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Facilitating Improvement of Design for Safety and Operations of a Seaweed Harvester: A Hybrid Traditional Safety Method

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Abstract: Sea harvester is a vital marine vessel needed in sea safety and cleanliness. Reliability and safety of the operations of the vessel need to be ensured via identification of hazards/failures that tends to affect the system and prevent them from occurring and also mitigate their consequences. In this research, a traditional hybrid methodology is employed in ensuring the reliability and safety of a sea harvester. The methodology is a logical combination of preliminary hazard analysis (PHA), risk matrix approach (RMA) and event tree analysis (ETA). Fire, flood, machinery failure and capsize that pose to affect optimal operations of a sea harvester are identified using a PHA method. RMA is incorporated in application of the PHA method to estimate the risks associated with them. Due the fact that risks associated with fire, flood, machinery failure and capsize are classified as very high, identifying preventing measures becomes necessary. Furthermore, systems which by means of their operability and non-operability can mitigate fire, flood, machinery failure, capsize and grounding consequences are captured using an ETA method. Therefore, the traditional hybrid methodology developed is successfully applied in design for safety, construction and operation of a sea harvester.

Keywords: PHA, ETA, Sea Harvester, Risk, Design, Safety

1. Introduction

The safety and reliability of sea harvester is important to enhance productivity, reduce risk to personnel onboard the vessel and damage to the environment. Design for safety of a sea harvester need to be constantly reviewed and incorporated to the vessel due to ever changing technology. New technology introduces hazards to marine and offshore vessels. Three broad categories of design, which are related to the design of various large marine and offshore products are: (i) original design: which involves producing an original solution for a system to carry out a new task; (ii) adaptive design: which involves adapting a known system to a changed task; (iii) variant design: which involves varying the size and/or arrangement of certain aspects of the chosen system, the function and the solution principle remaining the same [1][2]. Design for safety provides a systematic approach to the identification and control of high risk areas, and it would be beneficial to integrate it into the design process from the initial stages to reduce or eliminate major hazards [1]. However, due to the complexity of the safety assessment of large marine and offshore products and the lack of clear and complete guidance for a design for safety methodology, design for safety has not generally been specifically integrated into the design process for such products [1].

This has led to questions about the safety and reliability of small vessels such as sea harvesters too, because of hazards such as machinery failure, flood, fire etc. that may be introduced while they are in operation. The International Maritime Organization and International Association of Classification Societies have also contributed immensely in ensuring the safety and reliability of small vessels are acceptable during their classification exercise on systems and subsystems that make up any marine and offshore vessel. However, attention of researchers have been drawn to them on whether there is preventive or mitigative measures in place on identified and unidentified hazards, incorporated as part of design for safety during the design process of the sea harvesters and how to maintain such measures. From the available literature search, design for safety has not been incorporated in sea harvester and such exercise will be applied in a sea harvester under construction.

To address this challenge, a hybrid traditional safety methodology is developed. The hybrid traditional safety methodology is a combination of preliminary hazard analysis (PHA), risk matrix approach (RMA) and event tree analysis (ETA) method. The application of these techniques as a standalone has been proven in the works of [3-10]. [3] used an ETA method to model the consequences of various hazards of LNG carrier operations, while [4], adopted a PHA method in risk analysis of LNG carriers approaching the Panigaglia maritime terminal. [5] used RMA in combination with other advanced computing methods in risk analysis of LNG carrier operations. An ETA method was also used as an effective decision support tool for domino effect

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prevention and mitigation [6]. In [7], an ETA method was utilized in flood protection on critical infrastructure as a result of climate change in Finland. [9] used PHA to facilitate risk analysis of railway systems. The author proved the method is viable in his work. The successfully application of PHA was also demonstrated in hazard analysis of hypersonic vehicles as evidenced in [8]. [10] utilized RMA in solving unexpected failures, the loss of production, and higher maintenance costs in manufacturing systems, while [11] used RMA in identification of risks involved in private capital participation in government project. Another usefulness of RMA is demonstrated in risk evaluation of natural gas pipelines [12]. Other applications of PHA, RMA and ETA method have been demonstrated in the works of [13-19]. Other successes of safety and risk management of engineering systems have been recorded in various publications [20, 21]. To facilitate the application of the hybrid traditional safety methodology, the research is structured as follows. In Section 1, the introduction is presented. Section 2 shows the methodology of the research. In Section 3, the case study is presented while Section 4 concludes the research.

2. Methodology

This research targets to improve the operations and design of a seaweed harvester by reducing the risk using PHA and risk matrix approach. It also identifies systems that can improve the design for safety of seaweed harvester using an ETA method. The methodology of the research is illustrated in Figure 1. The information flow in Figure 1 starts from system identification/description. The next is design review/details, followed by identification of hazardous event. The next step is identification of hazardous event effect followed by classification of the risk of hazardous event using a risk matrix method. Once the risks have been classified and found not to be very low, then preventive measures will be identified, otherwise satisfactory result has been obtained. The next step is to identify systems that can mitigate the hazards consequences, followed by a check if the functionalities of the identified systems can mitigate consequence of the hazards. If positive, a satisfactory result has been obtained, otherwise go back to design review/details. Data that will be used in this study, will be obtained through use of questionnaire during brainstorming exercise of three designers that designed the sea harvester under investigation.

2.1 Preliminary Hazard Analysis (PHA)

The PHA is a safety/risk analysis technique that uses inductive method. It is used to identify hazards/failures that can hinder proper system operations at the early design stage of product development. It is also use when the system has been fully developed as a precursor for further analysis of hazards/failures associated with the system operations. It facilitates incorporation of other safety analysis techniques in comprehensive risk/safety analysis process of marine and offshore systems. Its usefulness has been shown in works of [9][4][8]. According to [9], the steps of PHA are:

- Identification of hazardous event.
- Identification of hazardous event cause.
- Identification of hazardous event effect.
- Classification of risk.
- Determination of preventive measure.

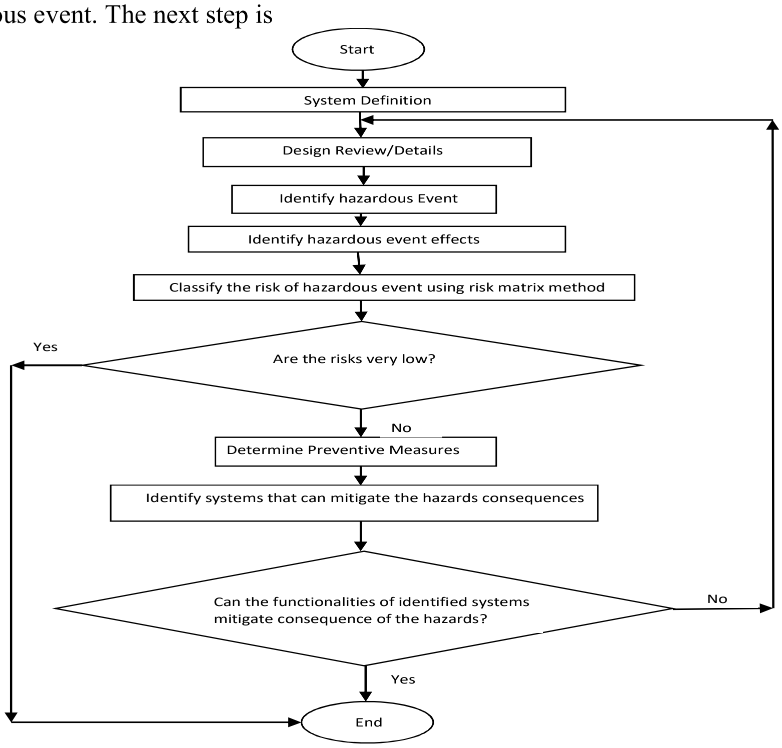

Fig. 1: A Flow Chart of Methodology of the Research

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2.2 Risk Matrix

A RMA is one of the traditional safety/risk methods use in marine and offshore industry [22][5]. It is classified as a qualitative risk analysis methods as evidenced in the works of [10][11][12]. The mechanism of risk matrix is made up of definition of occurrence likelihood and consequence of hazards associated with the system under investigation. The definitions of occurrence likelihood and consequence of hazards are used to facilitate development of risk matrix table as evidenced in Tables 1-3. Mathematically, risk is defined in Equation 1 and converted to logarithmic scale in Equation 2, so as to facilitate calculation of risk scores in development of risk matrix table.

Risk (R) = Occurrence likelihood of a Hazard × Consequence of the Hazard (1)

Log (Risk) = Log (Occurrence likelihood of a Hazard) + Log (Consequence of the Hazard) (2)

The logarithm expression of Equation 1, expressed in Equation 2, is used to develop the values in a risk matrix table developed in Table 3. In Table 3, remote, occasional, probable and frequent associated with scores of 1, 2, 3 and 4 respectively are used to describe occurrence likelihood of a hazard in the Row 2. While the Column 1 of Table 3, accommodated the use of negligible, marginal, critical and catastrophic with their respective scores of 1, 2, 3 and 4 in description of consequence of a hazard. The areas of intersections of the rows and the columns of Table 3 are the risks of the hazards with their associated scores (i.e 2 to 8), calculated using Equation 2. The description of the risk scores are shown in Table 4.

Table 1: Description of Consequence of a Hazard [5]

Linguistic term for consequence of a hazard	Description
Negligible	Less than minor system damage, less than minor injury/illness of personnel or negligible environmental damage.
Marginal	Minor system damage, minor injury/illness of personnel or minor environmental damage
Critical	Major system damage, severe injury/illness of personnel or major environmental damage
Catastrophic	System loss, death of personnel or severe environmental damage.

Table 2: Description of Occurrence Likelihood of a Hazard

Linguistic term for occurrence likelihood of a hazard	Description
Remote	The hazard might occur once every 20 years of the whole sea harvester fleet.
Occasional	The hazard might occur every ten years for a sea harvester.
Probable	The hazard might occur once every year of the whole sea harvester fleet.
Frequent	The hazard might occur every year for a sea harvester.

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Table 3: Risk Matrix Table [5]

Consequence of a hazard	Occurrence likelihood of a hazard			
	1. Remote	2. Occasional	3. Probable	4. Frequent
1. Negligible	2	3	4	5
2. Marginal	3	4	5	6
3. Critical	4	5	6	7
4. Catastrophic	5	6	7	8

Table 4: Description of Risk Levels and Risk Scores of the Risk Matrix Table [5]

Risk levels	Risk scores	Description of risk Levels
Very high	6, 7, 8	Vessel operations have to be prohibited until the risk is reduced to an acceptable level.
High	5	Vessel operations can continue while risk reduction measures are being applied at an acceptable cost.
Moderate	3, 4	Vessel operations continue while efforts are being made to reduce the risk, but the cost of prevention should be carefully measured and limited. Risk reduction methods should be implemented within a defined time period.
Low	2	No actions are required on the vessel while in operation.

2.3 Event Tree Analysis (ETA)

An ETA is a notable traditional safety/risk analysis tool used to develop and trace scenario and systems that can mitigate the consequence of a hazard (initiating event) under investigation in a logical manner. It uses graphical method to represent how the consequence of the hazard can be mitigated based on the functionality and non-functionality of the systems. The systems involved are logically related in terms of functionality and non-functionality with respect to the consequence of the initiating event that need to be mitigated. ETA may be used qualitatively or quantitatively depending on the availability of data and expert judgement. It can be applied during the design or operations phase of marine and offshore assets. The graphical nature of ETA actualized via brainstorming session of various experts has revealed and identified systems and sub-systems that can contribute in improvement of safety of marine and offshore systems as evidenced in various publications [5] [18] [14] [15]. To estimate the probability of occurrence of the consequences of initiating event (hazard), the probabilities of the functionalities and non-functionalities of systems on the paths of the event tree diagram, leading to occurrence of consequence of the initiating event are multiplied.

3. Case Study

The feasibility of the research methodology illustrated in Figure 1 is demonstrated in this section. A combination of PHA, risk matrix and ETA is systematically applied in hazardous event identification, risk estimation, consequence analysis and systems improvement of design for safety of a sea harvester. These traditional safety/risk methods will be prove to be useful tools in facilitation of improvement of design for safety of a sea harvester.

3.1 Application of PHA to a Sea Harvester Operations

As evidenced in Section 2.1, PHA has Steps1-5. Steps 1-3 will be carried out in this section. Steps 4 and 5 will be conducted in Sub-section 3.2 because RMA will be employed in addressing Step 4. In addition, Step 4 needs to be revealed before addressing Step 5. Using expert judgment and brainstorming session, Table 5 is developed.

3.2 Application of Risk Matrix in Risk Estimation Exercise of a Sea Harvester Operations

The methodology of RMA has been detailed in Sub-section 2.2. The methodology will be used to reveal the risk levels of fire, flooding, machinery failure and capsize. Information provided in Tables 1-4 will be employed in the risk estimation exercise (Step 4 of PHA). Using expert judgement and RMA, the consequence, occurrence likelihood and risk levels of fire, flooding, machinery failure, capsize and grounding during sea harvester operations are identified as shown in Table 6. As evidenced in Table 6, the risk levels of fire, flooding, machinery failure, capsize and grounding are classified as "very high", thus the sea harvester operations has to be prohibited until the risk is reduced to an acceptable level by identification of preventive measures (Step 5 of PHA). The preventive measures are identified using brainstorming of the designers and the result is shown in Table 7. Though preventive measures have been identified, however consequences analysis of fire, flooding, machinery failure, capsize and grounding happening in sea harvester operations due to failure or lack of needed system need to be conducted using an ETA. Table 6 is developed using information provided in Tables 3-4, and designers' judgement.

Table 5: Identification of hazardous event, cause and effect associated with Sea Harvester Operations

Step 1: Identification of hazardous event	Step 2: Identification of hazardous event cause	Step 3: Identification of hazardous event effect
Fire	1. Fuel spillage. 2. Faulty electrical component	1. System loss. 2. Injuries/death. 3. Environmental damage.
Flooding	1. Crack in the hull	1. System loss. 2. Injuries/death. 3. Environmental damage.
Machinery failure	1. Design error 2. Installation error 3. Lack of maintenance 4. Lubricating oil problems 5. Turbocharger problems 6. Alignment problems	1. Downtime. 2. Low production output.
Capsize	1. Loss of stability. 2. Flooding 3. Over loading.	1. System loss. 2. Injuries/death. 3. Environmental damage.
Grounding	1. Design error. 2. Over loading.	1. Environmental damage. 2. System loss. 3. Injuries/death. 4. Downtime.

Table 6: Estimation of Risk Levels of Fire, Flooding, Machinery Failure, Capsize and Grounding

Identification of a hazardous event	Consequence of a hazardous event	Occurrence likelihood of a hazardous event	Risk Level
Fire	Catastrophic	Occasional	Very high
Flooding	Critical	Probable	Very high
Machinery failure	Critical	Frequent	Very high
Capsize	Catastrophic	Occasional	Very high

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3.3 Application of ETA in Consequence Analysis and Improvement of Design for Safety of a Sea Harvester

A consequence analysis of functionality and non-functionality of systems logically linked together with respect to safety and reliability of a sea harvester and mitigation of occurrence of fire, flooding, machinery failure, capsize and grounding need to be revealed using an ETA. The methodology of ETA has been described in Sub-section 2.3. The graphical feature of ETA will be used quantitatively and qualitatively to analyze each initiating event. In this study, the initiating events are fire, flooding, machinery failure and capsize. The ETA diagrams of fire, flooding, machinery failure, capsize and grounding in a sea harvester are illustrated in Figures 2-5 respectively. Probabilities of occurrence and functionality of sequence of events are assigned in Figures 2-5 using expert judgment.

Table 7: Preventive Measures for Fire, Flooding, Machinery Failure, Capsize and Grounding

Identification of a hazardous event	Preventive Measure
Fire	1. Provision of temperature sensors. 2. Provision for fire alarm system. 3. Provision of fire extinguishers. 4. Provision of water sprinkler systems.
Flooding	1. Watch keeping 2. Good maintenance culture
Machinery failure	1. Redundancy of outboard engine 2. Good maintenance culture
Capsize	1. Use of stabilizers. 2. Provision of life jackets. 3. Provision of dead man key to automatically turn off the outboard engine incase of capsize.
Grounding	1. Use of echo sounder. 2. Watch keeping. 3. Good maintenance culture

3.3.1. Event Tree for Fire in a Sea Harvester

In Figure 2, it has been revealed that the probabilities of occurrence of consequences such as negligible damage, minor damage, limited damage, major damage, injuries/death in a sea harvester are 0.8, 0.098, 0.042, 0.042 and 0.018 respectively. Each of the probabilities of occurrence is calculated by multiplication of probabilities associated with the line of sequence of events from initiating event to consequence region. Therefore, the probabilities of occurrence of consequences are calculated as follows:

Negligible damage in a Sea Harvester = 0.8

Minor damage in a Sea Harvester = 0.2 x 0.7 x 0.7 = 0.098

Limited damage in a Sea Harvester = 0.2 x 0.7 x 0.3 = 0.042

Major damage in a Sea Harvester = 0.2 x 0.3 x 0.7 = 0.042

Injuries/death in a Sea Harvester = 0.2 x 0.3 x0.3 = 0.018

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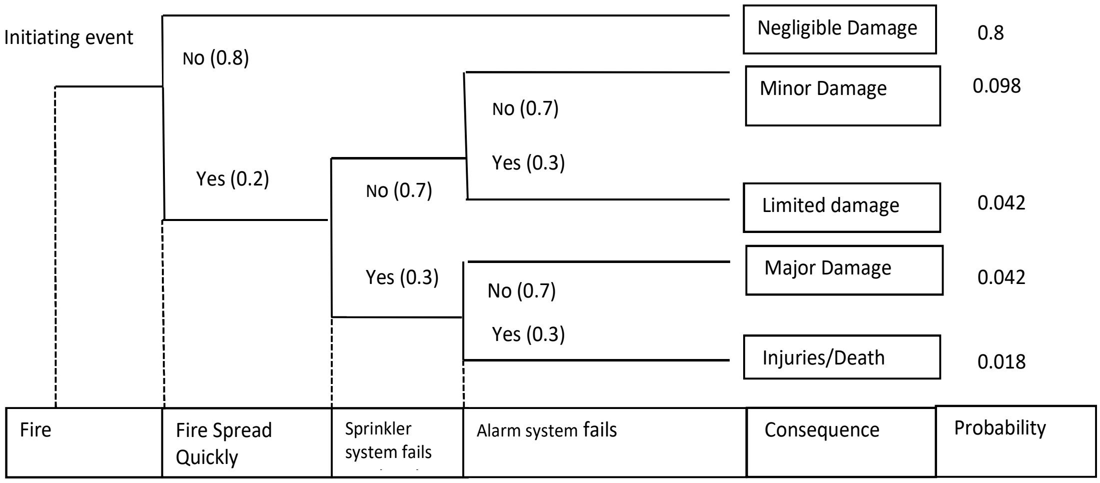

Fig. 2: Event Tree for Fire in Sea Harvester

As can be evidenced from the probabilities of occurrence of negligible damage in a sea harvester, the design for safety of the aforementioned vessel has been improved and is acceptable. Negligible damage, minor damage, limited damage, major damage, injuries/death in a sea harvester are 0.8, 0.098, 0.042, 0.042 and 0.018 respectively.

3.3.2. Event Tree for Flood in a Sea Harvester

The event tree of flood in sea harvester is illustrated in Figure 3. In a similar way to Sub-section 3.3.1, the probabilities of occurrence of consequences such as negligible damage, minor damage, limited damage, major damage, injuries/death are calculated as 0.75, 0.18, 0.045, 0.02 and 0.005 respectively. The design for safety of a sea harvester with respect to flood is acceptable because the probabilities of occurrence of negligible damage and injuries/death are 0.75 and 0.005 respectively. It means that the probability/chance of catastrophic consequence of flood in a sea harvester happening is very low and various systems/sequences of events that can mitigate the consequence of flood have been identified/installed.

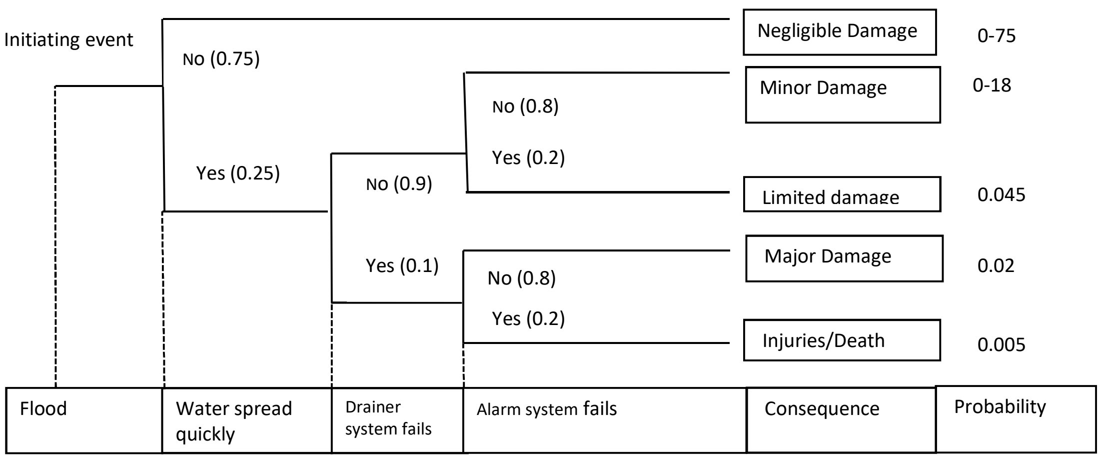

Fig. 3: Event Tree for Flood in Sea Harvester

3.3.3. Event Tree for Machinery Failure in a Sea Harvester

The Figure 4 is an event tree of machinery failure in a sea harvester. In Figure 4, the probabilities of occurrence of consequences such as negligible damage, minor damage, limited damage, major damage and injuries/death are calculated as 0.9, 0.064, 0.016, 0.016 and 0.004 respectively. The design for safety of sea harvester with respect to machinery failure is acceptable because of the values of probabilities of occurrence of negligible damage, minor damage, limited damage, major damage and injuries/death.

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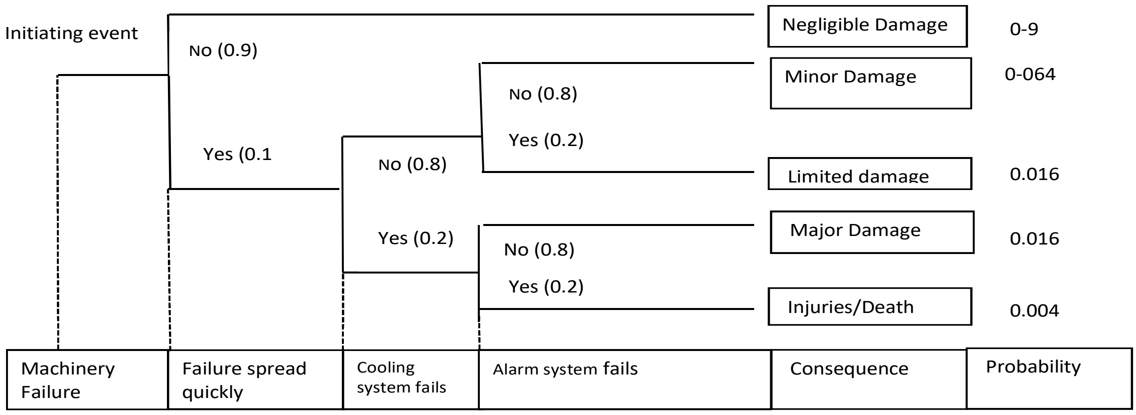

Fig. 4: Event Tree for Machinery Failure in Sea Harvester

3.3.4. Event Tree for Capsize in a Sea Harvester

The ETA of capsize of sea harvester is developed and illustrated in Figure 5. Adopting same approach in Subsection 3.3.1, the probabilities of occurrence of consequences such as no damage or capsize, major damage and no loss of life (when there is life jacket and dead man key on engine didn't fail), major damage and injuries/death (when there is no life jacket and dead man key on engine didn't fail), major damage and no loss of life (when there is life jacket and dead man key on engine failed) and major damage and injuries/death (when there is no life jacket and dead man key on engine failed) as a result of the capsize of sea harvester are calculated as 0.8, 0.1399, 0.0001, 0.0599 and 0.0001 respectively as evidenced in Figure 5. In view of the values of the probabilities of the consequences, the design for safety of a sea harvester with respect to capsize has been improved and is acceptable.

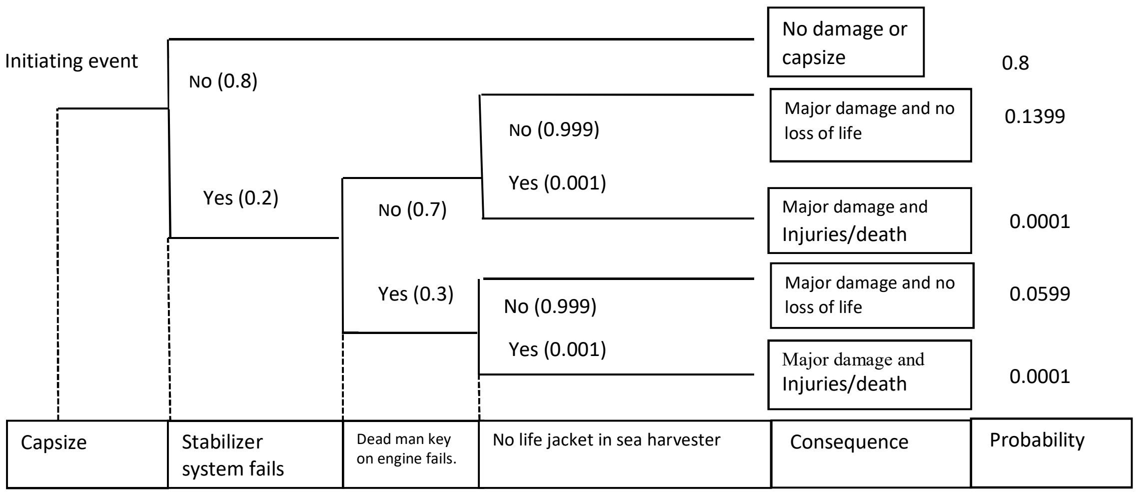

Fig. 5: Event Tree for Capsize of a Sea Harvester

3.3.5. Event Tree for Grounding in a Sea Harvester

The ETA of grounding of sea harvester is shown in Figure 6. Utilizing same approach in Subsection 3.3.1, the probabilities of occurrence of no damage or grounding, major damage and no loss of life (when navigational system failed, but power and alarm systems didn't fail), major damage and injuries/death (when navigational system failed, power system didn't fail, but alarm system failed), major damage and no loss of life (when navigational system failed, power system failed, but alarm system didn't fail) and major damage and injuries/death (when navigational, power and alarm systems failed) are estimated as 0.9, 0.0899, 0.0001, 0.00999 and 0.00001 respectively as shown in Figure 6. In view of the values of the probabilities of the consequences, the design for safety of a sea harvester with respect to grounding has been improved and is acceptable.

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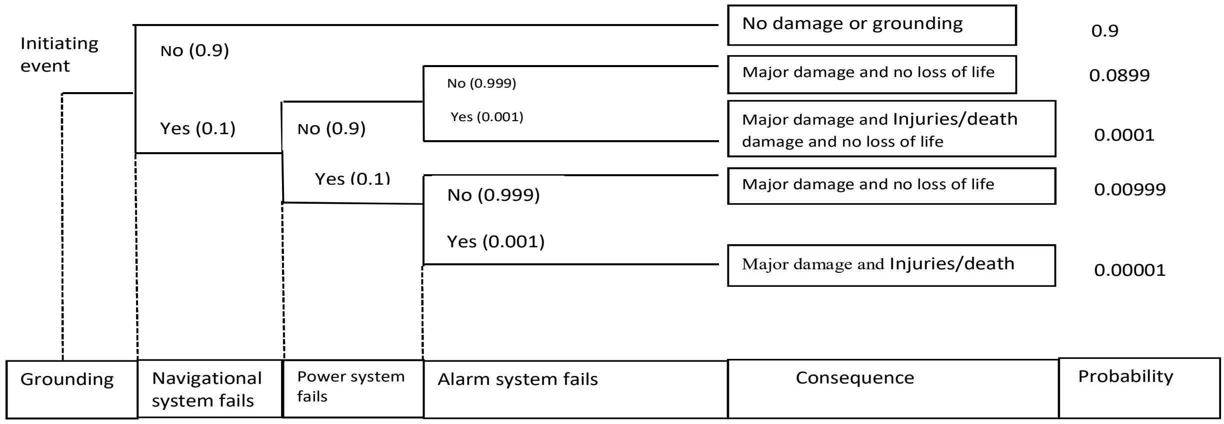

Fig. 6: Event Tree for Grounding of a Sea Harvester

4. Conclusion

Improvement of design for safety of seaweed harvester has been carried out using a combination of PHA, risk matrix and ETA methods. Hazardous events such as fire, flooding, machinery failure, capsize and grounding were identified as the ones that pose to be threats to operations of seaweed harvester using PHA step by step procedures. RMA was used to facilitate completion of application of PHA method. RMA was employed in determination of risk levels of fire, flood, machinery failure and capsize. The mechanism of RMA and expert judgment revealed that fire, flooding, machinery failure, capsize and grounding risks belong to very high-risk level/region/category. In view of this risk levels, preventive measures for fire, flooding, machinery failure, capsize and grounding were identified, which was the final step of PHA. The ETA approach was utilized in identification of systems that can be used to mitigate the consequences of fire, flooding, machinery failure, capsize and grounding which depended on the systems' functionality and non-functionality.

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