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Ontology-Based Fault Tree Analysis Algorithms in a Fuzzy Environment for Autonomous Ships

BEKIR SAHIN[1], **ANIS YAZIDI**[2], **(Senior Member, IEEE)**, **DUMITRU ROMAN**[3],
AND AHMET SOYLU[1,2]
[1]Department of Computer Science, Norwegian University of Science and Technology (NTNU) Gjøvik, 2815 Gjøvik, Norway
[2]Department of Information Technology Artificial Intelligence, OsloMet–Oslo Metropolitan University, 0167 Oslo, Norway
[3]SINTEF, 0314 Oslo, Norway

Corresponding author: Bekir Sahin (bekir.sahin@ntnu.no)

ABSTRACT This study deals with fault tree analysis algorithms based on an ontology-based approach in a fuzzy environment. We extend fuzzy fault tree analysis by embedding ontology-based fault tree structures. The ontology-based approach allows conducting advanced analyses grounded on rich domain knowledge. Two approaches as the conventional approach and rule-based method are applied for the calculations of failure probability and analysis of the fault tree. Collision and grounding of an autonomous ship are investigated in two scenarios. The structural design, probability calculations, and sensitivity analyses prove that the proposed system is applicable, robust, accurate and reliable. Thus, the propounded ontology-based fault tree algorithms fill a gap in safety engineering by its capability of comprehensiveness.

INDEX TERMS Ontology, rules, fault tree analysis, fuzzy sets, autonomous ships, model development.

I. INTRODUCTION

Fault trees are top-to-down structures associated to a problem, a failure or a casualty [1]. The problems, casualties and failures are the events that might not only be based on the past events, but they might also express future expectations. Fault trees allow analyzing a problem in a step-by-step manner, where the events connect to each other based on causation. Therefore, different measures for probability, vulnerability, sensitivity, and reliability of a system can be observed, assessed and computed. Fault tree analysis (FTA) is a robust, flexible, well-established and user-friendly technique to analyze the systems in terms of safety, finance, dependability, criticality, etc.; however, traditional FTA approaches do not exploit the rich domain knowledge available. For example, if the events in the fault trees are examined categorically, they can produce more effective results. Ontology-based systems, in this respect, can analyze an event in the most comprehensive way in terms of detail. Ontologies [2] are formal artefacts capturing the structure and semantics of a domain of interest at a high level of abstraction through standardized vocabularies allowing reuse and exchange [3]. They model domain concepts, their properties, and relationships between these concepts; for example an ontology may represent components of a system and all its failure situations [4], [5]. Hence, combination of ontologies and FTA is a promising direction for conducting advanced analyses grounded on rich domain knowledge.

Many facilitators, such as various gates and different event types are used when examining an event in the fault tree. If an event which has sub-categories is added in a fault tree, the gates are used, thus there should exist probability calculations for the sub-categories. This situation is against the principles of either comprehensiveness by providing and specifying only categories or reliability by creating a very detailed tree for sub-categories. Applying a categorical approach to fault trees can reduce the load on the system and provide a more meaningful and understandable perspective. By using an ontology-based approach, which has similarities with fault trees in term of structural aspects, the fault tree analysis could be made more powerful. To this end, in this study, ontology-based fault tree analysis algorithms are studied in a fuzzy environment. The inputs in the system can be obtained in many ways (automatically with the help of sensors or manually) as crisp numbers, fuzzy evaluations or both simultaneously. The fuzzy environment here symbolizes that the inputs for events or gates are expressed in fuzzy expressions rather than crisp numbers. Resorting to fuzzy expressions endows the system with flexibility and provides more rational results due to its proximity to the human

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thinking nature. In this paper, conventional and rule-based methods are provided, and structures of the fault tree based on ontology are shown. Three types of ontology-based fault tree analysis algorithms in fuzzy environment are introduced. Two scenarios for the autonomous ships are conducted to prove the robustness, comprehensiveness, flexibility and applicability of our approach.

Embedding the events that are linearly or categorically related to each other into the fault tree as if they have a causal relationship may cause problems in the accuracy of the results and system analysis. With this proposed system, we show how linearly or categorically connected events can be embedded into the fault tree. It has been observed in the sensitivity analysis that the system produces more reliable and accurate results. Our proposed system opens a discussion for the limitations of the conventional fault trees and ontology-based fault tree algorithms. The proposed system could also be used for the single agent decision support systems such as self-control of autonomous ships.

The rest of the article is structured as follows. Section II deals with the literature review, while Section III gives the background and proposed methodology. An application based on two scenarios is provided in the Section IV. Finally, discussion and conclusion are presented in Section V and Section VI.

II. LITERATURE REVIEW

In the literature, safety engineering and safety related studies for autonomous ships are very common. These studies are conducted in numerous application areas such as decision making on ships, accident analysis, risk assessment, etc. For instance, the challenges and threats of autonomous ships are examined in [6]. The work reported in [7] discusses the research directions for autonomous ships based on safety. Casualty analysis methods for autonomous vessels are given in [8]. The research [9] discusses the remote-controlled shipping based on the changing roles and regulations. A decision making system is proposed based on collision in [10]. A system theoretic process analysis is proposed for the safety of autonomous ships in [11]. Many studies in the literature show that the interest in autonomous ships is increasing day by day. Most of these studies focus on issues such as safety, risk, accident analysis, etc. Authors of the study [12] express the importance of the systematic safety management for autonomous vessels. The study [13] discusses and compares the different risk analysis methods. The fuzzy fault tree analysis (FFTA) method is commonly used in matters such as safety engineering and reliability evaluation failure and risk assessment. Some of the examples are fire alarm systems [14], safety assessment of gas storage [15], wind energy system [16] and so on.

In the literature, fault tree analysis applications are highly adopted for the maritime industry related problems. This method is preferred in many areas of the maritime industry because of its robustness, reliability and easy-to-use applicability. For instance, risk analysis for cargo liquefaction during the maritime transportation is studied in [17]. Collapse of an offshore platform based on FFTA is studied in [18]. Safety assessment for vessel operation is studied in [19]. Maritime transportation and ship collision are studied in [20]. The paper [21] studies a real-time continuous model for onboard ship in a dynamic environment. Cargo contamination for tankers in the maritime industry is studied in [22]. Marine accidents are investigated by using FFTA in [23]. Port state control is studied by implementing FTA method [24]. Crankcase explosion is studied in [25]. Technical factor for maritime accidents is studied and a systematic failure analysis is conducted in [26]. Human factor analysis for engine room fires is investigated in [27]. However, there exist a limited number of FTA applications for the autonomous ships. For example, the study [28] proposes a cooling system for autonomous ships. Maritime operation and safety analysis for autonomous ships are analysed based on FTA in [29]. The study [30] discusses the use of ontologies for capturing and using accident descriptions. They also mention about computer aided tools and the importance of consistency check for the accident construction. The paper [31] formalizes the safety management knowledge by proposing a construction safety ontology. The paper [32] develops a new learning HAZOP expert system called PetroHAZOP depending on case-based reasoning and ontology. The work reported in [33] proposes a dynamic hazard identification modeling methodology based on generating the situation specific Bayesian network. As a use case study, the latter study examined cloud explosion. To the best of our knowledge, this is the first study that combines ontology approach and FFTA method for the application of autonomous ships.

The literature review indicates that there is a need for the application of reliability based assessment techniques for autonomous ships.

III. METHODOLOGY

A. CONVENTIONAL APPROACH (C)

FTA is the elaboration of a pre-determined casualty like branches of a tree from top to bottom and its probabilistic analysis from bottom to top. The aim is to find the probability of an event occurring and calculate critical events in the system to support decision-makers or authorities. From designing the tree to determining events and making calculations, the whole process is carried out systematically [34]. Events determined from top to bottom are connected to each other by cause and effect relationship [35]. The main casualty is called as top event (TE), and the bottom event is called basic event (BE). TEs are more sensitive and critical events. BEs are events that have reached the boundary conditions of the system and no further investigation is required for the BE (denoted by circle). All events between BEs and TE are intermediate events (IE). In the conventional approach, the events are connected to each other, that is, the relationship between them, is expressed in gates.

Although there are many different events and gates, OR and AND gate are generally used (Figure 1).

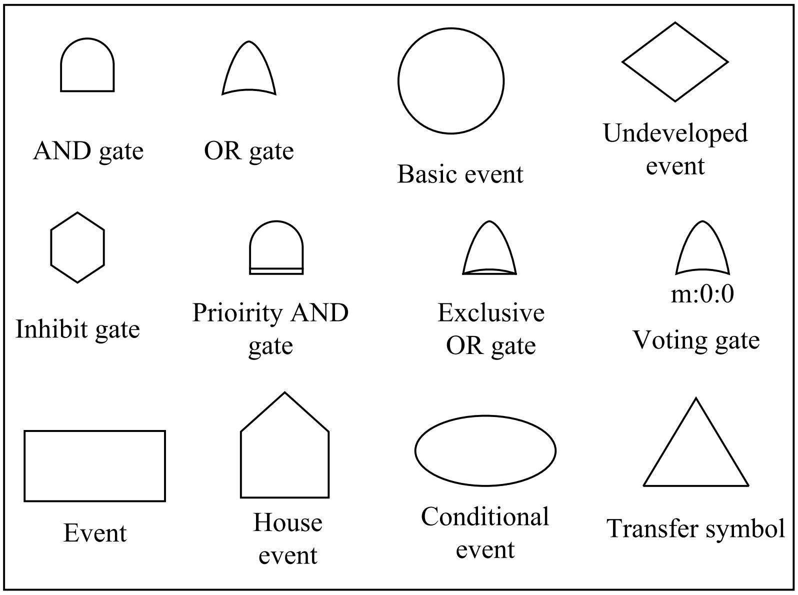

FIGURE 1. FTA symbols.

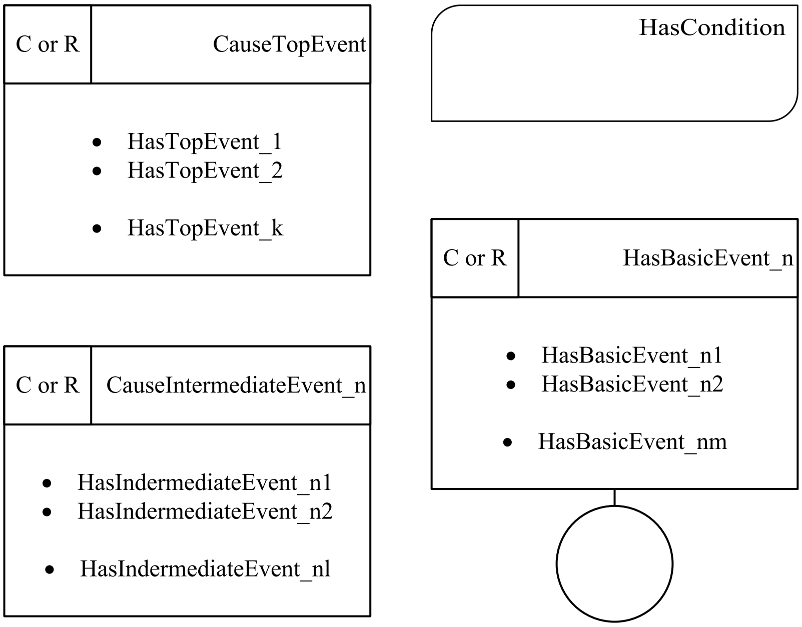

FIGURE 2. Structures of the fault tree based on ontology.

The structures for ontology-based fault trees are firstly introduced in this study as given in Figure 2. "C or R" represents whether Conventional approach or Rule-based approach will be employed. In this study, a new approach has been developed by introducing ontology-based events/gates and the fuzzy gates concept [36]. Fuzzy gates represent the rule-based approach without gates or the gates depending on rule-based approach. The symbols used in the study are presented in Section III-B. While performing the analysis, the probability of each level and event are found based on the relationship between them, from the lowest possible events (BE) to the upper event.

FTA is developed according to the following steps.

- The problem is framed, and it is decided to what level the casualty will be examined. The scope of the casualty and the details of the problem to be examined are at the user's sole discretion.
- The tree is set up and events are defined.
- Minimal cut set and path set rules are considered.
- Events are discussed and data entries are provided with quantitative/qualitative evaluations.

- The probabilities of all events and the fragility of the system and the sensitivity of the individuals are calculated with numerical or mathematical methods.
- The analyzed problem under given conditions and findings are reported.

NOTATION AND PROBABILITY CALCULATIONS OF LOGIC GATES

Let $\Gamma_0(t)$ be the TE's probability at time t, $\gamma_a(t)$ is the event (δ)'s probability, a occurs at time t. Minimal cut set (MCS)'s probability is denoted as $\psi_b(t)$ b fails at time t [22].

Let $\gamma_a(t) = P(\delta_a(t))$ for $i = 1, 2$. Probability of TE $\Gamma_0(t)$ be

$$\begin{aligned}\Gamma_0(t) &= P(\delta_1(t) \cap \delta_2(t)) \\ &= P(\delta_1(t) \cdot \delta_2(t)) = \gamma_1(t) \cdot \gamma_2(t)\end{aligned} \tag{1}$$

If n independent events connect each other with the AND gate;

$$\Gamma_0(t) = \prod_{b=1}^{n} \gamma_b(t) \tag{2}$$

Let $\gamma_a(t) = P(\delta_a(t))$ for $a = 1, 2$. TE probability $\Gamma_0(t)$ is

$$\begin{aligned}\Gamma_0(t) &= P(\delta_1(t) \cup \delta_2(t)) \\ &= P(\delta_1(t) + \delta_2(t) - \delta_1(t) \cap \delta_2(t)) \\ &= \gamma_1(t) - \gamma_2(t) - \gamma_1(t) \cdot \gamma_2(t) \\ &= 1 - (1 - \gamma_1(t)) \cdot (1 - \gamma_2(t))\end{aligned} \tag{3}$$

If n independent events connect each other with the OR gate;

$$\Gamma_0(t) = 1 - \prod_{b=1}^{n} (1 - \gamma_b(t)) \tag{4}$$

MCS represents the fragile chain of the fault tree and if one of the BEs fail in this chain, MCS fails and thus TE fails. The MCS's probability that b fails at time t is

$$\psi_b(t) = \prod_{a=1}^{n} \gamma_{b,a}(t) \tag{5}$$

In FTA applications, data entries are made with crisp data over BEs. However, it can be difficult to find crisp data, as the investigated events are specific and detailed. In fact, the events to be examined may be events that did not take place but could happen in the future. Therefore, we shall apply FFTA due to both its ease of use and suitability for human nature. It has many different applications in the literature.

FUZZY FAULT TREE ANALYSIS (FFTA)

If there is no past data on an event and inferences cannot be made, inputs are derived from expert consultations. FFTA is a system that can handle fuzzy expert opinions and transform the linguistic judgments of experts into numerical results. Different numbers of expert opinions are obtained for each BE of which the probability values are uncertain. Experts are asked to express fuzzy statements representing an approximate value or an interval for each BE. Expert opinions are aggregated during the evaluation process involving more than one expert. This process represents the final value of BE. The result obtained at the end of the aggregation process is the possibility value and it is as a fuzzy number. The conversion process of a fuzzy number into a crisp number is called defuzzification. At the end of the defuzzification process, fuzzy possibility is converted into crisp possibility. In the next step, crisp failure possibility is transformed into failure probability. The probabilities of all events (BEs, IEs and TE) are calculated with the probabilities of BEs. To calculate the probability of the whole system, it is sufficient to compute the probabilities of all BEs placed at the bottom of the system. The probability of all events highlights the fragility, vulnerability, reliability and sensitivity in the system. The sensitivity of the system is expressed as MCSs. MCSs represent a chain of events that enable occurrence of TE alone. After the probabilities of TE and MCSs are found, MCSs and BEs are ranked.

CATEGORIZATION OF BASIC EVENTS

BEs are categorized into two categories depending on whether the crisp values of the probability are known or unknown. If probability values are unknown, probability values are calculated by three different methods: Statistics, extrapolation and expert consultations [37]. Statistics covers the test process with experimental data. Extrapolation includes standard reliability manuals or by estimating models under similar conditions. Expert evaluation method is based on examining and predicting probabilities by experts [38].

EVALUATION PROCESS

In this process, experts in the field make personal subjective evaluations for each BE. Expert elicitation (educated guess) method is applied to eliminate uncertainty in the data resulting from limited resources or physical constraints [22], [39]. The expert prioritization method has been developed to increase the precision of the results. With expert prioritization, parameters such as expert knowledge, experience, training status can be included in the opinions of experts in the form of expert weights [40].

This method allows experts to provide opinions on their areas of interest. It also provides the opportunity to transform uncertainties into numerical probabilities with approximate estimates. In the literature, this approach has been used in many areas such as statistics, quantitative decision-making and optimization to obtain fuzzy data. Subjective evaluations to obtain failure probabilities are needed in the following situations.

- Insufficient and no gathered proof
- Using data from similar situations
- Controversial situations or resources
- Experiments that do not directly belong to physical processes

Expert opinions depend on their own personal judgments and point of views. Hence, the selection of experts is vital. It is almost impossible for expert opinions to be completely objective and to express probability values exactly. Here, attention is paid to the concepts of moderator effect and consensus. Two types of expert groups can be mentioned as homogeneous and heterogeneous. While the homogeneous expert group is a structure in which every expert has approximately the same characteristics, a heterogeneous group is a structure where people possess many different interests and experiences. Homogeneous groups may be less in number than heterogeneous groups. Decision systems that gather many different opinions and include different professional perspectives bring great advantages to the decisions made. A casualty analyzed in fault trees can also be examined in multiple dimensions. Therefore, the period and knowledge of experts to perceive the problem is directly proportional to their experience in that field. This also affects expert opinions, judgments, evaluations and analytical perspectives.

In this study, two scenarios (collision and grounding) are emphasized. Here, heterogeneous expert groups are used empirically. The weight scores (w) of the experts are calculated. Experts' weights are calculated according to the weight factors of the experts. Expert judgments are obtained through linguistic expressions that are useful when a complex situation cannot be expressed clearly, is misidentified or in ambiguity [41].

AGGREGATION PROCESS

Consensus should be obtained as a result of the evaluations made by different numbers of experts of different weights with different experiences and expertise. In this study, the used aggregation algorithm for heterogeneous and homogeneous groups is adopted from [42].

1) Degree of agreement:
Similarity (S) between two expert evaluations $R_u = (ru1, ru2, ru3, ru4)$ and $R_v = (rv1, rv2, rv3, rv4)$ as trapezoidal fuzzy numbers is calculated as follows where $S(R_u, R_v) \in [0, 1]$.

$$S(R_u, R_v) = 1 - 1/4 \sum_{i=1}^{4} |r_{ui} - r_{vi}| \tag{6}$$

2) Average agreement (AA) degree:

$$AA(E_u) = \frac{1}{(N-1)} \sum_{\substack{v=1 \\ u \neq v}}^{N} S(R_u, R_v) \tag{7}$$

E_u $(u = 1, 2 \ldots, N)$ E symbolizes the experts and N is the number of the experts.

3) Relative agreement (RA) degree:

$$RA(E_u) = \frac{AA(E_u)}{\sum\limits_{u=1}^{N} AA(E_u)} \tag{8}$$

4) Consensus coefficient (CC) degree:

$$CC(E_u) = \beta \cdot w(E_u) + (1 - \beta) \cdot RA(E_u) \tag{9}$$

where β is a relaxation factor. This gives the moderator a privilege for controlling and considering the expert responses [22].

5) Aggregation of expert evaluations:

$$\begin{aligned} R_{AG} = CC(E_1) \times R_1 + CC(E_2) \times R_2 \\ \cdots + CC(E_M) \times R_M \end{aligned} \tag{10}$$

DEFUZZIFICATION PROCESS (DP)

The defuzzification method is expressed as:

$$X^* = \frac{\int \mu_i(x) x \mathrm{d}x}{\mu_i(x)} \tag{11}$$

where X^* represents the output as a defuzzified crisp value, $\mu_i(x)$ is the aggregated membership function, x is the output variable.

According to the formula given above, DP of a trapezoidal fuzzy number $\widetilde{A} = (a_1, a_2, a_3, a_4)$ is expressed as:

$$\begin{aligned} X^* &= \frac{\int\limits_{a_1}^{a_2} \frac{x-a}{a_2-a_1} x \mathrm{d}x + \int\limits_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x \mathrm{d}x + \int\limits_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} x \mathrm{d}x}{\int\limits_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} \mathrm{d}x + \int\limits_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} \mathrm{d}x + \int\limits_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} \mathrm{d}x} \\ &= \frac{1}{3} \frac{(a_4 + a_3)^2 - a_4 a_3 - (a_1 + a_2)^2 + a_1 a_2}{a_4 + a_3 - a_2 - a_1} \end{aligned} \tag{12}$$

TRANSFORMATION OF CRISP FAILURE POSSIBILITY (CFP) OF BEs INTO FAILURE PROBABILITY (FP):

$$\begin{aligned} FP &= \begin{cases} \frac{1}{10^K}, & \text{if } CFP \neq 0 \\ 0, & \text{if } CFP = 0 \end{cases} \\ K &= \left[\left(\frac{1 - CFP}{CFP} \right) \right]^{\frac{1}{3}} \times 2.301 \end{aligned} \tag{13}$$

CALCULATION OF ALL MCSs AND TE OCCURRENCE

$$\begin{aligned} P(T) &= P(MCS_1 \cup MCS_2 \cup \cdots \cup MCS_N) \\ &= P(MCS_1) + P(MCS_2) + \cdots + P(MCS_N) \\ &\quad -(P(MCS_1 \cap MCS_2) + P(MCS_1 \cap MCS_3) \ldots \\ &\quad +P(MCS_i \cap MCS_j) \ldots) \ldots \\ &\quad +(-1)^{N-1} P(MCS_1 \cap MCS_2 \cap \cdots \cap MCS_N) \end{aligned}$$

where $P(MCS_i)$ is the occurrence probability of MCS_i and N is the number of MCS

RANKING OF MCSs

$$I_i^{FV-I}(t) = \frac{Q_i(t)}{Q_s(t)} \tag{14}$$

where $Q_i(t)$ is the probability of failure of MCS_i and $Q_s(t)$ of TE due to all MCSs. Fussell Vesely Importance Measure (FV-I) is the parameter for the contribution of MCSs to TE's probability [21].

B. RULE-BASED METHOD (R)

Conventional approach (fuzzy fault tree analysis method) can only function when there exist no dependencies among events. Rule based model presents a new approach based on a set of IF-THEN fuzzy rules [43]. It transports fuzzy information between the events in order to handle the uncertainties and describe the relationships between events [44].

Consider the rule 1 [45] and suppose the possibility weight of BEs $X_1, X_2, \ldots, X_n$ and upper event Y are expressed as $(X_1^1, X_1^2, \ldots, X_1^{k1})$, $(X_2^1, X_2^2, \ldots, X_2^{k2})$, …, $(X_n^1, X_n^2, \ldots, X_n^{kn})$ and $(Y^1, Y^2, \ldots, Y^{ky})$ which satisfy the below equations:

$$\begin{aligned}
&0 \le X_1^1 < X_1^2 < \cdots < X_1^{k1} \le 1\\
&0 \le X_2^1 < X_2^2 < \cdots < X_2^{k2} \le 1\\
&\ldots\\
&0 \le X_n^1 < X_n^2 < \cdots < X_n^{kn} \le 1\\
&0 \le Y^1 < Y^2 < \cdots < Y^{ky} \le 1
\end{aligned} \tag{15}$$

Rule based approach is represented by the following fuzzy rules given below:

Rule l ($l = 1, 2, \ldots, m$):
If X_1 is X_1^{i1} and X_2 is X_2^{i2}, …, and X_n is X_n^{in}, then the possibility of Y^1 is $P^l(Y^1)$, Y^2 is $P^l(Y^2)$, …, Y^{ky} is $P^l(Y^{ky})$.
Rule based approach handles both "AND", "OR" gates.
Fuzzy rule of "AND" gate:
If X_1 is 1 and X_2 is 1, …, and X_n is 1, then the possibility of $Y^1 = 0$ is 0, $Y^2 = 0$ is 0, …, the possibility of $Y^{ky} = 1$ is 1.
Fuzzy rule of "OR" gate:
If X_1 is 1 and X_2 is 1, …, and X_n is 1, then the possibility of $Y^1 = 0$ is 0, $Y^2 = 0$ is 0, …, the possibility of $Y^{ky} = 1$ is 1.

The fuzzy rules and possibility weights of BEs are derived according to real past data and experienced field expert judgments. Then the fuzzy logic is conducted to calculate the fuzzy failure possibilities of top event. Let possibility of BE is $X' = (X_1', X_2', \ldots, X_n')$, possibility of TE is found by the rule based approach as follows [36].

$$\begin{aligned}
P(Y^1) &= \sum_{l=1}^{m} \beta_l^*(X') P^l(Y^1)\\
P(Y^2) &= \sum_{l=1}^{m} \beta_l^*(X') P^l(Y^2)\\
&\ldots\\
P(Y^k) &= \sum_{l=1}^{m} \beta_l^*(X') P^l(Y^k)
\end{aligned} \tag{16}$$

where $\beta_l^*(X') = \frac{\prod_{j=1}^{n} \mu(X_j')}{\sum_{l=1}^{m} \prod_{j=1}^{n} \mu(X_j')}$, $\mu(X_j')$ is the membership of X_j' for the corresponding fuzzy set.

Suppose the fuzzy possibility of BEs $P(X_1^{i1})(i1 = 1, 2, \ldots, k_1)$, $P(X_2^{i2})(i2 = 1, 2, \ldots, k_2)$, …, $P(X_n^{in})(in = 1, 2, \ldots, k_n)$ then the fuzzy possibility of the rule l is: $P^l = P(X_1^{i1})P(X_2^{i2}) \ldots P(X_n^{in})(l = 1, 2, \ldots, m)$

Fuzzy possibility of TE is found as

$$\begin{aligned}
P(Y^1) &= \sum_{l=1}^{m} P^l \cdot P^l(Y^1)\\
P(Y^2) &= \sum_{l=1}^{m} P^l \cdot P^l(Y^2)\\
&\ldots\\
P(Y^k) &= \sum_{l=1}^{m} P^l \cdot P^l(Y^k)
\end{aligned} \tag{17}$$

The structures of the conventional and rule based approaches are given in Figure 3.

C. ONTOLOGY-BASED FFTA MODELS

Detailed structure of an ontology-based FFTA model is given in Figure 4, which is based on the study of [33]. System parameters of the autonomous ships are derived from the study of [46].

TYPES OF ONTOLOGY-BASED FAULT TREE ANALYSIS ALGORITHMS IN FUZZY ENVIRONMENT

1) Ontology-based FFTA (OFFTA)
   Structure of the OFFTA includes conventional gates of the FTA and BEs that are conventional BEs or ontology-based BEs. An example is given in Figure 5. As an example, the probabilities of each BEs are represented as fuzzy numbers in the Listing 1. The probability of TE is calculated via the conventional or rule-based methods which is given in Section III.
2) Conditional ontology-based FFTA (COFFTA)
   In this approach, intermediate or basic events depend on a single condition or multiple conditions which means if the condition is satisfied the probability of the corresponding event is calculated otherwise, it is omitted. The example is given in Figure 6. The structure and probabilities of each basic events are represented as fuzzy numbers in the Listing 1.
3) Fuzzy ontology-based FFTA (FOFFTA)
   In this system, rule-based approach is preferred over conventional gates. The structure of FOFFTA is given in Figure 7, and local probability distribution is provided in Listing 3.

As shown in Figure 3, if there is no gate in the fault tree (only the connection between events), it means that the fault tree has rule-based approach without gates or the gates depending on rule-based approach. Therefore, for the sensitivity analysis of FOFFTA, all failure probabilities should be calculated to calculate the MCSs and rankings.

IV. APPLICATION

Due to the nature of accidents, each accident has its own characteristics, uniqueness, actors, time and location. All accidents are different even if they possess the same type accident or are in the similar category such as collision,

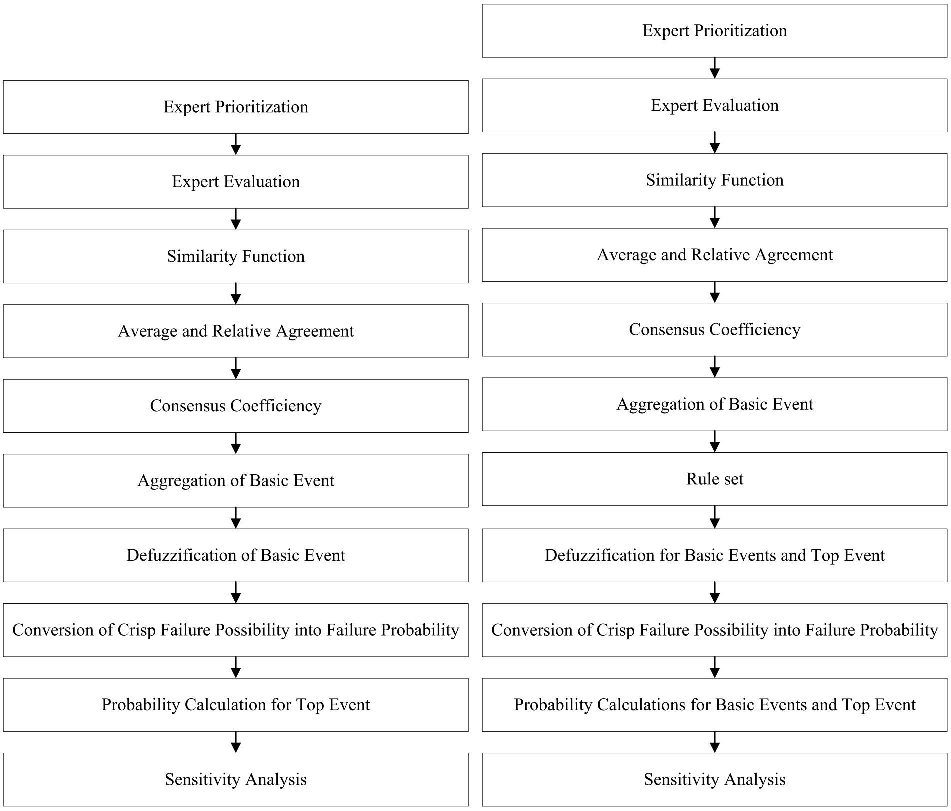

FIGURE 3. The structures for the conventional and rule based approaches.

```
If any Scenario has (TopEvent = true & Gate
   = OR_Gate) [If any Scenario have (BasicEvent = Basic_Event_1) [Basic_Event_11 = VL, Basic
       Event_12 = H, Basic_Event_13 = M]
   else if any Scenario have (IntermediateEvent = Intermediate_Event) [If any Scenario have
       (IntermediateEvent = true & Gate
      = AND_Gate) [If any Scenario have (BasicEvent = Basic_Event_2) [Basic_Event_2= VH]
      else if any Scenario have (BasicEvent = Basic_Event_3) [Basic_Event_31=VL,
          Basic_Event_32=H]
      ]
   ]
]
```

Listing 1. Local probability distribution for OFFTA.

TABLE 1. Expert prioritization parameters and weights.

	Professional position	Work experience	Education level	Weighting factor			TW	Weighting score
1	Academician	>10	P	5	3	3	11	0.23
2	Academician	5-10	P	5	2	3	10	0.21
3	Master	<5	B	3	1	1	5	0.11
4	Chief officer	<5	M	2	1	2	5	0.11
5	Operations manager	>10	B	4	3	1	8	0.17
6	2nd Engineer	<5	B	1	1	1	3	0.06
7	2nd Engineer	5-10	M	1	2	2	5	0.11

grounding, etc. This shows different fault tree designs might be structured for the same accident. In this study, two scenarios are designed based on ontology model of system safety analysis for autonomous ships. The faults are represented as Faults with their indices which are brought from hazards for the autonomous ships given in the Appendix section.

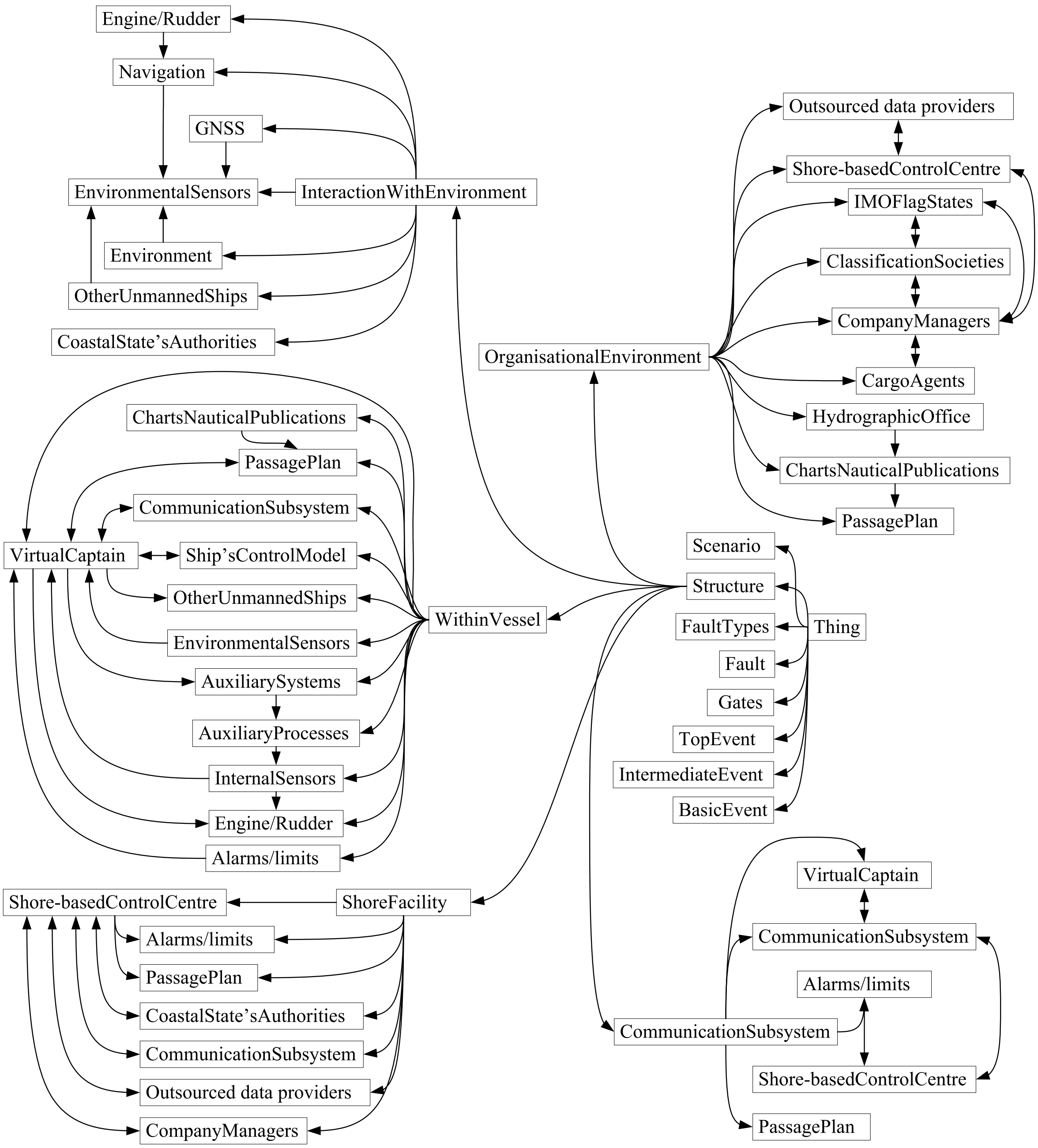

FIGURE 4. Ontology model of system safety analysis for autonomous ships.

A. AN EXAMPLE OF COLLISION

The first scenario is the collision of an autonomous ship which is given in Figure 13 – see also Appendix VI. As shown in the figure, there is a condition of 'No malware and attacks' and its probability is 1. $P = 1$ guarantees that there are no malware and attacks for that event chain. BE 4 and BE 5 are connected directly to the intermediate event 'Interaction with Environment'. The structure of the ontology-based fault tree made it simple since there exist eleven faults and their predefined relationships with each other. This is similar to the real-time accidents for the detailed fraction defective analysis [38].

First the expert prioritization is conducted, and the profiles of anonymous experts and weights for each expert are found as given in Table 1. The criteria and scores for determining the experts are preferred as in [22].

The symbols for events and their corresponding descriptions are given in Table 2. The experts evaluate each event as fuzzy evaluations (Table 3).

We utilized the study of [22] that gives the scale for linguistic terms and corresponding fuzzy numbers. Conversion of linguistic expressions into the fuzzy numbers for BE11 is shown in Table 4.

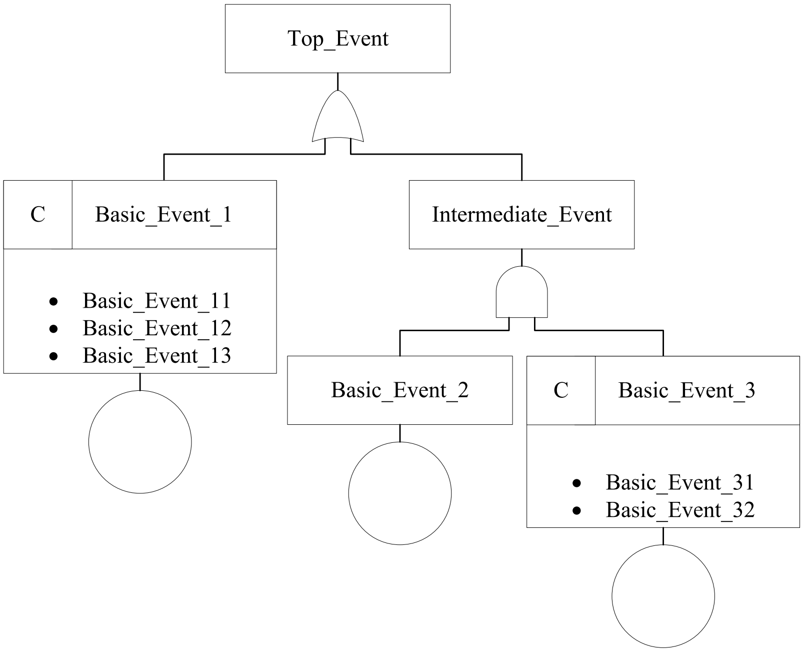

FIGURE 5. An example for the structure of OFFTA.

```
If any Scenario has (TopEvent = true & Gate
   = OR_Gate) [If any Scenario have (Condition_1 = true & BasicEvent = Basic_Event_1)
       [Basic_Event_11=VL, Basic Event_12 = H, Basic_Event_13=M]
   else if any Scenario have (Condition_2 = true & IntermediateEvent = Intermediate_Event)
       [If any Scenario have (IntermediateEvent = true & Gate
      = AND_Gate) [If any Scenario have (Condition_3 = true & BasicEvent = Basic_Event_2)
          [Basic_Event_2= VH]
      else if any Scenario have (BasicEvent = Basic_Event_3) [Basic_Event_31=VL,
          Basic_Event_32=H]
      ]
   ]
]
```

Listing 2. Local Probability Distribution for COFFTA.

```
If any Scenario has (TopEvent = true & Gate
   = Intermediate_Event_1) [If any Scenario have (IntermediateEvent = Intermediate_Event_1)
       [Intermediate_Event_11 = VL, Intermediate_Event_12 = H]
   else if any Scenario have (BasicEvent = Basic_Event_1) [Basic_Event_11 = VL,
       Basic_Event_12 = H, Condition_1 = true & Basic_Event_13 = M]
   else if any Scenario have (IntermediateEvent = Intermediate_Event_2) [If any Scenario
       have (Condition_2 = true & Gate
      = Intermediate_Event_2) [If any Scenario have (IntermediateEvent =
          Intermediate_Event_2) [Intermediate_Event_21 = VL, Intermediate_Event_22 = H]
      If any Scenario have (BasicEvent = Basic_Event_2) [Basic_Event_2 = VH]
      else if any Scenario have (Condition_3 = true & Condition_4 = true & BasicEvent =
          Basic_Event_3) [Basic_Event_31 = VL, Basic_Event_32 = H]
      ]
   ]
]
```

Listing 3. Local Probability Distribution for COFFTA.

Then, step by step calculations are completed as expressed in Tables 5 to 8. The results for all events given in Table 9.

Here, it is important to show how R BE31 BE32 is found. As it is known aggregation value of BE31 is 0.2081 0.2800 0.3401 0.4401 and BE32 0.1476 0.2328 0.3100

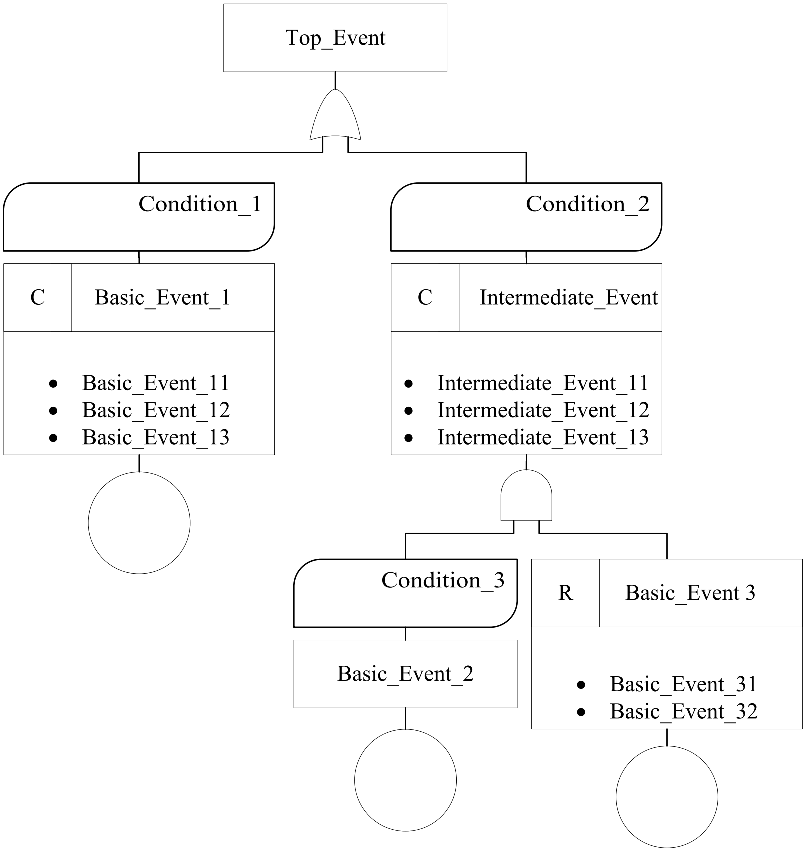

FIGURE 6. An example for the structure of COFFTA.

TABLE 2. The event codes, ontological sequences and descriptions of the hazards for collision.

Event code	Ontological sequence	Hazards
BE11	Fault 3.1	Technical faults in navigational equipment
BE12	Fault 3.2	Technical faults in maneuvering equipment
BE13	Fault 3.3	Technical faults in machinery, propulsion and auxiliary equipment
BE21	Fault 1.12	Environmental conditions restricting the ship's speed, movement and course
BE22	Fault 1.13	Access failures to external structures due to weather conditions
BE31	Fault 6.1	Both ways communication problems
BE32	Fault 6.4	Any interaction problems with others
IE11	Fault 7.1	Closest point of approach violations and interaction with others (manned ships, third party assets)
IE12	Fault 7.3	Improper positioning and wrong movement
BE4	Fault 1.4	Colliding with other ships or human-made large structures
BE5	Fault 1.5	Inability to handle external assistance and aids

0.4100 as given is Table 10. The rules for BE31 and BE32 are set as shown in Table 11. These rules might be set based on a known statistics, expert evaluations or randomly.

In Table 12, the values for the first rule (0.003 0.005 0.006 0.008) are found by the scalar multiplication of BE31 (A B C D = 0.2081 0.2800 0.3401 0.4401), BE32 (A B C D = 0.1476 0.2328 0.3100 0.4100) and the first rule (A B C D = 0.100 0.150 0.200 0.250). It is 0.2081*0.1476*0.100 = 0.0031, 0.2081*0.1476*0.150 = 0.0046, 0.2081*0.1476*0.200 = 0.0061 and 0.2081*0.1476*0.250 = 0.0077. The rule system is a more comprehensive, flexible and inclusive which ensures the permeability of events to each other. After finding the sum of all rules, its values of defuzzification, crisp failure possibility and failure probability are found as a normal process. Since there exist two trapezoid numbers there are

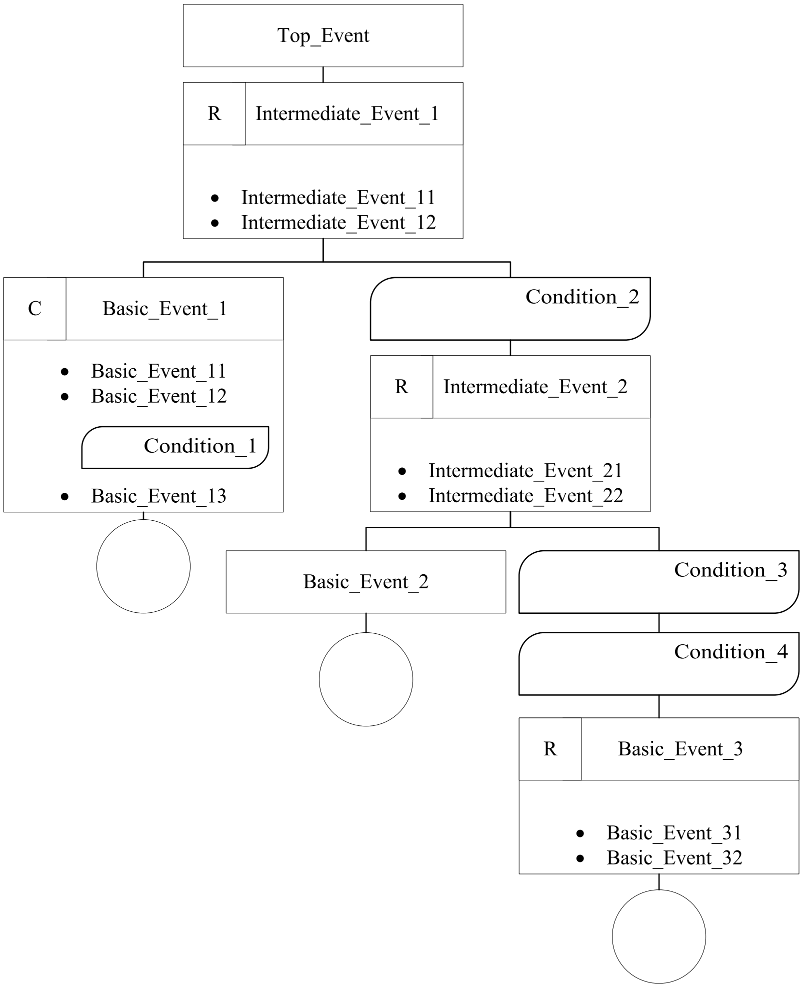

FIGURE 7. An example for the structure of FOFFTA.

TABLE 3. The expert evaluations for collision.

	E1	E2	E3	E4	E5	E6	E7
BE11	vl	l	vl	h	vh	vl	m
BE12	vl	vl	h	vl	vl	h	vl
BE13	l	vl	vl	h	vl	mh	m
BE21	vl	vl	vl	vl	l	vl	vl
BE22	m	l	vl	ml	vl	mh	ml
BE31	m	ml	vl	ml	vl	h	l
BE32	ml	ml	l	ml	vl	l	ml
IE11	vl	l	l	ml	vl	h	ml
IE12	m	l	l	l	ml	h	mh
BE4	mh	l	m	m	m	vl	mh
BE5	ml	m	m	m	ml	l	ml

TABLE 4. Corresponding fuzzy values of expert evaluations for BE11 of collision for autonomous ships.

Experts	Fuzzy evaluations			
	ru1	ru2	ru3	ru4
E1	0.00	0.00	0.10	0.20
E2	0.10	0.20	0.20	0.30
E3	0.00	0.00	0.10	0.20
E4	0.70	0.80	0.80	0.90
E5	0.80	0.90	1.00	1.00
E6	0.00	0.00	0.10	0.20
E7	0.40	0.50	0.50	0.60

4*4=16 rules. If the event number is 3, 4 or 5, the number of rules are 4^3=64,4^4=256 and 4^5=1024, respectively. When the number of events increases, the computational complexity increases, and reliability might decrease because of the massive data load.

The probability of the top event (collision) is found as 0.0000202. The step by step calculations are shown as seen in Table 13.

B. AN EXAMPLE OF GROUNDING

The first scenario is the grounding of an autonomous ship which is given in Figure 9 – see Appendix VI. By the help of Table 14 and Table 15, BE21 is found by multiplying Sensor capability P = VL (0.1 0.1 0.2 0.3) in Table 16 and the aggregation value of (0.3081 0.3823 0.4424 0.5291). The result is found as 0.0924 0.0765 0.0442 0.0529. In order to show its applicability, we set the same values for each connection as given in Table 17.

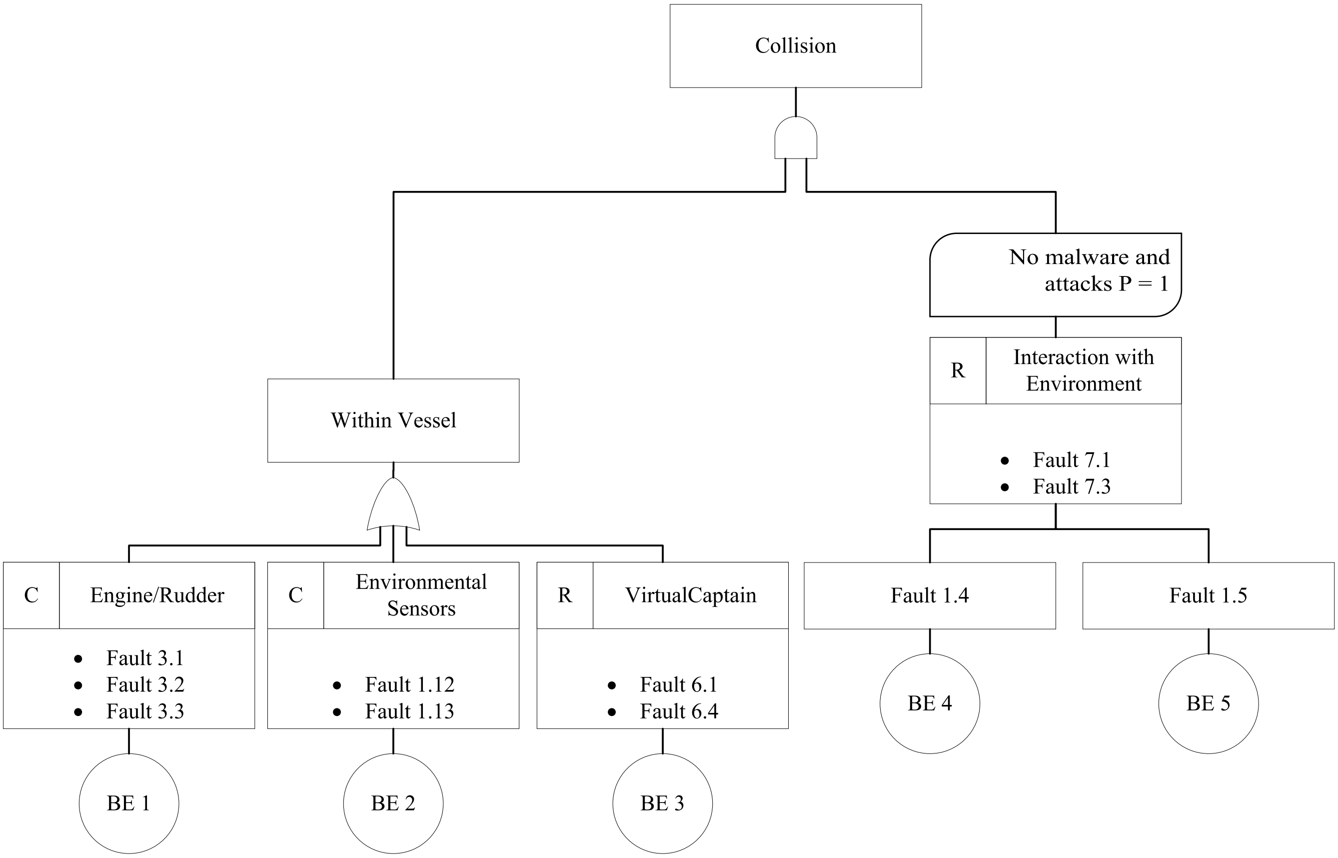

FIGURE 8. The first scenario of ontology-based fault tree for collision of autonomous ships.

TABLE 5. Similarity function and values for expert opinions.

No	Similarity function	Similarity function value
1	S(E1&E2)	0.875
2	S(E1&E3)	1
3	S(E1&E4)	0.275
4	S(E1&E5)	0.15
5	S(E1&E6)	1
6	S(E1&E7)	0.575
7	S(E2&E3)	0.875
8	S(E2&E4)	0.4
9	S(E2&E5)	0.275
10	S(E2&E6)	0.875
11	S(E2&E7)	0.7
12	S(E3&E4)	0.275
13	S(E3&E5)	0.15
14	S(E3&E6)	1
15	S(E3&E7)	0.575
16	S(E4&E5)	0.875
17	S(E4&E6)	0.275
18	S(E4&E7)	0.7
19	S(E5&E6)	0.15
20	S(E5&E7)	0.575
21	S(E6&E7)	0.575

The defuzzification of top event is 0.0448401431 and failure probability of grounding is found as 0.0000004183 under these constraints. The probability of top event is calculated from the aggregated fuzzy possibility of 0.0256 0.0384 0.0512 0.0641.

TABLE 6. Values for average and relative agreement of expert evaluations.

	Average agreement	Relative agreement
E1	0.6458	0.1595
E2	0.6667	0.1646
E3	0.6458	0.1595
E4	0.4667	0.1152
E5	0.3625	0.0895
E6	0.6458	0.1595
E7	0.6167	0.1523

TABLE 7. Consensus coefficient values.

Consensus coefficient	Value
CC1	0.1968
CC2	0.1887
CC3	0.1329
CC4	0.1108
CC5	0.1299
CC6	0.1116
CC7	0.1293

TABLE 8. Aggregation value of BE11 as a fuzzy number.

Aggregation of BE11			
0.2520	0.3079	0.3650	0.4520

Similar algorithms can be deployed autonomous systems where it might have a single agent or decision maker. If there is a single agent, there exist no aggregation stage and thus

TABLE 9. Defuzzification and failure probability values of events based on their calculation parameters.

Events	Defuzzification	Failure Probability	Aggregation of events			
BE11	0.3457	0.0014				
BE12	0.2022	0.0002				
BE13	0.2874	0.0008				
BE21	0.0966	0.0000				
BE22	0.3031	0.0009				
BE31			0.2081	0.2800	0.3401	0.4401
BE32			0.1476	0.2328	0.3100	0.4100
R BE31 BE32	0.3378	0.0013				
IE11			0.1344	0.1995	0.2605	0.3605
IE12			0.2743	0.3743	0.4026	0.5026
R IE11 IE12			0.1468	0.1933	0.2686	0.3252
BE4			0.3454	0.4367	0.4768	0.5768
BE5			0.2760	0.3760	0.4237	0.5237
R BE4 BE5 IE	0.4799	0.0043				

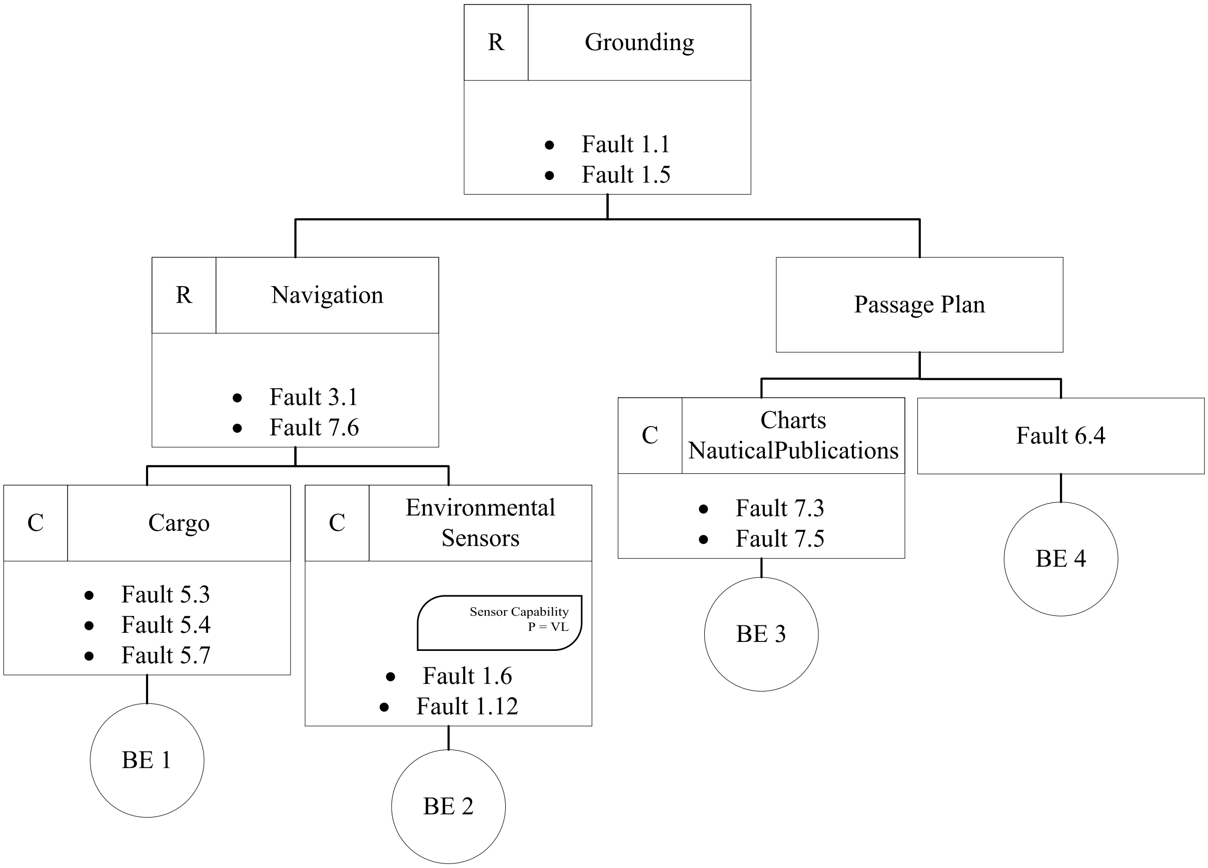

FIGURE 9. The second scenario of ontology-based fault tree for grounding of autonomous ships.

TABLE 10. The aggregation values of BE31 and BE32.

BE31				BE32			
A	B	C	D	A	B	C	D
0.2081	0.2800	0.3401	0.4401	0.1476	0.2328	0.3100	0.4100

the values are obtained from the sensors, databases or manual uploads.

C. SENSITIVITY ANALYSIS

For sensitivity analysis, if conventional gates are present in the fault tree, the MCSs and FV-I are found using conventional methods in the literature. If fuzzy gates (rule based connections) are used instead of conventional gates, then it means that the gates do not act as an OR gate or AND gate. Therefore, when calculating MCSs and FV-I in fault trees with fuzzy gates, all combinations must be considered and calculated. MCSs, occurrence probabilities, FV-I and rankings for collision are given in Table 18. The Table 18 shows all combinations of events and their vulnerability and criticality in the system. For instance, BE11 IE11 IE12 BE4 BE5 is the most critical chain for the collision with the probability of 1.971E-05.

TABLE 11. The rule values assigned for the connection of BE31 and BE32.

Rule	BE31	BE32	A	B	C	D
1	A	A	0.100	0.150	0.200	0.250
2	A	B	0.150	0.350	0.400	0.450
3	A	C	0.050	0.100	0.150	0.200
4	A	D	0.100	0.150	0.250	0.275
5	B	A	0.150	0.200	0.225	0.300
6	B	B	0.150	0.200	0.250	0.300
7	B	C	0.100	0.100	0.200	0.250
8	B	D	0.100	0.200	0.300	0.400
9	C	A	0.050	0.150	0.200	0.300
10	C	B	0.100	0.150	0.200	0.250
11	C	C	0.250	0.350	0.400	0.500
12	C	D	0.100	0.250	0.300	0.400
13	D	A	0.200	0.250	0.400	0.500
14	D	B	0.250	0.350	0.400	0.450
15	D	C	0.050	0.150	0.200	0.250
16	D	D	0.100	0.150	0.300	0.450

TABLE 12. Calculation and sum of the rules.

	A	B	C	D
	0.003	0.005	0.006	0.008
	0.007	0.017	0.019	0.022
	0.003	0.006	0.010	0.013
	0.009	0.013	0.021	0.023
	0.006	0.008	0.009	0.012
	0.010	0.013	0.016	0.020
	0.009	0.009	0.017	0.022
	0.011	0.023	0.034	0.046
	0.003	0.008	0.010	0.015
	0.008	0.012	0.016	0.020
	0.026	0.037	0.042	0.053
	0.014	0.035	0.042	0.056
	0.013	0.016	0.026	0.032
	0.026	0.036	0.041	0.046
	0.007	0.020	0.027	0.034
	0.018	0.027	0.054	0.081
Sum	0.172	0.285	0.392	0.503

We have to note that calculations of MCSs should be completed in accordance with the logic and the philosophy of the proposed approach. If the events of the MCSs are independent, the calculations are done separately. Otherwise, the probability results are used after implementing the calculation method (R or C). For example, for the MCS of BE11 IE11 BE4 are the multiplication of BE11 $\cong$ 0.0014 (Table 9), IE11 $\cong$ 0.0004 and BE4 $\cong$ 0.0037 since the events are connected to the TE by an AND gate. The probabilities of IE11 and BE4 are calculated separately by conducting the steps of defuzzification process, transformation of crisp failure possibilities into failure probabilities, and transformation of crisp failure possibility of an event into failure probability. Similarly, the probability of BE11 IE11 IE12 BE4 BE5 is calculated by multiplying BE11 and IE11 IE12 BE4 BE5 since the events are connected to the top event by an AND gate. The probability of BE11 is 0.0014 (Table 9) and the probability of IE11 IE12 BE4 BE5 is $\cong$ 0.0138 as it is known from the Table 13.

For the grounding, there exist 882 unique MCSs. This number is higher than the conventional studies because one of the benefits of this proposed ontology-based approach is to analyze all events and their combinations. The structure given in Figure 9 shows the flexibility of the system and the excessive number of MCSs prove that this system provides more information (all information) about the system. Therefore, the failure can be analyzed in any situation and possibility. The authorities and decision makers can benefit from these information about vulnerability, reliability and criticality of the system.

V. DISCUSSION

Different approaches such as summation (disjoint), multiplication (independent events), AND gate, OR gate or any other aggregation method can be utilized to calculate internal probabilities of ontology-based basic events depending on the relationships between events. Addition might not be preferred if sum of the probabilities is greater than 1. However, since the probability values are generally low, the probability calculation method can be decided according to the interrelationships of the sub-events. Ontology-based approach provides a flexibility for categorizing the events. For example, one can assign a probability value for a number of sub-events all together assuming them as a single event.

The algorithms mentioned here can be used as an autonomy and adaptation-based automatic anomaly detection system for unmanned ships. The data are obtained via sensors, and data handling becomes easier since there is only one expert which is the unmanned ship itself.

The following points have been reached:

- If there is a gate connecting the top event, the model can be solved in any case.
- If there is no gate in the model, the model can be solved with rule based system in any case.
- If all events in the model are connected to each other with gates, the model can be solved by rule based system or conventional system in any case.
- There is definitely a difference between first combining two events connected to AND or OR gates, then finding their probabilities, and first finding the probabilities, then combining them.

The following points should be considered in fuzzy (mixed) ontology-based FTA applications. In the rule based approach, the result is found as possibility, wherein the conventional approach the result is obtained as probability. Therefore, design of a fault tree is important due to probability calculations. Possibility can be transformed into probability in any case but probability cannot be converted into the possibility. The reason for this is that a single formula (Equation 12) is used for the defuzzification of a fuzzy number, and it is inadequate in the reverse conversion process. The number of the equations should be as much as the number of variables in a fuzzy number. Therefore, a probability value cannot be used in the rule based system. In the future, this system can be further developed when these problems are solved and the questions below are answered. Results of trapezoidal fuzzy numbers might be higher than 1 in rule based system.

TABLE 13. The structure for the probability of collision for autonomous ships.

			0.0000202		
			AND		
	0.0047			0.0043	
	OR			R BE4 BE5 IE	
0.0024	0.0009	0.0013		R IE11 IE12	
C BE11 BE12 BE13	C BE21 BE22	R BE31 BE32	BE4		BE5

TABLE 14. Expert prioritization parameters and weights.

	Professional position	Work experience	Education level	Weighting factor			TW	Weighting score
1	Academician	>10	P	5	3	3	11	0.35
2	Operations manager	5-10	B	4	2	1	7	0.23
3	Master	<5	M	3	1	2	6	0.19
4	Chief officer	<5	B	2	1	1	4	0.13
5	2nd Engineer	<5	B	1	1	1	3	0.10

TABLE 15. Expert evaluations of five experts.

	E1	E2	E3	E4	E5
BE11	ml	vl	vl	l	l
BE12	ml	vl	ml	l	m
BE13	vl	vl	h	l	m
BE21	vl	m	ml	vh	m
BE22	m	l	vl	ml	vl
IE11	m	ml	vl	ml	vl
IE12	ml	ml	vl	vl	m
BE31	vl	l	h	ml	vl
BE32	m	l	l	l	ml
BE4	l	l	m	m	m
TE1	m	l	l	l	ml
TE2	l	l	m	m	m

TABLE 16. Aggregation of events in fuzzy possibilities.

Events	Aggregation of events			
BE11	0.0858	0.1447	0.2126	0.3126
BE12	0.1709	0.2505	0.3197	0.4197
BE13	0.1919	0.2411	0.2919	0.3919
BE1	0.4486	0.6364	0.8243	1.1243
BE21	0.0924	0.0765	0.0442	0.0529
BE22	0.1610	0.2260	0.2776	0.3776
BE2	0.2534	0.3024	0.3218	0.4305
IE11	0.1858	0.2518	0.3248	0.4248
IE12	0.1568	0.2211	0.3071	0.4071
R IE11 IE12	0.1297	0.1945	0.2593	0.3242
R BE1 BE2 IE	0.3602	0.9004	1.0805	1.2606
BE31	0.1652	0.2207	0.2825	0.3825
BE32	0.1941	0.2941	0.3089	0.4089
BE3	0.3593	0.5148	0.5915	0.7915
BE4	0.2562	0.3562	0.3562	0.4562
R BE3 BE4	0.0322	0.0643	0.0965	0.1286
TE1	0.3613	0.4613	0.4613	0.5613
TE2	0.1618	0.2618	0.2831	0.3831
R TE1 TE2	0.2011	0.4022	0.7039	0.9050
R IE1 IE2 TE	0.0256	0.0384	0.0512	0.0641

TABLE 17. Rule values assigned for each connection.

Applied connection	Rule values			
IE11 IE12	0.100	0.150	0.200	0.250
BE1 BE2 IE	0.100	0.250	0.300	0.350
BE3 BE4	0.010	0.020	0.030	0.040
TE1 TE2	0.100	0.200	0.350	0.450
IE1 IE2 TE	0.010	0.015	0.020	0.025

1) How can a defuzzified number be converted into its original form (A B C D values)? Can a conclusion be drawn from the relationships between variables?
2) How can the probability value be included in rule based system?
3) If all values are probability in a fault tree without gates, can a solution be produced?
4) In what different ways can an ontology-based basic event be designed, and how their models and combinations are calculated?

The model has a flexibility when it comes to the number of experts during the expert consultation process. Different number of experts might involve in assessing the events, sub-events in the decision making process. For example, seven and five experts involved in all decision making processes for collision and grounding, respectively.

One of limitations of this study is the massive data load and its process. For the rule based approach, rules should be set and the calculations should be completed. This is a time consuming process based on massive data handling and calculations. Depending on the connections and relationships between events, massive data might cause deviations from accuracy and reliability. Secondly, the applications given in this study are based on fuzzy expressions and random rules, therefore there is a dependency on human thoughts and subjectivity. For the autonomous ships, an automatic sensor systems might be deployed, for which the proposed system is convenient.

In the future, a user-friendly software could be developed with a human machine interaction interface and dynamic control. A real-time dynamic model for autonomous ships with its sensory systems could be developed. Comparison studies based on fault tree analysis methodology or a literature review based on ontology-based hazard analysis could be conducted. Finally, different versions of the proposed

TABLE 18. Sensitivity analysis for collision.

MCSs	Probability	FVIM	Rank
BE11 IE11 BE4	2.228E-09	3.449E-05	23
BE11 IE11 BE5	1.389E-09	2.150E-05	33
BE11 IE12 BE4	1.116E-08	1.728E-04	9
BE11 IE12 BE5	6.959E-09	1.077E-04	13
BE11 IE11 IE12 BE4	2.797E-09	4.330E-05	21
BE11 IE11 IE12 BE5	1.744E-09	2.699E-05	28
BE11 IE11 IE12 BE4 BE5	1.971E-05	3.051E-01	1
BE12 IE11 BE4	3.615E-10	5.595E-06	48
BE12 IE11 BE5	2.253E-10	3.488E-06	50
BE12 IE12 BE4	1.811E-09	2.803E-05	26
BE12 IE12 BE5	1.129E-09	1.747E-05	38
BE12 IE11 IE12 BE4	4.538E-10	7.023E-06	47
BE12 IE11 IE12 BE5	2.828E-10	4.378E-06	49
BE12 IE11 IE12 BE4 BE5	3.198E-06	4.950E-02	7
BE13 IE11 BE4	1.202E-09	1.860E-05	37
BE13 IE11 BE5	7.491E-10	1.159E-05	45
BE13 IE12 BE4	6.020E-09	9.318E-05	15
BE13 IE12 BE5	3.753E-09	5.808E-05	19
BE13 IE11 IE12 BE4	1.508E-09	2.335E-05	31
BE13 IE11 IE12 BE5	9.403E-10	1.455E-05	42
BE13 IE11 IE12 BE4 BE5	1.063E-05	1.645E-01	5
BE21 IE11 BE4	2.220E-11	3.436E-07	54
BE21 IE11 BE5	1.384E-11	2.142E-07	56
BE21 IE12 BE4	1.112E-10	1.721E-06	51
BE21 IE12 BE5	6.932E-11	1.073E-06	52
BE21 IE11 IE12 BE4	2.787E-11	4.313E-07	53
BE21 IE11 IE12 BE5	1.737E-11	2.689E-07	55
BE21 IE11 IE12 BE4 BE5	1.964E-07	3.040E-03	8
BE22 IE11 BE4	1.436E-09	2.223E-05	32
BE22 IE11 BE5	8.954E-10	1.386E-05	43
BE22 IE12 BE4	7.196E-09	1.114E-04	12
BE22 IE12 BE5	4.486E-09	6.943E-05	18
BE22 IE11 IE12 BE4	1.803E-09	2.791E-05	27
BE22 IE11 IE12 BE5	1.124E-09	1.740E-05	39
BE22 IE11 IE12 BE4 BE5	1.271E-05	1.967E-01	4
BE31 IE11 BE4	1.694E-09	2.622E-05	29
BE31 IE11 BE5	1.056E-09	1.634E-05	40
BE31 IE12 BE4	8.487E-09	1.314E-04	11
BE31 IE12 BE5	5.290E-09	8.188E-05	16
BE31 IE11 IE12 BE4	2.126E-09	3.291E-05	24
BE31 IE11 IE12 BE5	1.326E-09	2.052E-05	34
BE31 IE11 IE12 BE4 BE5	1.499E-05	2.320E-01	3
BE32 IE11 BE4	1.046E-09	1.619E-05	41
BE32 IE11 BE5	6.518E-10	1.009E-05	46
BE32 IE12 BE4	5.239E-09	8.108E-05	17
BE32 IE12 BE5	3.266E-09	5.054E-05	20
BE32 IE11 IE12 BE4	1.313E-09	2.032E-05	35
BE32 IE11 IE12 BE5	8.182E-10	1.266E-05	44
BE32 IE11 IE12 BE4 BE5	9.251E-06	1.432E-01	6
BE31 BE32 IE11 BE4	2.063E-09	3.194E-05	25
BE31 BE32 IE11 BE5	1.286E-09	1.991E-05	36
BE31 BE32 IE12 BE4	1.034E-08	1.600E-04	10
BE31 BE32 IE12 BE5	6.444E-09	9.973E-05	14
BE31 BE32 IE11 IE12 BE4	2.590E-09	4.009E-05	22
BE31 BE32 IE11 IE12 BE5	1.615E-09	2.499E-05	30
BE31 BE32 IE11 IE12 BE4 BE5	1.825E-05	2.825E-01	2

methodology could be studied and compared each against other.

VI. CONCLUSION

In this study, we explore ontology-based fault tree analysis methods in fuzzy settings. Ontology-based structures are proposed and deployed in a fuzzy fault tree analysis algorithm. The ontology-based approach enabled allowed us capturing fault tree structures with respect to available rich domain knowledge in an intuitive manner. The two approaches (conventional and rule-based) are applied for the failure probability of top event and system analysis. Two scenarios are implemented as collision and grounding of an autonomous ships. The robust, accurate, and reliable results are obtained by using a structural design for the fault tree and probability calculations.

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APPENDIX

HAZARDS FOR THE AUTONOMOUS SHIPS:

1 The entire environment surrounding the ship
  1.1 Ship's inability to adapt to weather conditions and atmospheric effects
  1.2 Floating objects under human control or belonging to third parties
  1.3 Obstacles on the surface as a result of nature (debris, garbage, ice, etc.)
  1.4 Colliding with other ships or human-made large structures
  1.5 Inability to handle external assistance and aids
  1.6 Reliability faults of hydro-graphic geographic and atmospheric data
  1.7 Damages on the autonomous ship due to technical faults caused by other manned or autonomous ships
  1.8 Damages on the autonomous ship due to unsafe actions and operational faults of other ships
  1.9 External technical or operational faults that occur during the cargo un/loading and bunkering process
  1.10 Faults at the large structures such as bridges, canals, and quays
  1.11 External faults associated with offshore oil exploration and oil extraction
  1.12 Environmental conditions restricting the ship's speed, movement and course
  1.13 Access failures to external structures due to weather conditions
2 The ship's hardware, design, ergonomics, arrangement and location of assets and facilities
  2.1 Strength of the ship's hull is weak and the ship's horsepower is insufficient
  2.2 Lack of technical excellence on the ship that weakens the strength
  2.3 Stability failures
  2.4 Faults due to ship's maneuvering characteristics
  2.5 Ship equipment and design faults that will cause fire or leakage
  2.6 Ship equipment and design faults for the cargo and stowage
  2.7 Lack of design required for updating, development, cleaning and maintenance attitudes of ship systems

2.8 Faults of all equipment contributing to ship movement

1) [3]Technical faults

3.1 Technical faults in navigational equipment
3.2 Technical faults in maneuvering equipment
3.3 Technical faults in machinery, propulsion and auxiliary equipment
3.4 Technical faults in cargo related equipment
3.5 Technical faults in remote and automatic control systems
3.6 Technical faults in emergency and safety devices
3.7 Technical faults in un/mooring, un/berthing and anchoring equipment
3.8 Other technical failures

4 Operational faults

4.1 Design and ergonomics failures of the equipment, hardware or control systems for ship operations
4.2 Control system interface problems
4.3 Operation faults related to cargo handling
4.4 Other factors that cause operational faults

5 Faults of cargo, chemicals, energy sources

5.1 Fire or other damages caused by dangerous. Flammable, and explosive cargo itself
5.2 Lack of fire or other damage prevention systems
5.3 Stability and ballast related faults due to cargo handling processes
5.4 Failure to provide cargo security
5.5 Leakage from liquid cargoes or transportation systems
5.6 Energy sources, dangerous chemicals and energy consumption problems
5.7 Improper cargo load, stowage and maintenance
5.8 Cargo deliver problems in unchanged conditions
5.9 Problems with the combustion parameters
5.10 Problems with tanks, oil, oily mixture, and integration process
5.11 Power supply and usage problems
5.12 Other factors related to cargo, fuel, chemicals and energy

6 Organization failures and communication faults

6.1 Both ways communication problems
6.2 Denial or other problems related to local authorities
6.3 Unintentional communication of the autonomous ship's communication subsystems with others and probable undesired consequences
6.4 Any interaction problems with others

7 Faults of software, algorithm, control system and navigation

7.1 Closest point of approach violations and interaction with others (manned ships, third party assets)
7.2 Autonomous ship enters out of task vicinity; being in a wrong position
7.3 Improper positioning and wrong movement
7.4 Fault of human machine interaction in a need of assistance
7.5 Timing problems, late or early arrivals to the destination
7.6 Navigation incapability
7.7 Ship causes traffic congestion or timing problems because of traffic congestion
7.8 Software or control system does not meet required standards
7.9 Vessel causes the environmental problems

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BEKIR SAHIN received the Ph.D. degree from the Graduate School of Science and Technology, Istanbul Technical University, in 2015. He is currently an Associate Professor of the management fields of supply chain, logistics, transportation, and shipping business. He is also a Postdoctoral Researcher with NTNU Gjøvik, Norway. His research motivation comes from emerging debates in the supply chain and logistics management while developing original methods and proposing novel industrial approaches in behavioral science, optimization, technology management, safety science, and risk assessment. He also serves as an academic editor and a board member for distinguished journals, and has numerous articles published in peer reviewed journals and conferences.

ANIS YAZIDI (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees from the University of Agder, Grimstad, Norway, in 2008 and 2012, respectively. He is currently a Professor with Oslo Metropolitan University, Oslo, Norway, and leading the Research Group in Applied Artificial Intelligence. He is also an Adjunct Professor with the Norwegian University of Science and Technology (NTNU), Trondheim, Norway, and a Senior Researcher with the Oslo University Hospital, Oslo. His current research interests include machine learning, learning automata, stochastic optimization, group decision making, and autonomous computing.

DUMITRU ROMAN is currently working as a Senior Research Scientist with SINTEF, Norway. He has wide experience with initiating, leading, and carrying out (research-intensive) projects on data management and service-oriented topics. He is also active in the data management field, particularly in the emerging Data-as-a-Service (DaaS) domain. He holds an Adjunct Associate Professorship with the University of Oslo, Norway.

AHMET SOYLU received the Ph.D. degree in computer science from the University of Leuven, in 2012. He is currently a Professor with Oslo Metropolitan University, Oslo, Norway. He was previously a Postdoctoral Research Fellow with University of Oslo, Oslo; a Visiting Researcher with the University of Oxford, Oxford, U.K.; and a Postdoctoral Researcher with KU Leuven, Leuven, Belgium. He took part in several EU projects, such as iCamp, ROLE, LEGIS, LEFIS, and TREE. His current research interests include big data, data-driven innovation, data management, and decision making.

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