An Overview of PSA Importance Measures

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An overview of PSA importance measures

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Abstract

The present paper deals with the use of probabilistic safety assessment (PSA) importance measures to optimise the performance of a nuclear power plant. This article is intended to give an overview on the subject for PSA practitioners. The most frequently used importance measures are shortly addressed. It is shown that two importance measures are sufficient to describe the character of the coredamage-equation. The most often used are the risk achievement and Fussell–Vesely importance, in combination with each other. In the field of nuclear power plant test and maintenance activities the Birnbaum importance is advocated.

Keywords: Probabilistic safety assessment; PRA; Risk importance measures; Safety importance measures; Birnbaum importance; Risk achievement worth; Fussell–Vesely importance; Figures of merit

1. Introduction

The design and maintenance of nuclear power plants has been a well-subsidised business for a long time. It is only in the last decades that money has been considered a very important aspect in this matter, for nowadays the budgets are limited and need to be taken into account very carefully. Therefore, a need has arisen to be able to make reliable and cost effective choices with respect to the improvements that are to be made in case of (re)design- or maintenance-projects. Probabilistic safety assessment (PSA) is commonly used in the nuclear sector as a methodology to evaluate the effects of improvements that are being made. For the interpretation of the results of PSA, measures are defined which can provide us with an importance-ranking of the components.

Most applications of importance measures can be assigned to the following three areas:

1. (Re)Design: optimisation of the plant design by adding or removing components or systems.
2. Test and maintenance: optimisation of the plant performance by changing the test and maintenance strategy for a given design.
3. Daily configuration control: what will be the effect of taking a component out of service.

It will be shown that two importance measures are sufficient to describe the character of the coredamage-equation in all above mentioned applications.

2. Definition of importance measures

Because nuclear power plants are designed according to the defence-in-depth principle, one single failure of a component or other basic event will probably not result in a large accident. More likely, a large accident will be the result of combinations of multiple basic events. The PSA methodology determines all-important cutsets that could result in a large accident. The final results of a PSA-study are then represented in the risk equation. In this equation, risk can be any measure such as, core melt frequency, expected dose, large release frequency, etc.

The mathematical representation of this Boolean expression could be written as follows:

$$R(X) = K(X) + L(X) \tag{1}$$

Here $K(X)$ represents the cutsets containing a specific basic event x_i, whilst the cutsets not containing x_i are represented by $L(X)$. The risk equation $R(X)$ can be manipulated in various ways to produce the risk importance measure we need. Risk in this respect is represented as the frequency that a certain unwanted event will take place. A risk importance measure gives an indication of the contribution of a certain component to the total risk. It must be stressed here that a certain risk importance measure is dependent on the unwanted event to be studied. This means for example that the components that are most important to prevent

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Table 1
Risk importance measures

Measure	Abbreviation	Principle
Risk reduction	RR	$R(\text{base}) - R(x_i = 0)$
Fussell–Vesely	FV	$\dfrac{R(\text{base}) - R(x_i = 0)}{R(\text{base})}$
Risk reduction worth	RRW	$\dfrac{R(\text{base})}{R(x_i = 0)}$
Criticality importance	CR	$\dfrac{R(x_i = 1) - R(x_i = 0)}{R(\text{base})} \times x_i(\text{base})$
Risk achievement	RA	$R(x_i = 1) - R(\text{base})$
Risk achievement worth	RAW	$\dfrac{R(x_i = 1)}{R(\text{base})}$
Partial derivative	PD	$\dfrac{R(x_i + \partial x_i) - R(x_i)}{\partial x_i}$
Birnbaum importance	BI	$R(x_i = 1) - R(x_i = 0)$

coremelt need not necessarily be the same to prevent a large release. In Table 1 the most frequently used risk importance measures are given [1–3]. In principle, most of these risk importance measures are variations of

1. risk reduction (RR),
2. risk achievement (RA), and
3. partial derivative (PD).

Another group of importance measures, the uncertainty importance will be discussed in Section 5.

In Table 1 the following definitions are used:

$R(x_i = 1)$, the increased risk level without basic event x_i or with basic event x_i assumed failed,
$R(x_i = 0)$, the decreased risk level with the basic event optimised or assumed to be perfectly reliable,
$R(\text{base})$, the present risk level,
$x_i(\text{base})$, present unavailability of component i.

The first two groups of risk importance measures in Table 1 are generally used in characterising risk properties and in aiding decision making. RA and the RR, both measures are expressed on an interval scale. When these measures are defined as a ratio, they are named the risk reduction worth (RRW) and the risk achievement worth (RAW). The RAW presents a measure of the 'worth' of the basic event in 'achieving' the present level of risk and indicates the importance of maintaining the current level of reliability for the basic event. The RRW represents the maximum decrease in risk for an improvement to the element associated with the basic event. In most cases basic events represent component unavailabilities.

As a RR indicator, Fussell–Vesely (FV) importance is most commonly used and as a RA indicator, RAW is most often used. FV importance is a normalised RR importance, and is comparable to RRW.

If the risk measure is defined to be the system unavailability or unreliability then the more generally applied

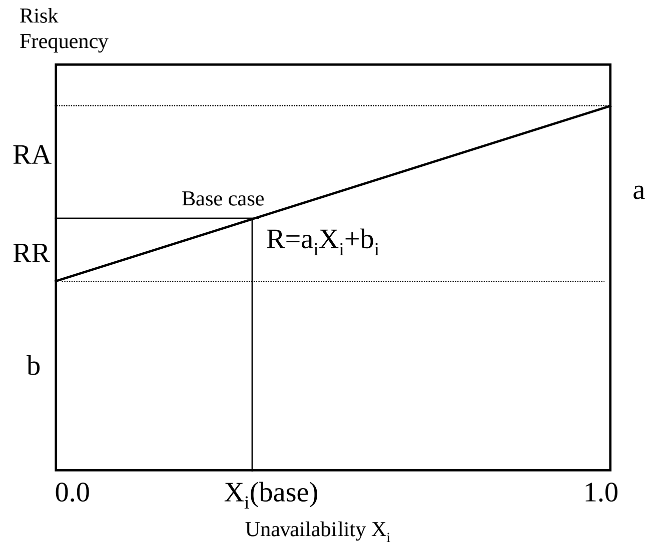

Fig. 1. Sensitivity of risk frequency to basic event unavailability.

Birnbaum importance (BI) is used, which is sometimes called the reliability importance of the component being considered. The BI is completely dependent on the structure of the system model and is independent of the current probability of the basic event.

For a better understanding of risk importance measures Eq. (1) can be represented as the following linear equation.

$$R(X_i) = aX_i + b \tag{2}$$

Eq. (2) is suggested by Wall [4]. It is simple but correct when basic event i is independent from other basic events in the equation. Although in most applications this assumption is not completely fulfilled, it is implicitly used in the calculation of all risk importance measures that are listed in Table 1. This equation is presented in Fig. 1. The importance measures in Table 1 are all mathematical variations of a_i, b_i and $X_i(\text{base})$. Since normally the current reliability of the component is known, you need two importance measures to correctly describe the character of Eq. (2). For example, RAW and FV importance could be used to describe the influence of the components unavailability completely. In many applications, only one risk importance measure could be sufficient. Depending on the application the best-suited importance measure(s) must be chosen.

From Fig. 1 you can determine that the importance measures are interrelated,

$$\text{FV} = \frac{aX_i(\text{base})}{aX_i(\text{base}) + b} = \frac{\text{RR}}{R(\text{base})} \tag{3}$$

$$\text{RRW} = \frac{a}{b}X_i(\text{base}) + 1 = \frac{1}{1 - \text{FV}} \tag{4}$$

$$\text{CR} = \frac{aX_i(\text{base})}{aX_i(\text{base}) + b} = \text{FV} \tag{5}$$

$$\mathrm{RAW} = \frac{a+b}{aX_\mathrm{i}(\mathrm{base})+b} = \frac{\mathrm{RA}}{R(\mathrm{base})} + 1 \tag{6}$$

$$\mathrm{PD} = \mathrm{a} = \mathrm{RA} + \mathrm{RR} = \mathrm{BI} \tag{7}$$

3. Risk significance and safety significance

In many papers [5–9,13] risk significance and safety significance are regarded as complementary ways of identifying the role of components in the risk of a nuclear power plant. The FV importance measure is often used as a measure of risk-importance and RAW as a measure of safety-importance. This corresponds with the idea that you need two importance measures to describe the character of Eq. (2) fully.

In this paper we do not go into the deeper philosophy of the terms risk- and safety significance. See Ref. [6] for more. We will try to explain these concepts by examples. Starting with rewriting Eq. (3):

$$\mathrm{FV} = \frac{aX_\mathrm{i}(\mathrm{base})}{aX_\mathrm{i}(\mathrm{base})+b} \approx \frac{a}{b}X_\mathrm{i} \quad \text{when } aX_\mathrm{i} \ll b \tag{8}$$

So FV is proportional to the unavailability X_i of component i. Risk significance, e.g. FV importance represents the direct effect of the components unavailability on the unwanted event core melt, etc.

Using the same approximation safety significance can be explained:

$$\mathrm{RAW} = \frac{a+b}{aX_\mathrm{i}(\mathrm{base})+b} \approx \frac{a}{b} + 1 \quad \text{when } aX_\mathrm{i} \ll b \tag{9}$$

So RAW is a weak function (almost independent) of the unavailability of X_i of the component. So RAW does not represent the component itself, but the defence of the rest of the installation against a failure of component i. It could be said [4] that a low RAW reflects a strong defence in depth for the component in question. This is the concept of safety significance.

What is explained here for RAW is completely true for BI. So BI is preferred to represent safety significance.

4. Usage of importance measures

The importance measures mentioned, contain different information, and for this reason they have their own use. As explained in last paragraph, for most applications the combination of two importance measures is needed. For some applications one importance measure could be sufficient.

Using the concept of risk- and safety significance Table 2 is produced. We prefer to use BI instead of RAW, because it is completely independent on the present value of the component unavailability. Realise that FV could be high by either a high component unavailability or a weak defence in depth. When both FV and BI are high, safety can be improved by decreasing the components unavailability or by improving the defence in depth against a failure of the component. The combination FV = high and BI = low is very unlikely and can only exist when the present component unavailability X_i is extremely high.

This table indicates that FV importance alone is able to identify potential components for safety improvement. To identify components for potential relaxation both FV and BI are needed.

4.1. Test and maintenance activities

Nowadays the most important area where importance measures are applied is in test and maintenance programs. The influence of T&M is completely connected to the change of the unavailability and not to a change in the defence in depth against a failure of the component.

Special attention needs to be given to basic events that normally have a low failure rate (because of good maintenance), and for that reason do not appear in the risk equation (truncation problem). Truncation has an impact on the importance evaluation, in that events with high RAW may be deleted. Such basic events could (theoretically) be safety significant, although they are missed in all categories of importance measures, because they are not in the risk equation. For most applications this is a minor problem, because drastically decreasing the test and maintenance activities of these basic events, will not increase the failure rate to one. In reality, changing test and maintenance activities will at the most change the failure rate by a factor of 10–100.

FV alone could be used to identify potential components for safety improvement. To identify components for T and M-relaxation both FV and BI are needed. Since combinations of FV = high and BI = low are very unlikely, BI alone could be used for this purpose.

This last remark is specially useful when ranking is performed. Because two-parameter ranking is complex, we prefer FV-ranking for safety improvement applications and BI-ranking for T&M-relaxation usage.

Table 2
Information in risk measures

Risk significant FV	Safety significant BI	Potential for safety improvement	Potential for relaxation
High	High	Component, defence in depth	No
High	Low	Component	No
Low	High	Do not degrade component	No
Low	Low	No	Component, defence in depth

4.2. Daily configuration control

Another use of importance measures is daily configuration control. Central in this application is the question 'what will be the result (coremelt-frequency) when a certain component is taken out of service'. The most suited importance measure for this usage is RAW. Two warnings must be made to use RAW for this application.

1. *Truncation problem:* the final cutset-equation is only applicable for changes around the average unavailabilities. When the unavailability of a component is changed from average to 1, as is done in the definition of RAW, the truncation-rules are not applicable anymore. Because of the truncation problem the final cutset-equation is incomplete and produces an incorrect and non-conservative RAW-list.
2. *More components unavailable:* when two or more components are unavailable, RAW can not be used to calculate the new coremelt-frequency.

To overcome these two problems so called risk monitors (safety monitor) are developed. A risk monitor is a fast running PSA-model, that can easily calculate the new result when one or more components are shut-off.

A risk monitor can also produce a 'real RAW-list'. This is a RAW-list that takes care of the truncation problem, by recalculation of the model for every component.

4.3. Design of nuclear power plants

A traditional application of importance measures is in the design or redesign of nuclear power plants. When a first conceptual plant design exists, this design could be optimised by risk importance ranking of the components. When risk significant components are selected this way, the risk frequency can be improved by decreasing the unavailability of the selected component, by improving the defence in depth against failure of the component or by decreasing the contributing initiating event frequencies. So potential remedies are not only to be found in the component itself. Therefore, the complementary use of two importance measures is typical for this application. The combination of FV and BI is advised. This also applies to the process of backfitting nuclear plants.

FV importance could be used for the selection of candidate components for improvement. In the engineering process complementary BI information is very useful. When BI is high and the basic components unavailability already fairly low, one could think of introducing extra redundancy, etc.

5. Uncertainty and uncertainty importance measures

All importance measures mentioned before are based on point estimates of the unavailabilities and unreliabilities that go in the equation. Uncertainty is connected to the basic uncertainty of the component itself, but also in the estimates of all other basic events that are used in the importance measure equation. For a certain importance measure and component an uncertainty-curve can be produced by performing Monte Carlo calculations. Moddares reported about such an approach [10]. For applications where the ranking of components is essential, the insights of his paper are very important.

In most applications the exact ranking is not important. More important is the determination if a component is yes or no risk significant. Also, for this kind of applications one has to take into account the aspect of uncertainties. There are several approaches to do this:

1. Determine a low/high-limit that includes the uncertainty aspect and calculate best estimate importance measures (conservative approach).
2. Perform Monte Carlo calculations and rank (for example) the 90%-value of the importance measure.
3. Use an uncertainty importance measure complementary to other importance measures.

The quantification of parameter uncertainties is usually done by considering a PSA result (e.g. frequency of core damage) as the output of a model which has as inputs, parameters which are characterised as random variables. The probability distribution function assumed for each parameter then quantifies the uncertainty that is due either to lack of knowledge about the exact value of this parameter or to an actual variability of the value of the parameter.

A useful measure for controlling the uncertainty of the top-event probability R is the so-called 'uncertainty importance measure of a basic event (UIMB)' which is used to assess the contribution of the uncertainty (usually expressed in terms of variance V, or error factor) of each basic event to the uncertainty of R. The UIMB can be used to identify those basic events whose uncertainties need to be reduced to effectively reduce the uncertainty of R.

Table 3 shows some uncertainty importance measures that are reported.

The first measure assesses the expected percentage reduction in V due to ascertaining the value of x_i. To evaluate this measure, V needs to be computed. For large-sized fault trees, it is very complicated to analytically compute V,

Table 3
Uncertainty importance measures

Iman	$\dfrac{\mathrm{Var}_{x_i}\,[E(R\|x_i)]}{V} \times 100\%$
Iman and Hora	$\dfrac{\mathrm{Var}_{x_i}\,[E(\log R\|x_i)]}{\mathrm{Var}(\log R)}$
Cho and Yum	$\dfrac{\text{Uncertainty of } \ln R \text{ due to the uncertainty of } \ln x_i}{\text{Total uncertainty of } \ln R}$

and therefore, V is very often estimated by Monte Carlo simulation. This is difficult because of the instability of V.

To obtain a stable uncertainty importance measure of each basic event, Iman and Hora suggested the second measure in Table 3. This measure represents the percentage variance of log R explained by x_i.

The third measure from Cho and Yum assesses the so-called main effect of the uncertainty involved in a log-transformed basic-event probability on the uncertainty of ln R, under the assumption that all basic events are independent and the probability of each basic event follows a lognormal distribution.

When uncertainty importance measures are calculated this way, they could be presented complementary to for example, FV and RAW. To treat uncertainty importance in a balanced way, one has to set a safety significance limit for this parameter. We do not know any method to define such limit in balance with the limits for FV and RAW. For that reason we prefer the first method (the conservative method).

6. Limitations of importance measures

Much more a concern to the usefulness of importance measures than the last mentioned uncertainty-aspect [11,12], is the inaccuracy caused by the dependency between cutsets. When a proper Boolean reduction is performed on the final cutset-equation of the PSA-results theoretically there is no dependency between cutsets. But in reality the unavailabilities of comparable components are coupled in a numerical way. For the same components there is no reason to postulate different unavailabilities, having the same maintenance program and that are operated in the same manner. When producing importance measures this kind of components should be treated as a group. As far as we are aware there is no method that fully takes care of this problem. For the time being, we advise the following approach.

To our opinion the most important cutset-coupling-groups are covered by the common-cause groups, that are already modelled in the PSA. These common-cause groups must be included in the importance measure analysis and the result of a common-cause basic event must be transferred to all components that are included in such a group.

When many changes in a group of components are suggested based on the use of importance measures, one needs to recalculate the complete PSA using all the changed unavailabilities, to check that no numerical coupling effect is overlooked.

7. Conclusions

PSA is a very useful tool to make a ranking of the risk important components. Depending on the application, several safety importance measures are available. For maintenance and operation optimisation applications a combination of RAW and FV importance is often used. In this case, two lists much be combined. Instead of RAW we prefer to use BI. The use of two importance measures is advisable. In applications where ranking is important, only one importance measure is needed. To identify potential components to improve safety, FV alone could be used. To identify potential components for T&M-relaxation, BI alone could be used. At the moment, there is no method available to treat the problem of numerical coupling between cutsets. We advise carefully examining the ranking of the common-cause groups and to transfer the results to the components that belong to such a group.

References

[1] True D et al. PSA applications guide, EPRI Report TR-105396, 1995.
[2] Lambert HE. Measures of importance of events and cutsets in fault trees, reliability and fault tree analysis. Philadelphia: SIAM Press, 1975 (p. 77–100).
[3] Vesely WE et al. Measures of risk importance and their applications, NUREG/CR-3385, 1983.
[4] Wall IB, Worledge DH. Some perspectives on importance measures. Proceedings of PSA-96, ANS, 1996.
[5] Fleming KN. Developing useful insights and avoiding misleading conclusions from risk importance measures in PSA applications. Proceedings of PSA-96, ANS, 1996.
[6] Cheok MC, et al. Use of importance measures in risk-informed regulatory applications, reliability and fault tree analysis. Northern Ireland: Elsevier Science Limited, 1997 (p. 213–26).
[7] Cho J, Yum B. Development and evaluation of an uncertainty importance measure in fault tree analysis. Reliab Engng Syst Safety 1997;57:143–57.
[8] Pörn K. A decision-oriented measure of uncertainty importance for use in PSA. Reliab Engng Syst Safety 1997;56:17–27.
[9] Reg. guide 1.165, 1.166.
[10] Modarres M, Agarwal M. Considerations of probabilistic uncertainty in risk-based importance ranking. Proceedings of PSA-96, ANS, 1996.
[11] Vesely WE. The use of risk importances for risk-based applications and risk-based regulation. Proceedings of PSA-96, ANS, 1996.
[12] Vesely WE. Supplemental viewpoints on the use of importance measures in risk-informed regulatory applications. Reliab Engng Syst Safety 1998;60:257–9 (letter to the editor).
[13] Cheok MC, Parry GW, Sherry RR. Response to supplemental viewpoints on the use of importance measures in risk-informed regulatory applications. Reliab Engng Syst Safety 1998;60:261 (letter to the editor).