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Pohjoismainen ydinturvallisuustutkimus
Nordisk kjernesikkerhetsforskning
Nordisk kärnsäkerhetsforskning
Nordic nuclear safety research

NKS-44
ISBN 87-7893-097-9

Decision criteria in PSA applications

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November 2001

Abstract

Along with the adoption of risk informed decision making principles, the need for formal probabilistic decision rule or criteria has been risen. However, there are many practical and theoretical problems in the application of probabilistic criteria. One has to think what is the proper way to apply probabilistic rules together with deterministic ones and how the criteria are weighted with respect to each other. In this report, we approach the above questions from the decision theoretic point of view. We give a short review of the most well known probabilistic criteria, and discuss examples of their use. We present a decision analytic framework for evaluating the criteria, and we analyse how the different criteria behave under incompleteness or uncertainty of the PSA model. As the conclusion of our analysis we give recommendations on the application of the criteria in different decision situations.

Keywords

Decision criteria, PSA, risk informed decision making

NKS-44
ISBN 87-7893-097-9

Pitney Bowes Management Services Danmark A/S, 2002

The report can be obtained from
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Espoo, 8.11.2001

Acknowledgements

The work has been funded by Nordic Nuclear Safety Research (NKS) SOS-2 project, the Finnish Nuclear Safety Authority (STUK), and the Finnish Ministry of Trade and Industry (KTM). The report is also a part of the METRI (Methods for Risk Analysis) project carried out by FINNUS, the Finnish Research Programme on Nuclear Power Plant Safety.

CONTENTS

NOTATIONS

BIR	Burden of Importance Ratio
CCDP	Conditional Core Damage Probability
CDF	Core Damage Frequency
CLERP	Conditional Large Early Release Probability
EVOPI	Expected Value of Partial Information
FV	Fussell-Vesely Importance
LERF	Large Early Release Frequency
NPP	Nuclear power plant
RAW	Risk Achievement Worth
RRW	Risk Reduction Worth

1 Introduction

The management of a nuclear power plant (NPP) throughout its lifetime involves decisions related to design, re-design, commissioning, maintenance and operation of the system. Also unplanned incidents might affect the system in a way that requires decision-making with respect to operability and accident management. The decisions are made according to legislation, design and safety regulation rules or criteria.

Recently, the adoption of so called risk informed decision making principles, the application of PSA has reached a new stage. Along this development, the need for more or less formal probabilistic decision rule or criteria has been risen. Earlier safety management principles, such as ALARP (As Low as Reasonably Practicable), have been completed by probabilistic safety goal and targets.

However, there are many practical and theoretical problems in the application of probabilistic criteria. One has to think what is the proper way to apply probabilistic rules together with deterministic ones, i.e., can the good values of probabilistic risk indexes compensate the poorly fulfilled deterministic design principles. In the case of several criteria, one has to think how the criteria are weighted with respect to each other.

Another set of problems is related to the type of the criteria: should relative criteria used instead of absolute ones, or, should the criteria take into account the whole operating time of the plant instead of instantaneous risk estimates. Further, should the criteria be posed based on system reliability level, accident sequence frequency or core melt level, or should they be based on level 2 PSA results? Is it reasonable to use conditional criteria? Should the criteria take into account also economical characteristics of the plant operation? The use of probabilistic criteria requires that certain numerical limits are given e.g. for the risk indices (e.g. the temporal increase of the core melt frequency should be less than 10% of the nominal risk level). How these numerical values should be selected, and what is their meaning?

Problems are also caused by the fact that PSA like all other models are approximations and include uncertainties. How this should be reflected in the definition and application of criteria? How the criteria should take into account the expert judgements behind PSA results, and how they should deal with incompleteness of the model? How these facts should affect on the relative weights of the deterministic and probabilistic criteria? How can the decision maker be sure that the criteria do not lead to poor decision?

In this paper, we try to approach to the above questions from the decision theoretic point of view. We give a short review of the most well known probabilistic criteria, and discuss examples of their use. We present a decision analytic framework for evaluating the criteria. In addition to this, we analyse how the different criteria behave under incompleteness or uncertainty of the PSA model. In other words we discuss the robustness of the criteria.

As the conclusion of our analysis we give recommendations on the application of the criteria in different decision situations (such as in evaluation of risk significance of certain activities or design changes, planning of maintenance, or resource allocation).

2 Decision analytic framework

2.1 Introduction

Decision theory gives criteria and principles that should be followed by the decision maker in order to be rational. According to the subjective expected utility theory, a decision maker is rational, when he/she makes such decision which maximise the expected utility. This requires that the decision maker can explicate the objectives and can evaluate the outcomes of different decision options. In addition to this the uncertainties related to outcomes must be evaluated in a probabilistic way. In the presence of uncertainty, the decision maker has to express his/hers risk attitude by using multi-attribute utility function. If there is no uncertainty, it suffices to use a multi-attribute value function, which correspond to the values of the decision maker.

In principle, one could argue that decision theory gives a direct basis for developing criteria for safety related decisions. However, there are reasons for which the decision theory can not be directly applied in nuclear regulatory context. First, NPP is a very complex system, and all the consequences of decisions cannot be easily quantified. Secondly, the task of safety authorities is not to optimise the total utility (e.g. the economical aspect of the NPP operation) of an NPP, but to ensure that safety rules are followed and that the licensee operates the plant in a safe way.

2.2 Levels for treatment of uncertainties in decision models

The use of PSA in decision making involves checking of the PSA scope and models, production of probabilistic results relevant to the decision making under consideration, selection of probabilistic and other relevant decision criteria and implementation of the decision. PSA can be used for decision making only if its scope includes failure modes, initiating events and phenomena relevant for the decision case. In order to be useful, these should have been modelled properly in the PSA. In practice, the decision rule or criteria are defined on the basis of PSA scope and results. Thus, different decision criteria are useful for different decision cases.

It is possible to identify three levels in dealing of uncertainty in safety related decision making. The most formal way is the direct application of the utility theory: PSA-model yields the probability distribution of consequences of a decision option. The decision maker expresses his/her preferences and risk attitudes in the form of an utility function, and the decision option with maximum expected utility is selected. In this format, all uncertainties are expressed in a probabilistic way (see Fig. 1). Actually, in this approach there is only one decision criterion: the expected utility alone determines the optimal decision. The different decision attributes, such as economical outcomes, radioactive releases or material losses are included in the utility function.

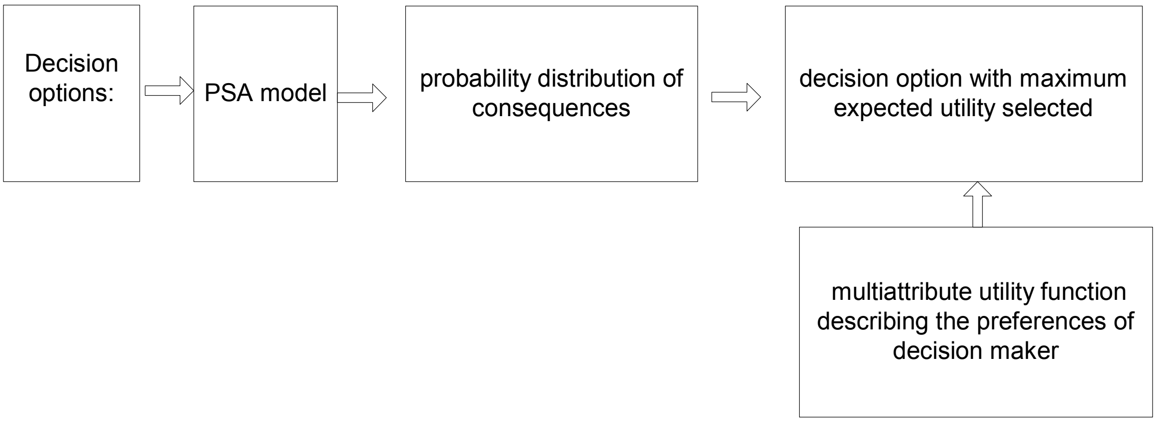

Figure 1. A utility theoretic approach to decision making

Another approach is based on the use of value function models. The PSA-model yields the probabilities of different consequences. However, the outcome of PSA-model is seen as one attribute of a value function, together with the various consequences. The decision maker expresses his/her preferences in the form of this value function, and weights the different attributes. The decision option with maximum value is selected. In this approach, the deterministic and probabilistic criteria are imbedded into the value model, and it is feasible to make trade-off between them (see Fig. 2) It is possible to interpret e.g. the ALARA-type approaches and risk-informed decision making from this perspective.

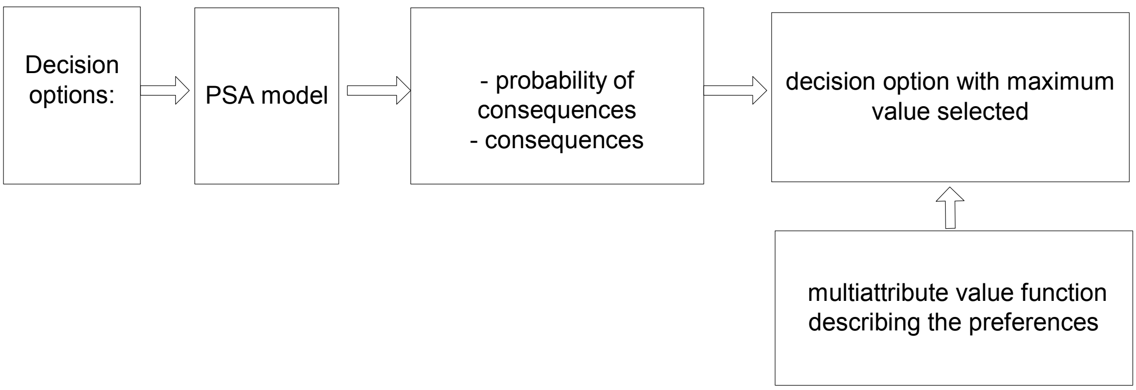

Figure 2. A value theoretic approach to decision making.

The third approach to use criteria is more informal. It admits that the decision context is extremely complex and only part or some aspects of it can be described with exact models. The PSA-model yields the probabilities of consequences, but the validity and uncertainties of it are evaluated in a case dependent way, basically in qualitative way. The values and preferences of the decision maker are expressed informally. The decision criteria are developed for each case. The decision is made by using case dependent decision criteria, and decision panels or other group decision approaches are utilised (Fig. 3). This approach represents rather well the informal risk-informed decision making.

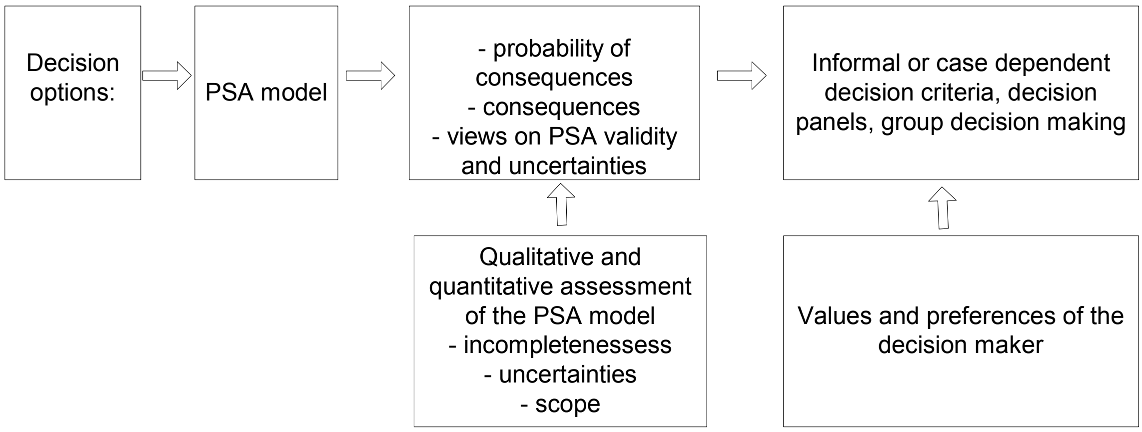

Figure 3. An informal approach to decision making.

The first of the above decision making approaches follows coherently the Bayesian decision theory (ref. 1). The third approach describes the practices followed in safety related decision making. In all of the above approaches, the decision criteria are used in different ways, and they have different roles.

2.3 Decision rules

2.3.1 ALARA

Nuclear community has adopted some general principles to guide safety related decision making. The most well known are the ALARA (As Low As Reasonable Achievable) and ALARP (As Low As Reasonably Practicable) which aim at taking into account both the risk and its economical constraints. Although in very general way, they try to treat the multi-criteria decisions encountered in nuclear safety area.

According to the ALARP- principle, the risk associated with a system is viewed in terms of the benefit and cost associated with risk reduction efforts. According to the principle, the risk should be reduced “As Low as Reasonably Practicable”, focusing on the definition of tolerable risk. Figure 4 shows an ALARP diagram, where the risk is represented graphically as an inverted triangle. As the risk is reduced, the triangle becomes smaller until the risk becomes negligible.

The risk of a system is essentially divided into three parts: Acceptable, Intolerable, and ALARP. In the ALARP region, the cost associated with the system change option is compared with the amount of risk reduction achieved. The ALARP principle assumes that one "knows" a level of risk that is tolerable to the public and requires that the risk posed by any new system shall at least be below that level. How far below is where the term "reasonably practicable" comes in: large amount of effort could reduce the risk to an very low level, but that amount of effort will be very expensive to implement. So we have to identify a second level of risk that so low that the public will accept that "it’s not worth the cost" to reduce it further. The ALARP principle is the described in IEC 61508 (ref. 2), in Annex B to Part 5 of the standard. See also ref. 3.

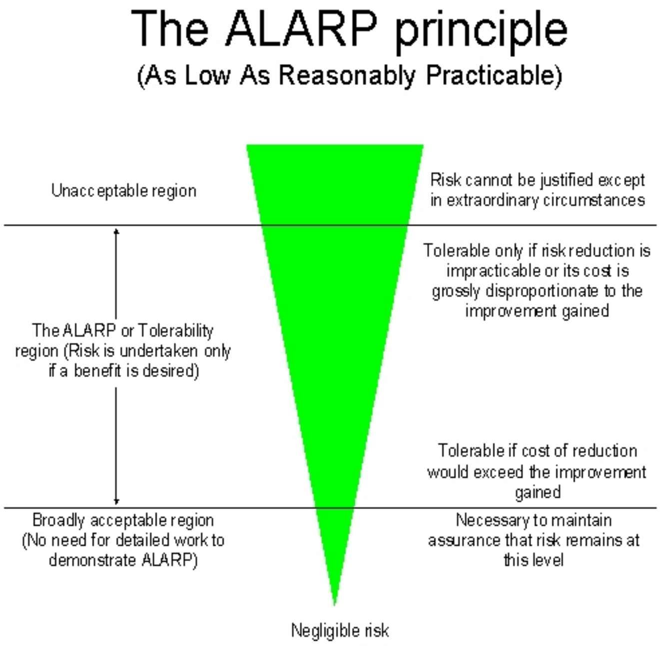

Figure 4. The ALARP principle.

Another general principle is ALARA (As Low As Reasonably Achievable), which is a basic radiation protection concept or philosophy. It is an application of the "Linear No Threshold Hypothesis," which assumes that there is no "safe" dose of radiation. Under this assumption, the probability for harmful biological effects increases with increased radiation dose, no matter how small. Therefore, it is important to keep radiation doses to affected populations As Low As is Reasonably Achievable. Compliance with dose limits ensures that working in a radiation laboratory is as safe as working in any other safe occupation. The objective of a radiation safety program is to ensure that radiation dose to workers, members of the public, and to the environment is as low as reasonably achievable (ALARA) below the limits established by regulatory agencies. We can view ALARA as a specialisation of ALARP with its own jurisdiction regarding radiation exposure limits in various circumstances.

The French format for ALARA or ALARP is the GAMAB principle ("Globalement Au Moins Aussi Bon": globally at least as good), which assumes that there is already an "acceptable" solution and requires that any new solution shall in total be at least as good. The expression "in total" is important here, because it gives room for trade-offs: an individual aspect of the safety system may indeed be worsened if it is overcompensated for by an improvement elsewhere (see e.g. ref. 4).

The German MEM (Minimum Endogenous Mortality) principle starts off with the fact that there are various age-dependent death rates in our society and that a portion of each death rate is caused by technological systems. The requirement is then that a new system or system change shall not "significantly" increase a technologically caused death rate for any age group (see e.g. ref.4).

2.3.2 Decision rules and criteria

From a decision theoretic view decision criteria are equivalent to the objectives or attributes of the multi-criteria decision making situation. In that formalism, they are represented by the value or utility function, which is applied in determining the value or utility of each decision alternative. Each decision option fulfils each criterion with different degrees, which are weighted by the utility or value function. The decision is based on the numerical value of the value or utility function. In practice, the decision is made often by following certain rules, which may be based on PSA-results or deterministic principles. These rules are not decision criteria in the strict decision theoretic sense. However, they may be derived from a decision model and interpreted from the decision model point of view.

Decision criteria or rules can be classified according to dichotomies such as deterministic/probabilistic, instantaneous/long-term, absolute/relative and compensatory/non-compensatory. All these dichotomies are associated with certain points of view that are adopted in evaluating ‘risk significance’ and in defining formal, as well as informal, decision rules.

The design and operation rules can be interpreted as deterministic decision criteria. These rules must be fulfilled, and they cannot be compensated by any other characteristics of the system. A good example of such design rule is the single failure criterion. Usually the probabilistic criteria are based on the results of PSA level 1 or 2, or results of system reliability analyses. In some occasion, also the results of level 3 PSA have been applied as decision rules (ref 5). The Finnish regulatory guide YVL-2.8 applies probabilistic quantitative decision target on both safety function reliability, core melt frequency and large release level (ref. 6).

While instantaneous decision criteria refer to probabilistic rules set upon time dependent core melt frequency/system reliability, the long-term criteria usually refer to risk integrated over a certain period. Absolute (probabilistic) decision criteria are set in terms of certain PSA results with given acceptance region (e.g. CDF must not be larger than a limit). The relative criteria may be based on comparison of certain risk estimates, for example one may require that the risk contribution from a certain accident sequence cannot be more than a certain percentage of the total core melt frequency.

The compensatory decision criteria refer to situations where a poor performance with respect to one criterion can be compensated by a good performance with respect to another criterion (ref. 7). This kind of trade-off possibility is typical to multi-attribute decision making problems. Non-compensatory criteria can be seen as a set of decision rules that should all be fulfilled. In the case of conjunctive rule, a decision option is acceptable if and only if its performance satisfies the decision criterion associated with each objective (e.g. the deterministic design rules together with PSA-based criteria must be fulfilled). Another possibility is that the decision making is based on a set of criteria among which some have to be fulfilled, and others are taken into account by making trade-offs with respect to them. These criteria can be called disjunctive.

The meaningfulness of the decision rules depends on the role of the decision-maker. Typically, authorities evaluate action plans using non-compensatory decision rules, especially the conjunctive and the disjunctive decision rules. Plant management usually mixes non-compensatory and compensatory decision rules. These are usually logically interrelated such that one or several non-compensatory decision rules have to be satisfied first (including e.g. safety requirements by the authorities) for the screening of options, after which a compensatory decision rule might be utilised for ranking.

2.3.3 Trade-off between criteria under uncertainty

In some cases, decision maker may be uncertain about the form of the value function, e.g., trade-offs between criteria. One reason can be that there are several decision makers with different preferences, another reason can be uncertain data or assumptions.

The cases with several decision makers should be solved through negotiations. There are formal procedures, e.g., voting, that can be used for the formulation of the value function. Usually, however, unformal approaches to reach a consensus are applied. In this paper, we assume this latter approach.

The cases with uncertain data or assumptions can be resolved if values and knowledge on the outcomes or state of nature are handled separately. A prerequisite for use of value functions in decision analysis is that the decision maker can compare any two decision outcomes, given complete knowledge.

Specifically, we require weak order over the set of decision outcomes, i.e., transitivity and comparability. Then we can determine a value function, e.g., by means of trade-offs.

Comparing with the three levels for treatment of uncertainties described above, the utility theoretic approach (Figure 1) and the value theoretic approach (Figure 2) for dealing with uncertainties requires separate treatment of facts and values.

The practical risk-informed decision making approach is rather near to that described in Figure 3, and the uncertainties are easily mixed with decision criteria. In some cases, the uncertainty connected to decision options may become a decision criteria; which is not a desirable situation.

One way to tackle with the problem of uncertainties and trade-offs is the clear structuring of the decision making context and related issues. This should lead to well a defined value/utlitity model or at least to a structured decision table, which describes the outcomes and uncertainties of decision options. Further, it gives a possibility to make the trade-offs between criteria independently on the facts, and to make sensitivity analyses with respect to different weights of the criteria.

3 Review of existing PSA-criteria

3.1 PSA-criteria and PSA-application categories

PSA-criteria can be grouped according to application area, that is, decision contexts. Here, we have adopted a grouping into two general, distinct, application categories, each consisting of several application areas: 1) Decision Criteria for the Evaluation of Risk Significance, and 2) Decision Criteria for Risk-based Ranking (ref. 8). The grouping is pragmatic in the sense that in the first category, issues of acceptability/ intolerability are addressed, whereas in the second category the safety improvement potential of a system is addressed. Examples of application areas of these two categories are presented in Table 1.

Table 1. Examples of application areas of PSA criteria.

Examples of PSA applications	
Evaluation of risk significance	**Risk-based ranking**
LONG TERM • Analysis of TechSpecs • Backfit evaluations • Main Risk Contributors • Plant Change Assessments • IST /ISI • Compliance with safety objectives • Maintenance planning • Risk Follow-up of Licensee Events SHORT TERM • Analysis of safety margin after incident • Exemption from Tech Specs	• Prioritisation of plant changes • Prioritisation of testing / inspection • Identification of risk significant SSCs • Maintenance prioritisation

Examples of PSA-related criteria for various decision cases are listed in Table 2. Excluding the two last criteria (BIR an EVOPI), the acceptance or criticality values are based on core damage and large early release frequencies and the basic importance measures. These importance measures point out a specific aspect of the risk contribution of the basic event in question. The Fussell-Vesely and Risk Reduction importance measures are used to point out a risk reduction potential, whereas the Birnbaum and the Risk Achievement importance measures point out the risk increase potential of a basic event. The definitions of these importance measures are given in Appendix A. By combining the basic importance measures, additional insight can be achieved as pointed out by Rumpf (ref. 9).

Table 2. Examples of PSA-criteria for various decision cases.

Decision case	*Criteria*	*Acceptance or criticality values (reference)*
Acceptance of permanent risk	CDF	$< 10^{-5}$ yr^{-1} (ref. 6)
	LERF	$< 5x10^{-7}$ yr^{-1} (ref. 6)
	societal risk (level 3 criteria)	(ref. 5) $10^{-3}/N^2$/yr for $\geq$N prompt fatalities
Acceptance of temporary risk increase Exemptions from TechSpecs	CDP -Risk significance level -Non-risk significance level	(ref. 8) $> 1x10^{-5}$ $< 1x10^{-6}$
	LERP -Risk significance level -Non-risk significance level	(ref. 8) $> 1x10^{-6}$ $< 1x10^{-7}$
Consequence assessment of assumed initiating event Consequence categorisation in RIISI	CCDP	(ref. 10) $> 1x10^{-4}$ high $1x10^{-6} \cdots 1x10^{-4}$ medium $< 1x10^{-6}$ low
	CLERP	(ref. 10) $> 1x10^{-5}$ high $1x10^{-7} \cdots 1x10^{-5}$ medium $< 1x10^{-7}$ low
Risk contribution of a single event Selection of inspection policy	CDF - Component (e.g. weld) level	(ref. 11) $> 1x10^{-9}$ 100% inspection $1x10^{-10} \cdots 1x10^{-9}$ 10% inspection $<1x10^{-10}$ 0% inspection
Relative risk significance Ranking and prioritisation of activities	Risk Achievement Worth	(ref. 8) > 2 significant importance
		(ref. 12) > 10 very safety severe > 1.05 safety severe
	Risk Reduction Worth - System level - Component	(ref. 8) > 1.05 significant importance > 1.005 significant importance
	Fussell-Vesely Importance - System level - Component level	(ref. 8) > 0.05 significant importance > 0.005 significant importance
Risk-based resource allocation	Burden-Importance Ratio (BIR)	(ref. 13) = 1 effective resource allocation
Prioritisation of information collection efforts	Expected Value of Partial Information (EVOPI)	(ref. 14) no recommendations yet

Obviously, the basic importance measures or their combinations do not take into account the cost, i.e. what is the risk reduction worth in money. This question enlarges the decision context and cost-benefit analyses might have to be conducted. The Burden-

Importance Ratio (BIR) addresses this question by describing how well the resources are allocated with respect to the risk importance of the component.

The last mentioned EVOPI is a measure of uncertainty importance, that can be used to prioritise information collection efforts with respect to uncertain parameters in the PSA-model. For instance, if the cost of information is time only, then EVOPI could be directly used to rank the targets for information monitoring according to the probability model associated with the uncertain parameter. For more details see ref. 14.

When using PSA-based decision criteria and acceptance or criticality limits, it must be kept in mind that there are application specific conditions for their proper use. There are issues related to the level of details and coverage that have to be addressed, or conditions that have to be met by the PSA model to be valid. As an example, in risk-informed decision making related to in-service testing, the handling of CCFs should be considered. In risk-informed optimisation of in-service inspections, the results of LOCA- and flooding analyses should be included in the evaluation of risk importance.

PSA-criteria are rarely used alone in evaluation processes and decision rules. The decisions are based on a combination of PSA-criteria and deterministic criteria. Deterministic criteria typically relate to design features and operating conditions. The deterministic criteria are numerous and an exhaustive list can not be reproduced here. The most important criteria are the general deterministic design criteria, FSAR and Technical Specifications.

3.2 Decision criteria for risk-informed in-service inspections

In risk-informed in-service inspection (RI-ISI) approach, the aim is to redefine the piping inspection programme taking into account the results of PSA. The basic idea is to reduce inspection activities in locations with low risks and find out the more risky locations where to concentrate inspection efforts. The basic criteria used in the decision making together with the risk significance are the radiation dose and inspection costs. Availability aspects should also be considered, e.g. some low risk piping are inspected because of their importance to the plant availability.

In RI-ISI methodology, the piping systems are divided into segments, and for each segment the probability of degradation and consequence of a pipe failure is evaluated. The results of these evaluations are placed in a risk matrix or diagram (see Fig. 5). The risk diagram can only be used if both the degradation probability and the consequence have been quantified.

Usually, the power plant makes a proposal for a new inspection programme following some rules set by the authority. The authority has set criteria or rules for classifying piping segments and for the coverage of inspections according to the risk significance. Authority’s task is to verify that the bases for classifying the segments are acceptable.

H = high risk **M** = medium risk **L** = low risk		Consequence		
		Low	Medium	High
Degradation Potential	High	**M**	**H**	**H**
	Medium	**L**	**M**	**H**
	Low	**L**	**L**	**M**

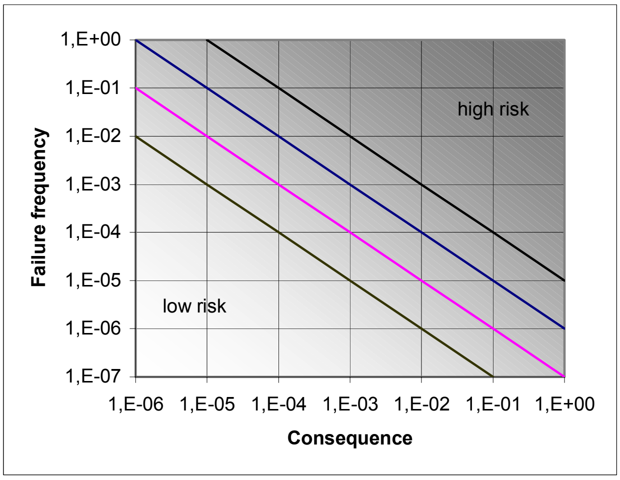

Figure 5. Risk matrix and risk diagram for RI-ISI evaluation.

From the utility point of view, the ranking of alternative inspection programmes is based on several criteria, one of them obviously economical. From the safety authority's point of view, the acceptance of the proposed ISI programme depends on the fulfilment of the safety criteria. However, as the reduction of inspections often implies reduction of radiation doses to inspectors, the nuclear authority may have to face the decision problem where core damage risk is set against occupational health.

Naturally the decision criteria depend on whether the analysis is mainly qualitative or quantitative. One extreme is the approach, where both the degradation probability and the consequences are evaluated more or less qualitatively, and the results are placed in a risk matrix (see Fig. 5). As the passive components such as piping are not usually modelled in details in the PSA, the numerical result for the evaluation may not be available in a satisfying degree of detail. Consequences are basically classified according to piping location (inside or outside containment, above or below reactor water level, etc.), which is often the resolution of the PSA results, and the expected degradation mechanism defines the severity class. In such cases, the rule for determining the coverage of inspections may be e.g. to inspect all piping in "high risk" -area, 10 % of "medium risk" -area and none from "low risk" -area.

A numerical evaluation of the safety impact of risk informed re-definition of inspection procedures is possible only when both the degradation probability and consequences are quantified. However, both the evaluation of pipe break frequencies due to various degradation mechanisms and consequences include large uncertainties.

In United States, risk-informed requirements for ISI/IST are defined in ASME code case N-577 (ref. 15). A review of implementation of risk-informed in-service inspection can be found in the NRWG-report (ref. 16).

3.2.1 Use of importance measures and other criteria in RI-ISI applications

When a risk matrix is used to classify the piping segments, some numerical limits are often set to define the consequence categories. In this connection, several importance measures are used. It is worth noticing that importance measures related to release of radioactive material, e.g. CLERP, conditional large early release probability, may be needed, because some structural components even though not important in terms of core damage, may be important in maintaining the integrity of containment.

One example of risk significance criteria based on Fussell-Vesely and Risk Achievement Worth importance measures is presented below (ref. 17):

Criterion	Risk category
FV > 0.001 (or > 0.005)	high
FV < 0.001 (or < 0.005) and RAW > 2	potentially high
FV < 0.001 (or < 0.005) and RAW < 2	low

In another application (ref. 18), the corresponding numerical value used for FV limit is 0.005. This is calculated for both CDF and LERF.

In EPRI's risk-informed procedure (ref. 10), the classification into consequence categories is based on conditional core damage probability (CCDP) and conditional large early release probability (CLERP). The numerical criteria are following:

Criterion	Consequence category
CCDP > 10^{-4} or CLERP > 10^{-5}	high
$10^{-6} \leq$ CCDP $\leq 10^{-4}$ or $10^{-7} \leq$ CLERP $\leq 10^{-5}$	medium
CCDP < 10^{-6} or CLERP < 10^{-7}	low

Electricité de France (EDF) has developed an approach to optimise the maintenance of piping in French nuclear power plants (ref. 12). The approach is similar to the RI-ISI methodology promoted in US, i.e. piping systems are broken down in segments, for which safety significance and degradation potential are evaluated. The contribution of structural failures to core damage frequency is evaluated by using the PSA model, and the segments are classified as "not safety severe", "safety severe" or "very safety severe". In cases where the segment is taken into account in the PSA model, following criteria are used for the classification:

Risk achievement worth (RAW) > 10	=>	very safety severe
1.05 < RAW < 10	=>	safety severe

If RAW < 1.05, the decision for classification as "safety severe" or "not safety severe" is made using technical specifications and safety class as additional criteria.

Numerical criteria for accepting or rejecting a proposal of a risk-informed in-service programme has been introduced e.g. the USNRC's regulatory guide 1.174 (ref. 19). If CDF decreases, the change is naturally acceptable. In addition it is stated, that if the CDF increases, the change should be small. Increase of less than 10^{-6} is regarded as sufficiently small.

In a study of use of RI-ISI at Oskarshamn plant (ref. 11), following criteria are suggested:

$CDF \geq 10^{-9}$	inspect 100% of locations
$10^{-10} \leq CDF \leq 10^{-9}$	inspect 10% of locations
$CDF < 10^{-10}$	no inspections

The CDF is calculated by multiplying the conditional core damage probability by the pipe failure frequency estimated using a probabilistic fracture mechanics model. It should be pointed out that these criteria have been suggested only for this specific case, and the same absolute values are not meant to be used straightforwardly in other applications.

3.2.2 Remarks on the RI-ISI

Modelling of piping in PSA is often not detailed, and there may be simplifications that have been meaningless in the evaluation of the core damage frequency, but may have importance when the PSA is used in some new decision making situations. Further, a RI-ISI application may require an analysis of secondary effects, such as flooding and water jets, and additional criteria based on qualitative analyses are often needed.

One should be careful when using numerical criteria suggested by other studies. In the decision panel of a Finnish pilot study on RI-ISI (ref. 20, 21), that was testing the applicability of the similar risk matrix as in the EPRI approach, it was found out that the resolution with the original categories was too low in many cases. Further, the CCDP limits for categorisation did not suit well to the analysed systems. One problem arose also from the simple conditioning by the LOCA-initiating event, because such approach is not applicable if the pipe break is not an initiating event. It is thus suggested that the categorisation rule should not be applied straightforwardly.

The ultimate goal of the RI-ISI approach is to define a new, better inspection programme. Inspections are done because they decrease the probability of pipe leaks and breaks. This impact on safety should be credited when the PSA models are further developed.

4 Evaluation of criteria

4.1 Evaluation principles

It is characteristic for nuclear safety related decision making that the decision criteria are partly pre-defined but the decision maker can have freedom to specify the criteria and can add some criteria of his/her own. For instance, a general requirement may be to use PSA for the evaluation of the decision options, but it is up to the decision maker (licensee) to define how. As can been seen e.g. in Section 3, a great number of different PSA-related decision criteria have been proposed.

The purpose of this section is to discuss principles that can be used for evaluating the mixture of criteria that decision maker may consider to use in the decision analysis process. We provide a general list of principles and compare PSA-criteria with these principles.

1. Criteria should promote a good decision analysis process

   A definition for a good decision analysis process is that which explicates the decision maker's assumptions, values, and perspective on the problem to attain highest practicable level of coherence (ref. 22). This is the highest level principle, and the following principles specify it.

   PSA is a powerful analysis tool. Thus the use of PSA-criteria promotes a good decision analysis process. However, everything depends on the decision making context and on the other criteria that are applied for decision making.

2. Criteria should correspond to decision maker's preferences

   This principle should be evident. However, it is often difficult to take into account all objectives of the decision maker. Objectives should be explored thoroughly during the structuring of the problem.

   PSA-criteria correspond to the objective to minimise the core damage frequency. PSA-criteria, however, measure differently core damage risk, e.g., absolute vs. relative criteria.

3. Criteria should be unambiguous

   All parties of the decision making situation should have a clear understanding of the meaning of criteria.

   Definitions and formulas for PSA-criteria are usually unambiguous. The problem with PSA-criteria is that PSA-studies have different qualities. It is not fair to use same CDF-criterion for two studies that have different scope.

4. Attributes that are used for measuring the satisfaction of criteria should be comprehensive and measurable (ref. 23)

   An attribute is comprehensive if, by knowing the level of an attribute in a particular situation, the decision maker has a clear understanding of the extent that the associated objective is achieved.

   An attribute is measurable if it is reasonable both to obtain a probability distribution for each alternative over the possible levels of the attribute and to assess the decision maker’s preferences for different possible levels of the attribute.

Most PSA-criteria are quantitative. If the criterion is unambiguous, then it is comprehensive.

PSA-results are probabilities. It is questionable whether one should try to define uncertainty distribution over PSA-results. PSA-criteria are not measurable in that sense. However, we may require that the decision maker should be able to make trade-offs between PSA-results and other criteria.

5. Criteria should lead to utilisation of all relevant information

   To obtain deeper understanding of the problem, we should look at it from several perspectives and we should try to retrieve information from various sources. For instance, if there is a plant-specific PSA, then PSA should be used for safety-related decision making. Criteria should not restrict the information retrieval process.

   PSA can provide many kinds of results. This principle suggests the use of several PSA-criteria.

6. Criteria should be effective in the sense that they rank different decision options

   The criteria should have enough resolution in order to make difference between decision options.

   PSA-criteria are quantitative and thus can rank decision options.

7. Criteria can be derived from more general (high level, major) objectives

   Decision maker should understand the basis for the use of each criteria. For instance, that core damage frequency criterion is related to nuclear safety.

   CDF- and LERF-criterion can be derived from the objective to minimise risk for external releases and economical losses. However, what is the basis for numerical criteria like CDF should be less than 1E-5/yr? Further, what is the basis for using risk importance measure based criteria?

8. Criteria should promote a cost-effective decision analysis process

   Criteria should focus on the evaluation of relevant issues and avoid assessment of unnecessary issues. Available resources (time frame, expertise, information) should be taken into account.

   In some PSA-applications, it is cost-effective to restrict the number of criteria to be used.

9. The use of mixture of criteria should be based on logical procedure

   It should be clear which criteria are non-compensatory and which compensatory. Rules of combining criteria should be specified and presented. This principle belongs to the general requirement that the decision model should be transparent.

The procedure should be specified in each PSA-application.

10. Preference dependency should be taken into account

    Preferential dependency between criteria means that the way a decision option satisfies one criterion affects the value judgements based on other criteria. It is important to recognise possible preference dependencies between criteria, since otherwise we may unintentionally pay too much attention to certain attribute (double counting). If we use formal decision models like additive multi-attribute value function or utility function models, preferential independence of criteria is required.

    PSA-criteria are inter-related. One should be very careful, when using them in a multi-attribute value function model.

11. It should be possible to qualify the decision model

    Qualification is part of the quality assurance of the decision making process. Firstly, it should be validated that the decision model includes necessary and sufficient criteria, and the rules for using mixture of criteria have a sound basis. Secondly, it should be possible to verify the relationship between input and output of the decision model. Thirdly, the input data should be validated.

    PSA-related acceptance criteria should be validated in some way.

12. Criteria should acknowledge uncertainties

    This principle is important in decision making under uncertainty or risk. In nuclear safety management application we have uncertainties on one hand regarding outcomes (core damage/no core damage), and on the other hand regarding input data. Therefore we use PSA. However, it is impossible to include all uncertainties in the PSA-model, which appears as "second level" uncertainty in PSA-evaluations, e.g. uncertainty regarding core damage probability. This is philosophically a difficult question, but should be acknowledged in the decision analysis.

    PSA-criteria should not be used without sensitivity studies. See also Section 4.2 regarding behaviour of PSA-criteria with a biased model.

13. Criteria should not suppress creativeness of the human decision making process

    This principle cautions against blind use of given decision criteria.

    PSA-criteria may lead to over-confident thinking that all reactor safety related issues have been accounted.

4.2 Behaviour of the PSA-criteria with a biased PSA-model

An essential fact to be acknowledged in PSA-application is that the PSA-model has biases. In some cases we may have sense about the biases. Many of them, however, remain unknown. Biases cause that the rank orders or acceptance/rejection decisions may be biased too. Biases have different effects on different PSA-criteria, which will be shown below.

We discuss four types of biases in the PSA-model:

1. incompleteness regarding modelled hazards
2. conservatism
3. biased failure data
4. incompleteness regarding assessment of consequences.

We study the cases with respect to PSA-criteria core damage frequency, and risk importance measures Fussell-Vesely (FV) and Risk Achievement Worth (RAW). See appendix A for definitions and notations. We use the following decomposition based on the minimal cut set representation for the core damage frequency, f:

$$f = p_x \cdot f_1(x) + f_0(x),$$

where p_x = the probability of the basic event x (unavailability of component x)
$f_1(x)$ = conditional core damage frequency of the minimal cut sets including the basic event x, given that the basic event is TRUE.
$f_0(x)$ = core damage frequency of the minimal cut sets not including the basic event x.

4.2.1 Incompleteness regarding modelled hazards

Incompleteness regarding modelled hazards means that the core damage risk is underestimated. Incompleteness can affect both the term p_x, $f_1(x)$ and the term $f_0(x)$. We denote the "complete" model by

$$f' = (p_x + p'_x) \cdot (f_1(x) + f'_1(x)) + f_0(x) + f'_0(x),$$

where p'_x = missing probability term of the unavailability model for x
$f'_1(x)$ = missing term of $f_1(x)$
$f'_0(x)$ = missing term of $f_0(x)$.

Regarding core damage frequency, it is obvious that $f' > f$. If f is higher than the acceptance criterion then f' is also higher. However, if f is below the acceptance criterion then we cannot say whether f' is higher or lower than the acceptance criterion. Thus incompleteness is a problem from the acceptance point of view, but not from the rejection point of view.

The revised risk importance measures are

$$C'(x) = ((p_x + p'_x) \cdot (f_1(x) + f'_1(x))) / f',$$

and

$$A'(x) = (f_1(x) + f'_1(x) + f_0(x) + f'_0(x)) / f'.$$

Regarding risk importance measures, incompleteness may affect the rank order of the issues (basic events). We consider the following cases:

a) $f'_1(x) = 0, f'_0(x) > 0, p'_x = 0$
b) $f'_1(x) > 0, f'_0(x) = 0, p'_x = 0$
c) $f'_1(x) = 0, f'_0(x) = 0, p'_x > 0$.

In case a) both $C(x)$ and $A(x)$ will be overestimated, i.e., $C'(x) < C(x)$ and $A'(x) < A(x)$. Naturally the situation is vice versa in case b). In case c), we can see that $C'(x) > C(x)$ but $A'(x) < A(x)$.

As can be concluded from above, the effect in rank order depends on whether basic events belong to the category corresponding case a), b) or c).

If we compare two basic events x and y, incompletenesses in the model may affect the mutual rank. Only if the incompleteness is of type a), the rank order is preserved.

The behaviour of PSA-measures in case of incomplete PSA-model are summarised in Table 3.

Table 3. Behaviour of PSA-measures in case of incomplete PSA-model.

Type of incompleteness	**CDF**	**F-V**	**RAW**
a) $f'_1(x) = 0, f'_0(x) > 0, p'_x = 0$	$f' > f$	$C' < C$	$A' < A$
b) $f'_1(x) > 0, f'_0(x) = 0, p'_x = 0$	$f' > f$	$C' > C$	$A' > A$
c) $f'_1(x) = 0, f'_0(x) = 0, p'_x > 0$	$f' > f$	$C' > C$	$A' < A$

4.2.2 Conservatism

Conservatism means that the core damage risk is overestimated. We denote the 'realistic' model by

$$f' = (k_p \cdot p_x) \cdot (k_1 \cdot f_1(x)) + k_0 \cdot f_0(x),$$

where k_p = "realism adjustment" factor ($0 < k_p < 1$) regarding the failure probability p_x
k_1 = "realism adjustment" factor regarding $f_1(x)$
k_0 = "realism adjustment" factor regarding $f_0(x)$.

Regarding core damage frequency, it is obvious that $f' < f$. If f is lower than the acceptance criterion then f' is also lower. However, if f is above the acceptance criterion then we cannot say whether f' is higher or lower than the acceptance criterion. Thus conservatism is a problem from the rejection point of view, but not from the acceptance point of view.

Concerning importance measures, the effect of conservatism is analogic to incompletenesses. We consider the following cases:

a) $k_1 = 1, k_0 < 1, k_p = 1$
b) $k_1 < 1, k_0 = 1, k_p = 1$
c) $k_1 = 1, k_0 = 1, k_p < 1$

The effect of conservatism to the PSA-measures is presented in Table 4.

Table 4. Behaviour of PSA-measures in case of conservative PSA-model.

Type of conservatism	**CDF**	**F-V**	**RAW**
a) $k_1 = 1, k_0 < 1, k_p = 1$	$f' < f$	$C' > C$	$A' > A$
b) $k_1 < 1, k_0 = 1, k_p = 1$	$f' < f$	$C' < C$	$A' < A$
c) $k_1 = 1, k_0 = 1, k_p < 1$	$f' < f$	$C' < C$	$A' > A$

4.2.3 Biased failure data

Possible cases with biased failure data handle either overestimation or underestimation. Thus these cases can be brought back to incompleteness cases or conservatism cases.

Sometimes we can say that the bias is caused by the quality of data. If the analyst is able to assess uncertainties regarding the data, uncertainty importance measures could be used to compare different subjects in the model.

4.2.4 Incompleteness regarding assessment of consequences

For most nuclear power plants, there are level 2 PSAs that represent the risk in terms of frequencies of various release categories. This information is, however, incomplete to be used in an expected utility function based decision model. An expected utility based treatment requires an assessment of the costs (and utilities) of possible outcomes. For that purpose, we need a level 3 PSA.

Expected utility decision model cannot be used, fully explicitly, in PSA-applications. In stead, we use CDF- and LERF-criteria, and related decision criteria. These criteria can miss plant and site specific factors that can vary a lot between different nuclear power plants. Moreover, it is impossible to compare the expected utility of operating a nuclear power plant and the utility of shutting down the plant.

4.2.5 Discussion

A biased model can naturally lead to wrong decision, from the theoretical point of view. Some possible biased decisions are:

- An incomplete model can lead to acceptance of system or process that actually have an unacceptably high accident frequency.
- A conservative model can point out measures for risk reductions that have minor importance.
- Biased failure data can bias the risk rank of basic events — optimal risk reduction measures are missed.

- Incomplete assessment of consequences makes comparisons of expected utilities of different decision options implicit — verification of the full rationality of the decision is impossible.

Since there are always biases in PSA, a recommendation is pay attention to identification and analysis of uncertainties. Conclusions made in PSA should be validated, or questioned, e.g. by using sensitivity studies.

5 Conclusions and recommendations

The basic issues in using probabilistic decision criteria are connected to the PSA-model applied in solving and formulating the decision cases. The realism, the scope and completeness of the model determines its usefulness and possibilities to apply probabilistic criteria. This means that the criteria should be compatible with the PSA model.

In each application the PSA models' resolution and suitability to support the decision making should be explicitly evaluated. In this connection, the weight of PSA-based criteria should be evaluated accordingly. The parties of the decision situation (authorities, power companies, different experts) should have a common understanding of the quality of the PSA-model before probabilistic criteria can be used.

One could think that it is possible to set up general probabilistic criteria. However, due to the limitations of the PSA-model, all important issues are not modelled in the same way. In some cases, the probability estimates are based on expert judgement, in some cases they lean on generic data and in some cases plant specific data are used. The decision alternatives to be compared can not always be modelled in same degree of detail. Phenomena related to some decision alternatives may not even have generally accepted quantitative models (e.g. programmable automation). In certain extreme cases, the alternatives may not be comparable according to a common set of criteria. Thus, the decision criteria must be selected or applied in a context sensitive way. The use of criteria in the decision problem must be justified and evaluated, e.g. according to the principles discussed in chapter 4 of this report. In order to make sure that the criteria are measurable in the case under consideration, the calculation of the numerical values of the criteria should be explained in detail, and the impact of uncertainties, the role of expert judgement and model incompletenesses should be evaluated.

The advantage of quantitative probabilistic criteria is that they make it possible to compare decision alternatives in a straightforward way. However, the criteria are usually reduced to single numbers, which hide the information about uncertainties and modelling principles. There is a danger that they lead to too simplistic or even automated analyses, which is not the idea of risk informed decision making.

In making safety related decisions, all the relevant information should be utilised effectively. The use of probabilistic criteria, if selected properly taking into account the context, may drive the decision making process in this direction.

The participants of the decision making process represent different backgrounds or disciplines. Their knowledge and preferences may differ a lot. The applied decision rules should correspond to the different views and preferences in a balanced and impartial way.

A fundamental difference between safety authorities and power companies is that the latter is an economic enterprise the aim of which is to bring profit to the owners. Due to this, the power companies must take the cost of safety enhancements into account. The decisions should be cost effective, which in some cases may be interpreted as trade-off between economy and safety. The consistency and stability of regulatory environment is a prerequisite for economically feasible safety management. Thus, it is important that the authority expresses and applies the probabilistic (or other) decision criteria in a transparent and well-defined way. For example, the authority should specify clearly which of the decision rules are compensatory and non-compensatory.

Risk-informed principles, together with well selected decision criteria, help in achieving a better decision making environment between authorities and utilities. However, the adoption of risk-informed decision making may entail a need to readjust regulatory principles, practices and guides.

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Appendix A. Definitions of risk importance measures

Risk importance measures are used to express relative importance of different elements of PSA-model, such as basic event probabilities and reliability parameters. Here we define the usually applied risk importance measures with respect to certain basic event x. If the core damage frequency, f, is evaluated based on the minimal cut set representation, the core damage frequency expression can be decomposed, with respect to x, as follows:

$$f = p_x \cdot f_1(x) + f_0(x),$$

where p_x = the probability of the basic event x (unavailability of component x)
$f_1(x)$ = conditional core damage frequency of the minimal cut sets including the basic event x, given that the basic event is TRUE.
$f_0(x)$ = core damage frequency of the minimal cut sets not including the basic event x.

The following table summarises the most common risk importance measures and their definitions:

Symbol	Importance measure (alternative names)	Formula
FV	Fussell-Vesely importance (Criticality, Fractional Contribution)	$p_x \cdot f_1(x) / f$ or $(f - f_0(x)) / f$
RAW	Risk Achievement Worth (Risk Increase Factor, Increased Risk Ratio)	$(f_1(x) + f_0(x)) / f$
RRW	Risk Reduction Worth (Risk Decrease Factor)	$f / f_0(x)$
DRR	Decreased Risk Ratio (Risk remainder)	$f_0(x) / f$
I_B	Birnbaum	$f_1(x)$

As can been seen, the risk importance measures are interrelated. If one measure is calculated, the others can be derived from the first one. It should be noted that the calculation procedure could play a role, if the number of minimal cut sets have to be truncated.

Risk importance measures can be analogically defined for groups of basic events that, e.g., can represent a system.

Bibliographic Data Sheet **NKS-44**

Title	Decision criteria in PSA applications
Author(s)	Jan-Erik Holmberg, Urho Pulkkinen, Tony Rosqvist & Kaisa Simola
Affiliation(s)	VTT Automation, Finland
ISBN	ISBN 87-7893-097-9
Date	November 2001
Project	NKS/SOS-2.1
No. of pages	24 + 1 app.
No. of tables	4
No. of illustrations	5
No. of references	23
Abstract	**Along with the adoption of risk informed decision making principles, the need for formal probabilistic decision rule or criteria has been risen. However, there are many practical and theoretical problems in the application of probabilistic criteria. One has to think what is the proper way to apply probabilistic rules together with deterministic ones and how the criteria are weighted with respect to each other. In this report, we approach the above questions from the decision theoretic point of view. We give a short review of the most well known probabilistic criteria, and discuss examples of their use. We present a decision analytic framework for evaluating the criteria, and we analyse how the different criteria behave under incompleteness or uncertainty of the PSA model. As the conclusion of our analysis we give recommendations on the application of the criteria in different decision situations.**
Key words	Decision criteria, PSA, risk informed decision making

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