.5 and the failure costs are shown in Table 4.7. Plugging these values into Equation (44) and (45) yields the risk of root cause for each path.

Since only the two paths are initiated by root cause  $C_R$ , the risk of  $C_R$  is obtained by adding the results of Equation (44) and Equation (45) together.

$$R(C_R) = R_1(C_R) + R_2(C_R) \quad (46)$$

The lower bound of the expected cost for each path is calculated by Equation (47) and Equation (48).

$$R_1(C_R)^l = 0.1 \times 0.7 \times 0.95 \times 0.95 \times 5600 = \$353.78 \quad (47)$$

$$R_2(C_R)^l = 0.1 \times 0.7 \times 0.95 \times 0.01 \times 0.6 \times 0.8 \times 10300 = \$32.8776 \quad (48)$$

The lower bound of the total expected cost of root cause is given by

$$R(C_R)^l = R_1(C_R)^l + R_2(C_R)^l = 353.78 + 32.8776 = \$386.6576 \quad (49)$$

The upper bound of the expected cost for each path is calculated by Equation (50) and Equation (51).

$$R_1(C_R)^u = 0.2 \times 0.8 \times 0.95 \times 0.99 \times 5600 = \$842.688 \quad (50)$$

$$R_2(C_R)^u = 0.2 \times 0.8 \times 0.95 \times 0.05 \times 0.7 \times 0.9 \times 10300 = \$49.3164 \quad (51)$$

The upper bound of the total expected cost of root cause is given by

$$R(C_R)^u = R_1(C_R)^u + R_2(C_R)^u = 842.688 + 49.3164 = \$892.0044 \quad (52)$$

The total expected cost of the root cause  $R(C_R)$  is given by

$$\$387 \leq R(C_R) \leq \$892 \quad (53)$$

#### 4.6. COMPARISON OF RISKS BETWEEN TWO CASE STUDIES

The comparison of interval risks between the two root causes are shown in Table 4.8.

Table 4.8. Comparison of Interval Risks (in Dollars)

$C_R$	$R(C_R)^l$	$R(C_R)^u$
Corrosive environment	1732	3307
Tremendous change in flow velocity	387	892

It is quite obvious that the first root cause has higher risk, because both the lower bound and upper bound of the first root cause are higher than those of the second one. And the two ranges have no intersection in between, which makes the comparison straightforward. The first root cause “Corrosive environment” has higher risk and corrective actions should be taken with priority to reduce the risk.

However, for other cases, when risks are compared with each other, it is very likely that an intersection exists between two risk intervals. If this happens, comparison is not straightforward anymore. Different approaches on decision making under interval probabilities have been made. The approaches can be found in [48-51]. However, in this paper, two general approaches are proposed to address this issue. One is to directly compare the average value of the two intervals. The other one is the worst case approach, which only compares the upper bound of the two intervals.

## 5. CONCLUSIONS AND FUTURE WORK

In the traditional FMEA method, risk is evaluated by risk priority number (RPN), which is the product of  $O$  (occurrence),  $S$  (severity), and  $D$  (detection). Failure modes with higher RPN values are considered having higher risks. Corrective actions are then taken to reduce the RPN values. This method has been implemented in industry since last century. However, it has the following drawbacks:

- The subjectivity in RPNs is considerably high.
- The comparison of RPNs between products or processes is difficult.
- The accuracy and reliability of the results provided by the traditional FMEA are questionable.

Many methods have been developed for improving FMEA. The methodology proposed in this work employs the expected cost as the tool to evaluate risks so that the subjectivity in risk results can be minimized and comparison of risks is facilitated. Moreover, the new method uses the cause-effect chain structure to represent failure scenarios given a root cause so that more possible end effects are under consideration, and the results become more accurate and reliable.

### 5.1. CONCLUSIONS

In this work, a modified FMEA approach is proposed and demonstrated. It is applied to the hydrokinetic system being developed at Missouri S&T to evaluate the risks of root causes that might incur failures to turbine blades of the system. This new approach proved its advantages over the traditional way in the following aspects:

- First, the new method employs cause-effect chain structures which are constructed based upon failure scenarios and the Bayesian network. The structures overcome the following drawback of the traditional FMEA: only the most serious end effects are taken into account to calculate the RPN. However, this is not the case in reality, because several different end effects are all possible to occur even if there is only one root cause. The implementation of failure scenarios and Bayesian network can take many possible end effects into consideration, and in a cause-effect chain structure, all possibilities from a root cause are included. This makes the results of risk analysis more accurate and reliable.
- Second, RPN as the key element in the traditional FMEA method has always been most criticized. When conducting FMEA, assigning precise ratings for *O* (occurrence), *S* (severity), and *D* (detection) is difficult, especially when historical data are not available. The RPNs are considered subjective because sometimes the experience of the team members is the only source of information. However, the new method does not employ RPN as the tool to evaluate risk; instead, occurrence and severity ratings are substituted by the expected cost, which is adopted as a new tool to evaluate risks. In this way, not only more reasonable results can be obtained, but also the subjectivity of the results can be reduced.
- Moreover, in the new method, the detection rating is replaced by the probability of either successful or unsuccessful detection, which is directly related to the maturity of detection techniques implemented in applications. This makes the results more reliable and realistic.

- Last, in the traditional FMEA, comparison of risk information represented by RPNs is quite difficult and sometimes impossible. In this new method, risk is evaluated by expected cost, which makes the comparison of risk information straightforward.

## **5.2. FUTURE WORK**

Although the new method improves the traditional FMEA, there is room for further improvement.

In the method proposed in this paper, risk is evaluated in terms of expected cost, which is the product of the probability of failure and failure cost. Since the information on probabilities and costs are all obtained from historical data and sometimes appropriate assumptions, uncertainties exist in the components of expected cost, such as detection time, fixing time and so on. Sensitive analysis can be conducted on these components to determine which of them has the most significant influence on the risk results. Then the accuracy and reliability of the results can be improved efficiently by reducing uncertainty in this component.

Hydrokinetic technologies are still in the developmental phase, and not many turbines have been built and deployed for commercial use, so data for hydrokinetic turbines are very limited by far. In the application of the proposed method to the hydrokinetic turbine, interval probabilities are used to accommodate uncertainties due to insufficient data. However, the intervals can be modified to represent the real situation more precisely when more hydrokinetic systems are deployed in rivers or oceans. Risks with higher accuracy and reliability can be obtained.

Moreover, when comparing the two interval risks in Section 4, it involves the technique of decision making under interval probabilities. Although two approaches are made to address this issue, a more reliable method needs to be conceived.



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