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The Implementation of Importance Measure Approaches for Criticality Analysis in Fault Tree Analysis: A Review

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ABSTRACT

THE IMPLEMENTATION OF IMPORTANCE MEASURE APPROACHES FOR CRITICALITY ANALYSIS IN FAULT TREE ANALYSIS: A REVIEW. Fault tree analysis (FTA) has been widely applied in nuclear power plant (NPP) probabilistic safety assessment to evaluate the reliability of a safety system. In FTA, criticality analysis is performed to identify the weakest paths in the system designs and components. For this purpose, an importance measure approach can be applied. Risk managers can apply information obtained from this analysis to improve safety by implementing risk reduction measure into the new design or build a more innovative design. Various importance measure approaches have been developed and proposed for criticality analysis in FTA. Each important measure approach offers specific purposes and advantages but has limitations. Therefore, it is necessary to understand characteristics of each approach in order to select the most appropriate approach to reach the purpose of the study. The objective of this study is to review the current implementations of importance measure approaches to rank individual basic events and/or minimal cut sets regarding their contributions to the unreliability or unavailability of NPP safety systems. This study classified importance measure approaches into two groups, i.e. probability–based importance measure approaches and fuzzy–based importance measure approaches. This study concluded that clear understanding of the purpose of the study, the type of reliability data at hands, and the uncertainty in the calculation need to be considered prior to the selection of the appropriate importance measure approach to the study of interest.

ABSTRAK

IMPLEMENTASI PENDEKATAN *IMPORTANCE MEASURE* UNTUK ANALISIS KRITIKALITAS PADA ANALISIS POHON KEGAGALAN: SEBUAH KAJIAN. Analisis pohon kegagalan telah digunakan pada analisis keselamatan probabilistik pembangkit listrik tenaga nuklir (PLTN) untuk mengevaluasi keandalan sistem keselamatan. Dalam analisis pohon kegagalan, analisis kritikalitas dilakukan untuk mengetahui desain atau komponen yang sangat rentan terhadap kegagalan dengan menggunakan pendekatan *importance measure*. Manajer resiko dapat menggunakan hasil analisis ini untuk memperbaiki kinerja sistem keselamatan dengan menerapkan konsep pengurangan resiko melalui perubahan desain yang lebih inovatif. Beberapa pendekatan *importance measure* telah diaplikasikan dalam analisis kritikalitas pada analisis pohon kegagalan. Setiap pendekatan memiliki tujuan yang spesifik dan menawarkan keunggulan tetapi juga memiliki kelemahan. Oleh karena itu, karakteristik dari setiap pendekatan yang ada perlu dipahami agar dapat memilih pendekatan yang paling sesuai dengan penelitian yang sedang dilakukan. Tujuan dari penelitian ini adalah untuk mengkaji pendekatan *importance measure* yang ada saat ini yang telah digunakan untuk mengevaluasi tingkat kritikalitas kejadian dasar dan *minimal cut set*. Penelitian ini mengklasifikasikan pendekatan *importance measure* menjadi dua grup yaitu pendekatan *importance measure* berbasis probabilitas dan pendekatan *importance measure* berbasis *fuzzy*. Penelitian ini menyimpulkan bahwa untuk memilih pendekatan *importance measure* yang paling sesuai maka perlu pemahaman tujuan dari analisis yang sedang dilakukan, jenis data keandalan yang dimiliki dan ketidakpastian dalam perhitungan.
Kata kunci: *Importance measure*, analisis kritikalitas, analisis pohon kegagalan, pembangkit listrik tenaga nuklir.

1. INTRODUCTION

Fault tree analysis (FTA) has been widely applied in nuclear power plant (NPP) probabilistic safety assessment (PSA). It can evaluate the reliability of the safety systems of NPPs. For example, the unavailability of the containment cooling system of a typical four loops pressurized water reactor was evaluated using FTA[1]. Furthermore, Hadavi[2] developed accident scenarios and evaluated

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the performance of safety related systems of a typical WWER-1000 nuclear reactor also using FTA. FTA was also applied to evaluate the reliability of the Indian Prototype Fast Breeder Reactor[3], the failure probability of the containment spray injection system[4] and the reactor protection system[5] of a typical PWR, and the reliability of the AP1000 passive safety systems[6-9].

A fault tree is a graphical representation of parallel and/or sequential fault events leading to the top event, which is logically depicted using Boolean gates and mathematically quantified using corresponding Boolean algebras[10-13]. The fault tree can show potential accident scenarios of a system being represented[14-16].

There are three types of events in a fault tree, i.e. basic events, intermediate events, and a top event. A basic event is a system component or element, which fails to perform its function and do not need further development. An intermediate event is an event generated when two or more basic events occur. This is the output of a Boolean gate. Meanwhile, a top event is the undesired state of the system of interest. This is the failure of the system being evaluated.

The output of two or more independent fault events combined by an OR Boolean gate and by an AND Boolean gate as shown in Figure 1 can be calculated using (1-2), respectively[17,18].

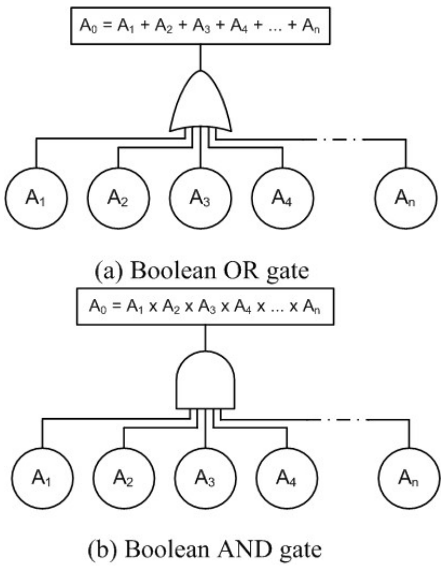

Figure 1. Fault Tree Representations[18].

In Figure 1(a), the undesired top event A_0 will fail if one of input events A_i fails. On the other hand, in Figure 1(b), the top event A_0 will fail if all input events A_i fail together at the same time.

$$P\left(A_0\right)=1-\prod_{i=1}^{n}\left\{1-P\left(A_i\right)\right\} \quad (1)$$

$$P\left(A_0\right)=\prod_{i=1}^{n}P\left(A_i\right) \quad (2)$$

where $P(A_i)$ is the probability of event A_i and n is the number of fault events.

In FTA, criticality analysis needs to be performed to identify the weakest paths in the system designs and components using an importance measure approach. An importance measure (IM) is an effective approach for assessing contributions of individual basic events and/or minimal cut sets to the failure of a system being interest. A minimal cut set is a group of basic events if they occur together can cause the undesired top event to occur.

The results of this measure is very useful in engineering system to identify the potential causes of the failure. Risk managers can apply information obtained from this assessment to improve the safety level of the system by implementing risk reduction measure into the new design or build a more innovative design. There are four design modifications that can be performed to improve the availability of a system, i.e. changing weak components with better quality, improving component maintenance activities, modifying component testing policy, and proposing redundancy[19,20]. For any modification made to the system, the failure probability of the top event needs to be recalculated to ensure that the safety goals are achieved in which failure probability of the system less than the objective probability [21].

Various importance measure approaches, such as Fussell - Vesely (FV) importance measure, Birnbaum's importance measure (BI), and α-cut method based importance measure (α-IM) have been developed and proposed for criticality analysis in FTA. Each important measure offers specific purposes and advantages but has limitations. Therefore, it is necessary to understand each importance measure approach prior to properly select the most relevant one to the study of interest. The objective of this study is to review the current implementations of importance measure approaches to rank individual basic events and/or minimal cut sets regarding their contributions to the unreliability or unavailability of NPP safety systems. The specific goals of each importance measure as well as its limitations are discussed.

2. METHODOLOGY

Based on how importance measures are implemented to rank basic events and/or minimal cut sets in NPP FTA, importance measure approaches can be classified into two groups, i.e. probability-based importance measure approaches and fuzzy-based importance measure approaches as graphically shown in Figure 2.

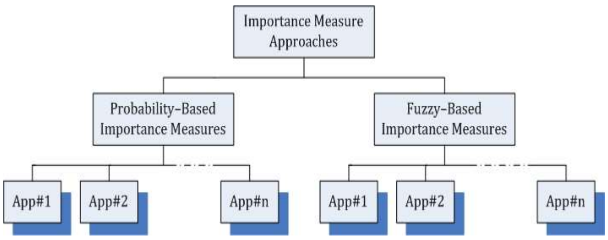

Figure 2. Classification of Importance Measure Approaches.

In probability-based importance measure approaches, contributions of individual basic events and/or minimal cut sets are quantified using probability distributions. Meanwhile, in fuzzy-based importance measure approaches, contributions of individual basic events and/or minimal cut sets are quantified using fuzzy probabilities. In this study, how probability-based and fuzzy-based importance measure approaches implemented in NPP PSA by FTA are reviewed. Specific purposes and limitations of each approach are discussed by referring to a wide range of publications.

3. RESULTS AND DISCUSSION

The main difference between probability-based importance measure approaches and fuzzy-based importance measure approaches are in the reliability data used to quantify the occurrence likelihood of individual basic events and/or minimal cut sets constructing the fault tree of the system being interest. Reliability data describes the performance of the component being investigated to successfully fulfil its functions.

Conventional FTA assumes that components always have precise probability distributions of their lifetime to failure and hence, their reliability can be statistically calculated from those available historical failure data. However, this is not the case in the real application. For example, if a system being investigated is new and hence, the system never fails before, there will be insufficient historical failure data to statistically estimate its component reliability. In this case, fuzzy FTA, which utilize fuzzy probability to describe component reliability, has been proposed to overcome the limitation of the conventional FTA.

In the sequel, each group of importance measure approaches are elaborated in details.

3.1. Probability-Based Importance Measure Approaches

In this group, the occurence likelihood of individual basic events and/or minimal cut sets are represented by probability distributions. A probability distribution is a mathematical function to represent the probabilities of occurences of different possible outcomes in a specific event. In more technical term, a probability distribution represents a random phenomenon regarding the probabilities of events.

Common and well known importance measure approaches in this group are Fussell – Vesely (FV), Birnbaum (BI), risk reduction worth (RRW), and risk achievement worth (RAW)[19,22]. Another common importance measure approach in this group is differential importance measure (DIM)[23]. The classification of this group of probability-based importance measure approaches is graphically shown in Figure 3.

Fussell – Vesely (FV) importance measure can describe the direct effect of component unavailabilities on an unwanted event. Those component unavailabilities refer to the occurrence of basic events. Meanwhile, the unwanted event refers to the occurrence of the top event. It quantifies the contributions of a basic event by dividing the summation of the probabilities of all minimal cut sets containing the evaluated basic event by the probability of the top event[24]. The results of the FV importance can be used to identify potential components to be changed to improve the safety of the related system[20]. Furthermore, Arshi, Nematollahi and Sepanloo[25] acknowledged that the FV importance measure can evaluate event contributions to the core damage and discourse reactor safety system drawbacks. Zio and Podofillini[26] studied that the importance of a component depends on the number of cut sets in which that component appears and the probability of the cut sets themselves. Celik et al.[27] demonstrated that FV can be used to rank minimal cut sets. This FV importance measure is also well-known as the top contribution importance[10, 28].

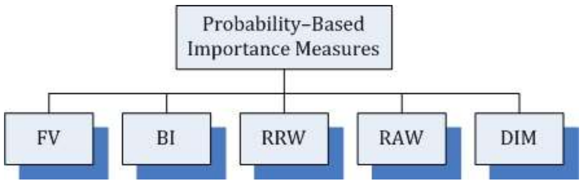

Figure 3. Classification of Probability-Based Importance Measure Approaches.

Birnbaum's importance measure (BI) deals with the importance of a single component[29]. It measures the change rate of the system reliability due to the reliability changes of a single component[30]. This measure often refers to a marginal reliability importance[26]. It can be used for sensitivity analysis by considering the effect of basic event probability changes to the top event probability[31]. Extra redundancy could be introduced into a system when BI is high and component unavailability is low[20]. Furthermore, Van der Borst and Schoonakker[20] acknowledged that the combinations of FV and BI can be applied for improving system safety. For example, when FV and BI are high, safety improvement can be realized by increasing component availability or by refining the defence in depth practice against component failures. This BI can not be applied to the system, which has common cause failures[30].

Risk reduction worth (RRW) evaluates the decrease of the top event probability when a given event does not fail[30]. This importance measure can evaluate how low the risk can be achieved when the availability of a basic event is improved[26]. Therefore, this measure can select which components that can potentially improve system reliability[31]. RRW importance measure is also well-known as the top decrease sensitivity[10, 32].

Risk achievement worth (RAW) is commonly used to determine whether the structure, system and component (SSC) degradation may be important to risk[24]. It measures risk relative increase due to the occurrence of a particular event, such as the unavailability of a system[26]. It can be used to evaluate the impact of a component to the risk when it is taken out from service[31]. This measure can estimate the risk significance of a component, which has been removed from the system being evaluated[30]. The largest impacts will be given by the component with the largest RAW. However, RAW cannot be applied to evaluate a system when there are two or more unavailable components[20]. RAW importance measure is also well-known as the top increase sensitivity[10].

RRW and RAW are commonly used in nuclear industry for risk-informed applications characterizing basic event importance. These basic events include element failures, human errors and common cause failure[20,23]. However, RRW and RAW have two limitations when they are applied to rank the criticality of groups or pairs of basic events[33]. The first limitation is that there is no direct relationship between a single component and a group of components. The second limitation is that the results somehow refer to extreme changes in the characteristics of the component unavailability. Meanwhile, the combination of FV and RAW can be well-applied for maintenance and operation optimization[20].

Differential importance measure (DIM) is another importance measure for risk informed applications[23]. It is a first-order sensitivity measure to rank risk model parameters by changing their values one at a time. However, it does not consider the interaction among components[26,34]. DIM offers additivity properties to overcome the limitations of RRW and RAW for risk informed decision making[23].

3.2. Fuzzy–Based Importance Measure Approaches

In this group, the occurence likelihood of individual basic events and/or minimal cut sets are represented by fuzzy probabilities. A fuzzy probability is a membership function of fuzzy numbers to represent the occurrence likelihood of events in fuzzy fault tree analysis. The most common shapes of membership functions in reliability engineering are triangular and trapezoidal fuzzy numbers[18].

Well-known importance measure approaches in this group are fuzzy important measure (FIM), fuzzy uncertainty importance measure (FUIM), fuzzy importance index (FII), and α-cut method based importance measure (α-IM). The classification of this group of fuzzy-based importance measure approaches is graphically shown in Figure 4.

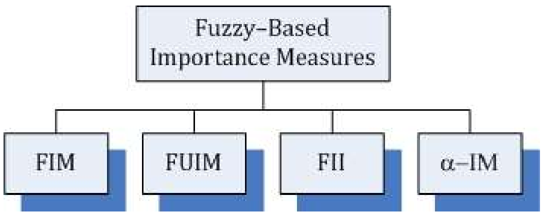

Figure 4. Classification of Fuzzy–Based Importance Measure Approaches.

Suresh, Babar and Venkat Raj[35] proposed a fuzzy importance measure (FIM) to evaluate critical components in fuzzy fault tree analysis. This measure evaluates the importance of a basic event by quantifying the Euclidean distance between the top event fuzzy probability, when the basic event being evaluated is fully available, to the top event fuzzy probability, when the evaluated basic event is fully unavailable[36]. They confirmed that the basic event with the biggest FIM is the most critical in the system. Hence, this basic event should be changed to improve the availability of the system.

Meanwhile, a fuzzy uncertainty importance measure (FUIM) has been developed and proposed to evaluate which components have the maximum uncertainty contribution to the uncertainty of the top event[35]. This measure evaluates the uncertainty contribution of a basic event by quantifying the Euclidean distance between the top event fuzzy probability with real fuzzy probability of the basic event being evaluated to the top event fuzzy probability when the evaluated basic event is fully unavailable[37]. They found that the basic event with the biggest FUIM is the biggest uncertainty contributor to the top event uncertainty.

A fuzzy importance index (FII) has also been proposed to evaluate how importance a basic event in a fuzzy environment. This measure evaluates the contribution of a basic event to the top event occurrence by quantifying the difference between the top event fuzzy probability involving all basic events and the top event fuzzy probability without the evaluated basic event[38]. The basic event with the largest index is the most important in the system being evaluated. This importance measure can also be called as fuzzy weighted index[39].

Purba, et al.[40] proposed α-cut method based importance measure (α-IM) for criticality analysis in fuzzy probability-based fault tree analysis (FPFTA). The occurrence likelihoods of the three types of events in FPFTA are represented by fuzzy probability and the Boolean algebras are represented by fuzzy arithmetics to propagate uncertainty from basic events to the top event[41,42]. In this approach, the basic event with the lowest α-IM score is the most critical in the system. Therefore, this basic event should be the focus of the designers and engineers to improve the performance of the system.

4. CONCLUSION

This study classified importance measure approaches into two groups, i.e. probability-based importance measure approaches and fuzzy-based importance measure approaches. Probability-based importance measure approaches include Fussell – Vesely (FV), Birnbaum (BI), risk reduction worth (RRW), risk achievement worth (RAW), and differential importance measure (DIM). Meanwhile, fuzzy-based importance measure approaches include fuzzy important measure (FIM), fuzzy uncertainty importance measure (FUIM), fuzzy importance index (FII), and α-cut method based importance measure (α-IM). This study concluded that in order to select the most appropriate importance measure approach, it is critical to firstly understand the main purpose of the study. Secondly, it is also necessary to confirm the type of available reliability data prior to the selection of the fault tree analysis to evaluate the performance of the system of interest. Finally, decisions on the most critical basic events or components should also consider their contributions to the uncertainty of the occurrence likelihood of the undesired top event.

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