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Impact of component unavailability uncertainty on safety systems unavailability

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HIGHLIGHTS

- Impact of component unavailability uncertainty on systems unavailability is analyzed.
- Analysis is done with Monte Carlo sampling and min cut upper bound approximation.
- The top event uncertainty depends on the basic events unavailability distribution.
- The top event uncertainty depends on the importance of the basic events.
- Introduction of lognormal distribution results in increased top event uncertainty.

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ABSTRACT

The increased and extended application of the probabilistic safety assessment requires appropriate consideration of uncertainties in the analyses and interpretation of the results. Inadequate treatment of uncertainties may lead to poorly supported or even wrong conclusions with final consequence of loss of adequate level of safety.

Epistemic uncertainty results from the imperfect knowledge or incomplete information regarding the parameters values in the underlying model. Epistemic uncertainty is considered in the probabilistic safety assessment models by probability distributions associated with the uncertain parameters.

This paper presents the results of the analysis of the introduction of probability distributions associated with component unavailability parameters, on the overall unavailability of the analyzed system. The normal and lognormal distributions are introduced as probability distributions associated with component unavailability. The minimal cut sets of the analyzed system are identified with application of the fault tree analysis. The distribution of the top event unavailability is assessed with application of the min cut upper bound approximation and Monte Carlo sampling.

The analysis of the uncertainty propagation is demonstrated using the fault tree of the auxiliary feedwater system of the nuclear power plant. The implications of the introduction of different probability distributions for the components unavailability on the obtained results are analyzed. Obtained results include skewness and kurtosis as measures of the goodness-of-fit of the top event unavailability to the normal distribution.

Obtained results show that the probability density function of the top event depends on the characteristics of the basic events unavailability distribution and the importance of the selected events. Introduction of the lognormal distribution for uncertainty characterization of the basic events unavailability results in positive kurtosis. Positive kurtosis is indicating increased probability of having top event unavailability larger than the mean value.

Decision making based on the mean value of the top event unavailability in case of positive kurtosis of the probability density function results in risk underestimation.

1. Introduction

Appropriate consideration of uncertainties shall be given in probabilistic safety assessment (PSA) and interpretation of their results. Inadequate treatment of uncertainties may lead to poorly supported or even wrong conclusions whose final consequence is a

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loss of adequate level of safety. Maintenance of the adequate level of safety is especially important for the nuclear power plants as high-consequence technology (Ahn et al., 2012; Ánchel et al., 2012; Bouloré et al., 2012; Carlos et al., 2013; Chevalier-Jabet et al., 2014; D'Auria et al., 2012; Lopez and Herranz, 2012; Povilaitis et al., 2013; Trivedi et al., 2012).

There are two aspects to uncertainty that must be distinguished and treated differently when creating models in probabilistic safety assessment. They are termed aleatory and epistemic uncertainty (Apostolakis, 1989, 1999; ASME, 2009; Helton et al., 2011; NRC, 2002). Aleatory uncertainty results from the effect of inherent randomness or unpredictable variability of the modelled phenomenon. Epistemic uncertainty results from the imperfect knowledge or incomplete information regarding values of parameters of the underlying model.

Epistemic uncertainty is typically classified into three different classes:

- Parameter uncertainty: associated with imperfect knowledge about the input parameter values used in the analysis.
- Model uncertainty: exists when there is no consensus approach to modelling specific phenomena or events.
- Completeness uncertainty: representing uncertainties due to the portion of risk that is not explicitly included in the analysis.

Parameter uncertainty relates to the uncertainty in the computation of the input parameter values used to quantify the probabilities of the basic events (BE) in the PSA. The parameters uncertainties result from their interdependence with modelling assumptions, lack of statistically significant data, expert opinion and rarity of modelled events (Kurisaka et al., 2014; Mezio et al., 2014; Vinod et al., 2008; Volkanovski and Čepin, 2011; Watanabe et al., 2005). The most of the events in risk models in the PSA are relatively rare resulting with scarce data and significant uncertainties (Apostolakis, 1989).

The normal and lognormal distributions are two commonly used distributions in the PSA for consideration of the parameters uncertainties (Breeding et al., 1985; Volkanovski and Čepin, 2011). The main characteristics of both distributions are given in the following section. The implications of introduction of these probability distributions for different number and sets of components are investigated for reference nuclear power plant safety system model. The obtained results are presented and discussed.

2. Top event unavailability analysis

Fault tree analysis is the deductive modelling tool used in PSA to identify and assess the combinations of the undesired events in the context of the system operation and its environment that can lead to the undesired state of the system (Roberts et al., 1981; Volkanovski et al., 2009). The undesired state of the system is represented by a top event. The fault tree analysis is based on Boolean algebraic and probabilistic basis that relates probability calculations to Boolean logic functions. The logical gates integrate the primary events to the top event, which corresponds to the undesired state of the system. The primary events are the events, which are not further developed, e.g. the basic events and the house events. The basic events are the ultimate parts of the fault tree, which represent the undesired events, e.g. the component or system failures.

Two types of results are obtained from the fault tree analysis. The qualitative results include the minimal cut sets which are the combinations of components failures causing system failure. The quantitative results include the numerical probabilities of the cut sets probabilities and systems failures (Čepin and Mavko, 2002).

Unavailability of each minimal cut set is calculated using the relation of simultaneous occurrence of independent events under assumption that the basic events are mutually independent:

$$Q_{MCSi} = \prod_{j=1}^{m} Q_{Bj} \tag{1}$$

where Q_{MCSi} – unavailability of the minimal cut set i, Q_{Bj} – probability of the basic event B_j describing failure of the component (i.e. failure probability of component B_j), m – number of basic events in minimal cut set i.

The quantitative fault tree analysis represents a calculation of the top event unavailability:

$$Q_{GD} = \sum_{i=1}^{n} Q_{MCSi} - \sum_{i<j}^{n} Q_{MCSi \bigcap MCSj} + \sum_{i<j<k}^{n} Q_{MCSi \bigcap MCSj \bigcap MCSk} - \cdots + (-1)^{n-1} Q \bigcap_{i=1}^{n} MCSi \tag{2}$$

where Q_{GD} – top event unavailability of the fault tree, $Q_{MCSi \cap MCSj}$ – probability of the intersection of the minimal cut set i and cut set j, n – number of the identified minimal cut sets.

The expression for the top event unavailability Q_{GD} given by Eq. (2), for mutually independent cut sets, can be written as:

$$Q_{GD} = 1 - \prod_{i=1}^{n} (1 - Q_{MCSi}) \tag{3}$$

If there is any overlap between minimal cut sets with same basic event occurring in more than one cut sets, then expression given with Eq. (3) is upper bound for Q_{GD} and is known as the min cut upper bound (Esary and Proschan, 1962, 1970; NRC, 1994). The min cut upper bound is superior to the rare event approximation and is widely used in standard PSA of the nuclear power plants for the accident sequence quantification (NRC, 1994).

The quantitative results obtainable from fault tree analysis include quantitative importance measures. The Fussell–Vesely Importance (FV) is quantitative importance measure defined as:

$$FV_k = 1 - \frac{Q_{GD}(Q_k = 0)}{Q_{GD}} \tag{4}$$

where FV_k – Fussell–Vesely importance for component k, $Q_{GD}(Q_k = 0)$ – top event unavailability when component k failure probability is set to 0.

The Fussell–Vesely importance gives fractional contribution of the basic event unavailability to the system unavailability.

3. Distributions characteristics

3.1. Normal distribution

Normal distribution is statistical distribution used in standard PSA for characterization of the input parameters of the basic events (Breeding et al., 1985; Volkanovski and Čepin, 2011).

The probability density function of the normal distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \qquad -\infty < x < \infty, \ -\infty < \mu < \infty, \ \sigma > 0 \tag{5}$$

where x – random variable, σ – standard deviation, μ – mean of the distribution.

Fig. 1 shows probability density function (pdf) and cumulative distribution function (cdf) of the normal distribution with $\mu = 1.5$