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Development of network-based probabilistic safety assessment: A tool for risk analyst for nuclear facilities

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ABSTRACT

The probabilistic safety assessment (PSA) methodology has been developed and utilized to assess the overall risks to a nuclear facility. However, PSAs are challenged when it comes to accurately describing relations among events, or to accommodate newly observed data, or to consider severe accident scenarios within a current framework. To overcome such challenges and take advantage of the merits of recent systems analysis concepts, this paper develops an improved PSA approach, by integrating the current fault tree-based PSA framework with a Bayesian network. The proposed approach enables one to account for event relations beyond logic gates, to incorporate additional field observations and to conduct vulnerability assessments in an accident condition. To demonstrate the proposed Bayesian-based method, it is applied to a nuclear research reactor recently constructed in JUST, Irbid, Jordan. Several case studies are conducted to demonstrate how realistic information about events and from field inspections changes the core damage risk. In addition, critical scenarios are investigated for an accident, to perform vulnerability assessment beyond a design-basis event. Consequently, it is shown that the proposed approach provides an enhanced framework for risk assessments at nuclear facilities. This framework is ultimately expected to improve decision support for risk-informed designs.

1. Introduction

Nuclear facilities such as nuclear power plants, research reactors, nuclear fuel cycle facilities, etc. operate as critical facilities in urban communities and support sustainable societies in many countries. Due to the risks inherently associated with nuclear development, the safety of these facilities is a major concern to residents living in areas near such facilities. To address these concerns, a probabilistic safety assessment (PSA) has been utilized as a useful tool for assessing the risk of nuclear facilities and to improve their safety (USNRC, 1982; IAEA, 1986; IAEA, 1989; IAEA, 1992; Fullwood, 2000; IAEA, 2001a,b; CNSC, 2005; OECD/NEA, 2007; ASME/ANS, 2009; ASCE, 2016). However, evaluating safety quantitatively is complex since it typically involves a large number of risks, of structures, components and systems, and their probabilistic behaviors.

In the nuclear industry, PSAs can generally be categorized into two types, (1) internal PSAs and (2) external PSAs. A PSA is basically performed using an event tree (ET) approach linked with a fault tree (FT) analysis (USNRC, 1982). From an analysis perspective, the approach used in the modeling and assessment of system-level safety depends entirely on the FT analysis. Examples include, but are not limited to PSAs for nuclear power plants and research reactors (USNRC, 1975; Nair and Krishnamoorthy, 1999; Aneziris et al., 2004; Keller and Modarres, 2005; Yang, 2012; Barati and Setayeshi, 2014; Kumar et al., 2016; Christian and Kang, 2017a,b). The references cited above are selective ones which are mostly focused on the PSA of nuclear facilities utilizing ETs and FTs. The examples beyond such area are not specifically referred since these are out of the scope of this study.

Because of this characteristic, the current PSA has limitations that are identical to those of FT analysis. The fundamental assumption when using the standard FT is that the basic events are considered to be statistically independent. The relationships between the basic/intermediate/top events are defined using logic gates, and the analysis depends on the information in the design-basis events. Therefore, the intrinsic characteristics of the standard FT analysis means that it includes specific limitations: (1) such an analysis is not able to express the statistical dependencies among events beyond the logic gates, (2) it cannot accommodate additional evidence and (3) it cannot deal with beyond-design-basis accident conditions of the entire system.

Some of the limitations of PSAs which adopt the standard FT analysis can be overcome by combining the FT with other techniques, or by employing an alternative approach. For example, the statistical dependencies between events can be handled by introducing correlation coefficients within the FT (Zhang, 1989; Fleming and Mikschl, 1999;

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Ebisawa et al., 2015). Alternatively, the concept of a Bayesian Network (BN) can also be employed. The BN approach is capable of managing not only the logic gate relationships, but also various statistical dependencies that cannot otherwise be represented by the standard FT. In previous work, Bobbio et al. (2001) proposed a mapping method which converts a FT into a corresponding BN, and demonstrated the potential of considering general dependencies between events. This type of network representation also facilitated the direct and simple implementation of Bayesian updating quite effectively, to accommodate new data/information (Hamada et al., 2004; Wilson and Huzurbazar, 2007; Kelly and Smith, 2009; Khakzad et al., 2011; Kwag and Gupta, 2016; Kwag et al., 2017). Kwag and Gupta (2017) conducted a beyond-design-basis accident analysis for a structural system subjected to external multiple hazards by utilizing a BN. Kwag et al. (2018) have attempted to apply the BN to a model verification and validation within a probabilistic risk assessment framework so that they predict the system level simulation accuracy based on component level simulation results.

Consequently, in this paper, in order to fully utilize the current state of the art in systems analysis area, we propose a new assessment approach in which a Bayesian network is embedded in the current PSA framework to supplement the standard FT technique. This proposed BN-based PSA approach can account for general statistical dependencies among events, while exploring scenarios relevant to beyond-design-basis accidents. The approach also allows the analyst to incorporate newly observed evidence from the field. The proposed approach is first applied to the risk quantification of a research reactor plant as an example. The effectiveness of the approach is demonstrated by comparison with a FT-based PSA. Based on the results, it is expected that the proposed approach can be utilized for identifying the real-time risk status of a nuclear facility, and to aid in making risk-informed decisions.

This paper is organized as follows. It initially presents a brief overview of the current PSA method used in nuclear facilities. In Section 3, the basic concept of the ET & FT linking approach adopted in the current PSA is explained, and the new concept of a BN, including a mapping algorithm, is introduced. The introduced concepts are limited to the aspects that are necessary in this study. In section 4, the proposed approach is presented. Essentially, the current PSA procedure is integrated with a Bayesian network to overcome the present limitations of the FT-based PSA. Section 5 illustrates the performance of the BN-based PSA when this approach is applied to the risk estimation of a pool-type research reactor plant; this section also discusses important findings. To accomplish this evaluation, we compared the results of a conventional FT analysis with those of the BN method, utilizing several cases. Section 6 concludes with a summary and discussion.

2. Overview: current practice of PSA in nuclear facilities

The probabilistic safety assessment (PSA) is a comprehensive method used to evaluate the risks of nuclear facilities, and to identify vulnerabilities in their design and operation. In this regard, the PSA has been widely utilized to enhance the safety of nuclear facilities in many countries for several decades (OECD/NEA, 2007; Yang, 2012). In the nuclear industry, the PSAs can be mainly categorized into two types, (1) internal PSAs and (2) external PSAs. The internal PSA estimates three levels of risk induced by internal accidents: (a) a level 1 PSA evaluates core damage frequency (CDF), (b) a level 2 PSA estimates the frequency of accidents which release radioactivity and (c) a level 3 PSA evaluates the consequences in terms of injury to the public and damage to the environment. The external PSA includes, but is not limited to, the seismic PSA, Fire PSA, Flood PSA, etc. The PSA models for external events are basically developed based on the internal PSA model. The unique characteristics of specific hazards are individually incorporated into such developed external event PSA models. The analysis results regarding external and internal event PSAs are integrated with respect to the level 1 plant PSA of some nuclear power plants. This study is focused on the application of a Bayesian network to the level 1 internal PSA.

The current PSA has been conducted in accordance with the methodology introduced in IAEA procedure guide (IAEA, 1992) and USNRC PRA procedure guide (USNRC, 1982). The methodology consists of six major tasks related to the level 1 internal event analysis, as follows:

- Task 1: Plant familiarization
- Task 2: Identification and selection of postulated initiating events
- Task 3: Development of various accident scenarios (ET Analysis)
- Task 4: System modeling (FT Analysis)
- Task 5: Collection and evaluation of reliability data
- Task 6: Accident sequence quantification

Task 1 collects the information needed to carry out the PSA. This involves all the information needed to identify appropriate initiating events, scenario investigation for the initiating events evolving into the core damage accident, determination of the success or failure criteria for systems, sub-systems and components, and the definition of relations among systems, sub-systems and components. Task 2 identifies and selects postulated initiating events. An initiating event is considered to be an event which can result in the core damage if it is integrated with associated system failures. Task 3 develops various accident sequences, which are combinations of initiating events and successes or failures of the systems. This task is achieved by employing the ET analysis. Task 4 models the system failures within each accident scenario. This is fulfilled using a FT analysis. Task 5 collects and estimates the reliability data demanded for the ET and FT analyses. The reliability data include the frequencies of initiating events, component hardware failure rates, common cause failure rates, human error probabilities, etc. Task 6 quantifies the accident sequences. The purpose of the accident sequence assessment is to evaluate the CDF for each sequence, and it identifies the critical contributors to a total CDF. The total CDF is evaluated by summing the frequencies of individual accident sequences resulting in the core damage. This task is basically conducted utilizing the ET and FT linking approach (USNRC, 1982).

Since this study is interested in improving the current systems analysis of the PSA practice, in the next chapter, we explain basic concepts of the ET and FT analysis, and the ET and FT linking approach in more detail, using an example. Based on these fundamentals, we introduce the new concept of BN, which is a more general framework than the standard FT analysis, and an algorithm for mapping from FT to BN.

3. Systems analysis

3.1. Event tree and fault tree linking approach

The event tree (ET) analysis quantitatively evaluates all possible consequences, serious or not, induced by an initiating event and the following sub-events. Each consequence constitutes a specific path consisting of the initiating event and related sub-events. Fig. 1 (a) shows a general ET example. The initiating event causes the first subsequent events. The first subsequent events consecutively induce the second subsequent events, the second subsequent events bring about the third subsequent events, and this process continues until nth subsequent events arrive at the final consequences. Here, given a specific subsequent event, the following sub-events are mutually exclusive. For example, under the assumption that the initiating event occurred, the first subsequent events following the initiating event are all mutually exclusive. Therefore, all paths in the ET represent all sequences of events resulting in all possible consequences. The probability which is associated with the occurrence of a specific path can be simply evaluated by the multiplication of the conditional probabilities of all the events on that path, as in the following Eq. (1):