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Basic Relation between RAW and RRW and Some of Its Implications on Risk Reduction Strategies

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ABSTRACT

In using risk-informed approaches for ensuring safety of operating nuclear power plants (NPPs), risk importance measures obtained from probabilistic safety assessments (PSAs) of the plants are integral elements of consideration in many cases. In PSA models and applications associated with NPPs the risk importance of a particular feature (e.g. function, system, component, failure mode or operator action) can be, most generally, divided into two categories: importance with respect to risk increase potential and importance with respect to risk decrease potential. The representative of the first category, as used for practical purposes, is Risk Achievement Worth (RAW). Representative of the second category, as mentioned in consideration of risk importance, is Risk Reduction Worth (RRW). It can be shown that the two risk importance measures, RAW and RRW, are dependent on each other. The only parameter in this mutual dependency is probability of failure of the considered feature. The paper discusses the relation between RAW and RRW and some of its implications, including those on the general strategies for the reduction of risk imposed for the operation of the considered facility. Two general risk reduction strategies which are considered in the discussion are: a) risk reduction by decreasing the failure probability of the considered feature; and b) risk reduction while keeping the failure probability of the considered feature at the same level. Simple examples are provided to illustrate the differences between two strategies and point to main issues and conclusions.

Keywords: *probabilistic safety assessment, risk importance measures, risk achievement worth, risk reduction worth*

1 INTRODUCTION

In using risk-informed approaches for ensuring safety of operating nuclear power plants (NPPs), risk importance measures obtained from probabilistic safety assessments (PSAs) of the plants are integral elements of consideration in many cases. In PSA models and applications associated with NPPs the risk importance of a particular feature (e.g. function, system, component, failure mode or operator action) can be, most generally, divided into two categories: importance with respect to risk increase potential and importance with respect to risk decrease potential. The representative of the first category, as used for practical purposes, is Risk Achievement Worth (RAW). Representative of the second category, as mentioned in consideration of risk importance, is Risk Reduction Worth (RRW).

There is a number of other importance measures which were defined and used in reliability and risk analyses. Some of them are defined in relative and some in absolute terms. Most of them are related to each other and some of them produce the same risk ranking. Their theory and use is described in a number of books such as [1], [2] or [3] and studies or engineer's handbooks and guidelines such as [4], [5], [6] or [7]. In this paper we want to focus on those which are most widely used in current PSAs for NPPs and we select the above mentioned two importance measures as representatives.

We will use their definitions from NUREG/CR-3385, [4], which can be considered as one of the early references to establish the use of risk importance measures in PSA applications. Let:

$R_0 =$ the present ("nominal") risk level;

$R_i^+ =$ the increased risk level with feature "*i*" assumed failed;

$R_i^- =$ the decreased risk level with feature "*i*" assumed to be perfectly reliable.

The first importance measure, risk achievement worth (RAW), related to risk increase potential, is defined as ratio:

$$RAW_i = \frac{R_i^+}{R_0} \tag{1}$$

(Besides ratio, NUREG/CR-3385 also defines the RAW on an interval scale as $R_i^+ - R_0$. These two values are related to each other. When one is known, the other can be calculated directly (considering that nominal risk R_0 would normally be known).)

The second importance measure, related to risk decrease potential, risk reduction worth (RRW), is defined as ratio:

$$RRW_i = \frac{R_0}{R_i^-} \tag{2}$$

(In the similar fashion, NUREG/CR-3385 also introduces the related RRW on an interval scale, as $R_0 - R_i^-$.)

2 THEORETICAL RELATION BETWEEN *RAW* AND *RRW* AND SOME DIRECT IMPLICATIONS

First, two basic terms are introduced which will be used in the considerations to come. Both of them are "events":

A Failure or unavailability of component or safety feature, when challenged. (This failure or unavailability is presented in a PSA model by specifically defined single basic event.)

B Occurrence of specified top event representing certain damage state of considered system or facility (e.g. reactor core damage).

The probability of top event *B*, i.e. *P(B)*, will be taken as a surrogate for the quantitative risk *R* which was used in the above general expressions for importance measures. This is normally done in PSA models. One issue with this is that some of the most important quantitative risk surrogates in PSAs are expressed as frequencies rather than probabilities, e.g. core damage frequency (CDF). The frequency is brought into the risk equation by initiators, which are frequency-type events. For the sake of simplicity, we will, without mathematical formalism, “bypass” this issue by assuming that frequency-type event can be interpreted as occurrence within specified time unit, i.e. frequency is interpreted as probability of occurrence within specified time unit interval (which can always be selected as sufficiently small, so that the interpretation is valid).

Particularly, RAW is, in principle, not defined for the initiators, as frequency type events. Setting the frequency to the value of “1” (i.e. occurrence guaranteed), would imply the assumption that initiator occurs once per unit of time considered. With the above interpretation, setting the frequency-type event to logical value of "1" corresponds to assuming that its occurrence is guaranteed within the time unit (or that the probability of its occurrence during the time unit is 1.0).

Based on their above definitions, the RAW importance measure (I_{RAW}) and the RRW importance measure (I_{RRW}) can, most generally, be defined as:

$$I_{RAW} = \frac{P(B|A)}{P(B)} \tag{3}$$

(i.e. the ratio of the conditional probability of top event under the assumption that considered component or feature would always fail when challenged and the base case top event probability)

$$I_{RRW} = \frac{P(B)}{P(B|\overline{A})} \tag{4}$$

(i.e. ratio of the base case top event probability and the conditional probability of top event under the assumption that considered component or feature would never fail when challenged).

By expanding the above definition of RAW into:

$$I_{RAW} = \frac{P(B|A)}{P(B)} = \frac{P(BA)}{P(B)P(A)} \tag{5}$$

and considering $B = B(A + \overline{A}) = BA + B\overline{A}$ and, consequentially, $P(B) = P(BA) + P(B\overline{A})$, it can easily be shown that:

$$I_{RRW} = \frac{1 - P(A)}{1 - P(A)I_{RAW}} \tag{6}$$

or:

$$I_{RAW} = \frac{I_{RRW} - 1 + P(A)}{P(A)I_{RRW}} \tag{7}$$

The above relation was discussed, e.g., in [8] which also provides its demonstration by calculations based on a PSA model.

Thus, the importance measures RAW and RRW for particular failure event are related to each other, with probability of considered failure event as a parameter. The first direct and simple implication is that if one of the importance measures RAW or RRW is known, then the other one is determined (assuming that the failure probability is known). It is useful to point out that the above relation is established on the basis of probability theory and is not specific for PSA modeling or for any kind of particular features of PSA model.

Second implication is related to the upper bounds for the two measures. Concerning RRW, its definition given by Eq. (4) implies that it can, theoretically, go to infinity. This would be the case when the system considered (top event) is represented by the considered feature, such that $B = A$ and $P(B) = P(A)$. In this case, if considered feature A is assumed to be "perfect" (i.e. $P(A) = 0$) the denominator in Eq. (4) would go to zero and RRW would go to infinity. Of course, the assumption is that nominal system failure probability is larger than zero. In the case of RAW, the definition given by Eq. (3) appears to imply that RAW can become arbitrarily large. However, RAW can actually acquire the values only within the interval $\langle 1, \frac{1}{P(A)} \rangle$. This can be clearly seen from Eq. (7) when letting I_{RRW} to go to large values. Figure 1 illustrates the case with $P(A) = 0.1$, which shows that RAW would asymptotically go to $\frac{1}{P(A)} = 10$.

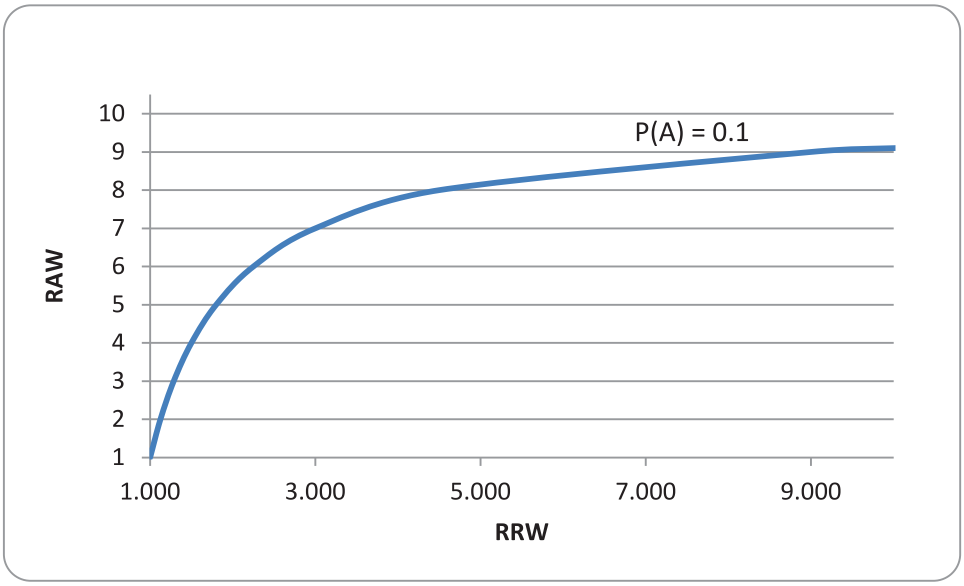

Figure 1: RAW as a Function of RRW with $P(A) = 0.1$ as Parameter

Then, there is third implication which is derived from the second one: large RAW importance measure (possibly implying not well balanced design from the risk perspective) is really a concern with small failure probability events (because RAW is bounded by $\frac{1}{P(A)}$). Non-reliable components cannot have huge RAW. They cannot achieve huge risk because they already are non-reliable (within the nominal risk estimate). On the other hand, a component with very low failure probability (low unavailability) or very high reliability can achieve huge risk (if there are no redundant or diverse means to compensate for its failure). For highly reliable component there is always hazard that its reliability (availability) may degrade. If such a component (or feature or a condition (e.g. failure mode) which may affect multiple components) represents a single line of defense then reliance on its high reliability or availability would reflect as high RAW value and may point to not well balanced risk profile.

This implication is further discussed in the next section through considering two strategies for reducing the overall risk of a system (facility) by reducing the RRW of its particular safety feature (e.g. component).

3 TWO STRATEGIES FOR REDUCTION OF FACILITY'S RISK BY CONTROLLING (DECREASING) RRW VALUE OF FEATURE A

Let us consider a situation where a safety feature (e.g. component) A within a system (facility) B has significant potential for reducing the system's risk *P(B)*, which reflects in significant value of its RRW measure, i.e $I_{RRW}(A)$.

There are two basic strategies for reducing the risk of the facility B with respect to particular feature A by controlling (decreasing) the RRW of considered feature A (i.e. $I_{RRW}(A)$):

Strategy I: *Decreasing the* $I_{RRW}(A)$ *with failure probability P(A) kept at the same level*. In this strategy, the feature A and the operational practices associated with it are kept the same. However, some additional feature is introduced into the facility which provides for diversity or redundancy of the feature A. In many cases, this strategy may require considerable budget. However, in a number of cases it may be implemented in a relatively affordable way by means of flexible equipment or equipment with relaxed safety requirements.

Strategy II: *Decreasing the* $I_{RRW}(A)$ *by decreasing the failure probability P(A)*. Examples of this strategy may include: reducing the test/inspection period; improving testing strategies (e.g. staggered versus sequential testing); extending the scope of inspection; improving the operating procedures or maintenance procedures; extending / improving preventive or predictive maintenance; etc.. In principle, these are, usually, relatively affordable (not so expensive) measures. However, if feature A is defined at the level of system's train or even a system as a whole, they may include design changes such as installation of redundant components or even trains (in which case they may require considerable budget).

Important property of the *strategy I* is that RAW value of feature A in the new constellation always decreases or, if already close to the asymptote (i.e. $\frac{1}{P(A)}$), remains the same (but never increases). In principle, this means that risk profile of the facility's new status (with lower risk) remains, as far as the feature A is of concern, as balanced as it was.

This is illustrated by Figure 2 where the RRW of considered feature A is reduced from an old value (RRW_{old}) to a new value (RRW_{new}) by moving downward through a curve defined by *P(A) = const*. Clearly, the respective RAW value would always decrease. (It should be noted that graphical presentation in Figure 2 is based on the same relation between RAW and RRW as in the case of Figure 1. The only difference is that the axes RAW and RRW have exchanged places and that Figure 2 shows only the segment of the curve corresponding to the RRW values between 1.0 and 1.3. This range of RRW values is more relevant from the perspective of practical applications of PSAs for NPPs.)

On the other hand, in the case of the *strategy II* the RAW value of feature A can, in the new constellation, increase. This means that although the overall risk is reduced, the risk profile may become unbalanced in the sense that there is over-reliance on the high reliability / availability of the considered feature A.

This is illustrated by Figure 3. In order to achieve the same decrease in RRW value of the considered feature A (i.e. from the same RRW_{old} to the same RRW_{new}), certain reduction in failure probability or unavailability *P(A)* would be needed. How large, exactly, the reduction in *P(A)* would be required (for the predefined decrease in RRW) would depend on the configuration of the facility or system B, i.e. on its elements other than A. Figure 3 clearly shows that reduction in *P(A)* from the initial 0.03 to 0.02 already causes the increase in the RAW of feature A. (Even smaller reductions in *P(A)* than from 0.03 to 0.02 may cause an increase in the RAW.) If reductions larger than this are needed, an increase in the RAW may be considerable.

The above should be considered in the context where there are already well established and recognized guidelines with safety significance threshold set at RAW > 2 (e.g. NEI 00-04, [9]).

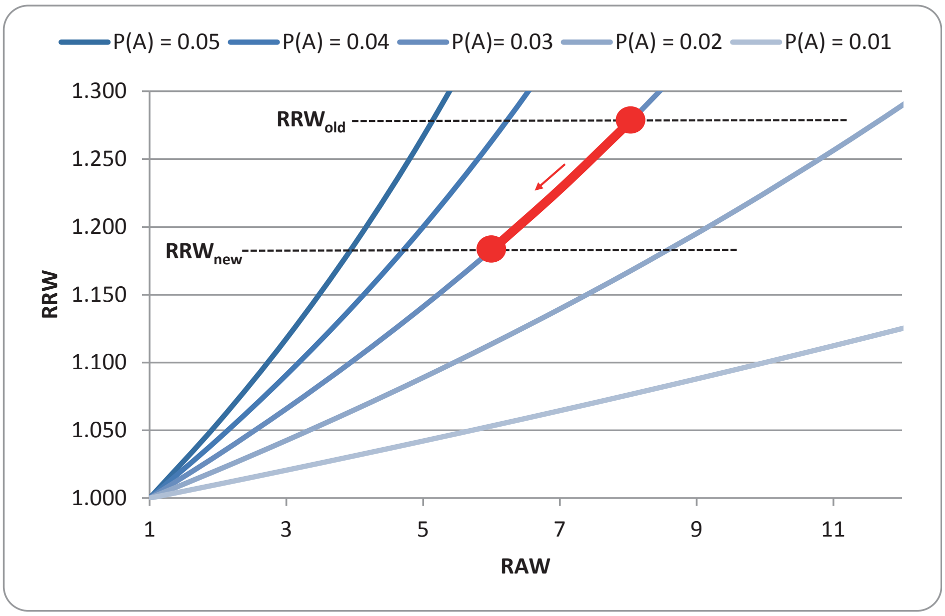

Figure 2: Reducing the Risk with Feature A Involved via Strategy I

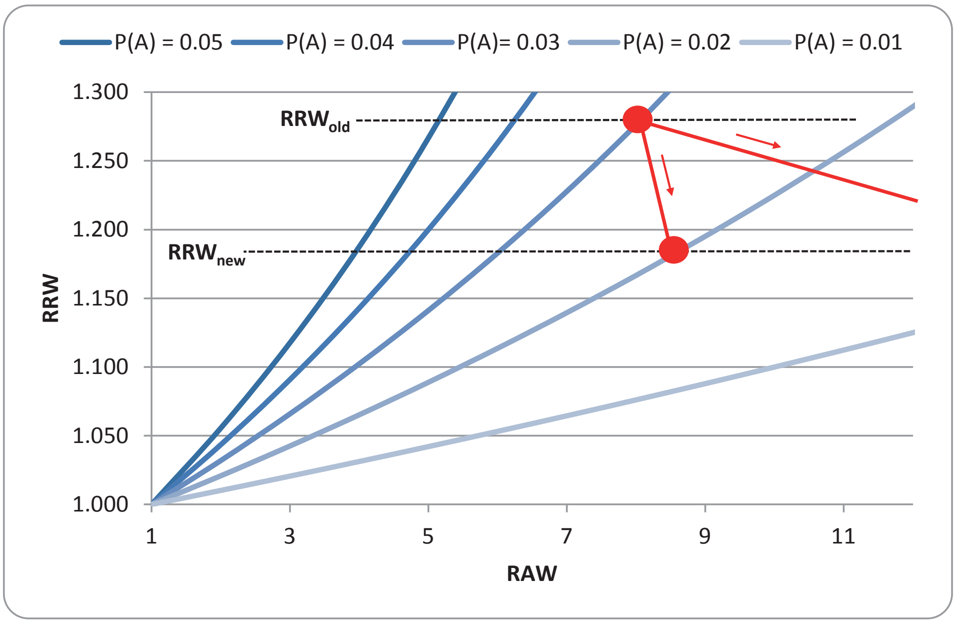

Figure 3: Reducing the Risk with Feature A Involved via Strategy II

The points of discussion will be illustrated on two very simple examples.

4 SIMPLE ILLUSTRATIVE EXAMPLES FOR THE TWO STRATEGIES

4.1 First Example: Feature "A" Represents Whole System

The first is an example where considered feature A represents the whole system (facility), so that its failure represents the failure of the whole system, i.e. $B = A$ and $P(B) = P(A)$. Under these circumstances, the RRW asymptotically goes to infinity (since $P\big((B|\bar{A}) = P(B|\bar{B})\big)$ goes to zero) while, according to Eq. (7), RAW becomes $\frac{1}{P(A)}$ (considering $P\big((B|A) = P(B|B) = 1\big)$). Although the example is elementary, it is still good enough to illustrate the point.

The initial value $P(A) = q_0$ will be set to 0.1. The initial $P(B)$ is then:

$$P_{init}(B) = q_0 = 0.1 \tag{8}$$

The initial RAW is 10 (i.e. $\frac{1}{P(A)}$).

The two strategies described above are, for this example, illustrated by means of simple reliability diagrams in Figure 4. In the *strategy I* reduction of risk (presented by reduction of the system failure probability) is obtained by adding a new feature R as an alternative to the existing feature A. New system status is, in terms of the reliability diagram, presented as parallel configuration of the two features. In the case of *strategy II* the overall reduction of risk (reduction of system failure probability) relies solely on reduction of failure probability of the existing feature A. There is no alternative "way out" (success path).

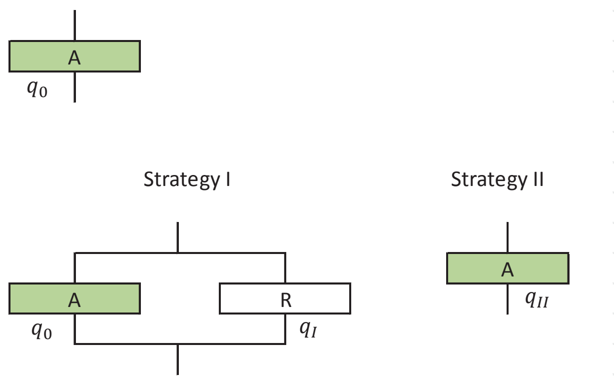

Figure 4: Two Strategies in the First Example

With notation as in Figure 4, the final system failure probability (upon implementation of a strategy) is obtained as

$$P_{fin,I}(B) = P(A)P(R) = q_0 q_I \tag{9}$$
$$P_{fin,II}(B) = P_{II}(A) = q_{II}$$

where indices I and II refer to the strategies I and II, respectively. (In the case of the strategy I the initial failure probability of feature A, $P(A)$, remains as is, in accordance with description of the strategy. System failure probability (i.e. risk) is controlled by the failure probability of alternative feature R.)

Table 1: First Example – Five Cases of Reduced Risk

Case	$P(B)_{fin}$	$P(R) = q_I$	$P_{II}(A) = q_{II}$
a	0.09	0.9	0.09
b	0.08	0.8	0.08
c	0.07	0.7	0.07
d	0.06	0.6	0.06
e	0.05	0.5	0.05

Table 1 shows five cases ("a" through "e") where failure probability of alternative feature *R* (*strategy I*) and new, reduced, failure probability of the existing feature *A* were selected in such a way that final system probability, *P(B)*, is same for both strategies (i.e. $P_{fin,I}(B) = P_{fin,II}(B)$, considering Equation (9)).

Thus, both strategies are equally successful in quantitatively reducing the overall risk.

However, the point of interest is the new RAW value of the feature *A* (which remains the main safety feature of the system in any case) in the new status of the system. Table 2 shows how the RAW value changes with reducing the risk through the same five cases shown in Table 1. It can be seen that in the case of the strategy *I* the RAW of the feature *A* remains the same whereas at strategy *II* as the risk decreases the RAW of the feature *A* increases. As the risk is cut in half, the RAW of *A* gets doubled. This comes from the fact that the feature *A* is a single line of defense and indicates, in a way, that the risk is not well balanced. It is worth mentioning that the same risk impact is at strategy *I* obtained with additional feature *R* which has relatively low reliability (failure probabilities in the range from 0.5 through 0.9).

Table 2: First Example – RAW Values in Five Cases Considered

Case	$I_{RAW,I}(A)$	$I_{RAW,II}(A)$
a	10	11.11
b	10	12.50
c	10	14.29
d	10	16.67
e	10	20.00

4.2 Second Example: Feature "A" As Part of Series Configuration

Second example, illustrated by the reliability diagram in Figure 5, is the case where considered safety feature *A* appears in series with another feature, designated as *L* in the mentioned figure. Therefore, feature *A* is necessary for operability of the system, but is not sufficient. In terms of risk (represented by a failure of the system), the risk cannot be eliminated solely by means of making the feature *A* "perfect" as was the case in the first example.

The initial value $P(A) = q_0$ will be set to 0.01 . The initial value of feature *L* will be set to the same value, i.e. $P(L) = p = 0.01$.

Under the rare event approximation the initial *P(B)* is:

$$P_{init}(B) = p + q_0 = 0.02 \tag{10}$$

The RRW under the same approximation is $\frac{p+q_0}{q_0} = 2$, and the initial RAW is $\frac{1}{p+q_0} = 50$.

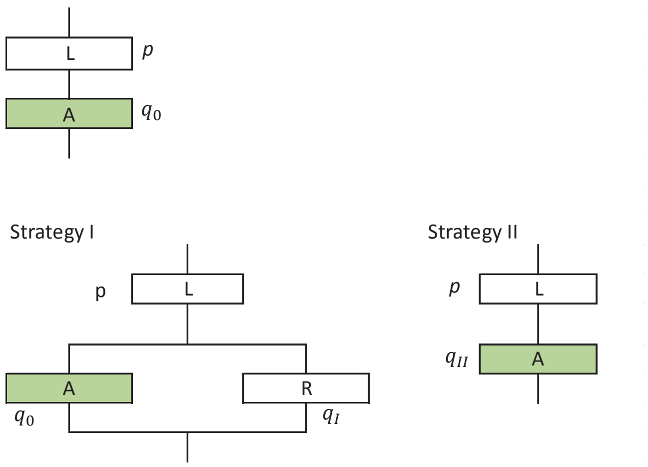

Figure 5: Two Strategies in the Second Example

With notation as in Figure 5 and under the rare event approximation, the final system failure probability (upon implementation of a strategy) is obtained as

$$P_{fin,I}(B) = P(L) + P(A)P(R) = p + q_0 q_I \tag{11}$$
$$P_{fin,II}(B) = P(L) + P_{II}(A) = p + q_{II}$$

where indices *I* and *II* refer to the strategies *I* and *II*, respectively.

In the similar manner as above, Table 3 shows five cases ("a" through "e") where failure probability of alternative feature R (*strategy I*) and new, reduced, failure probability of the existing feature A were selected in such a way that final system probability, *P(B)*, is same for both strategies (i.e. $P_{fin,I}(B) = P_{fin,II}(B)$, considering Equation (11)).

Thus, as before, both strategies are equally successful in quantitatively reducing the overall risk.

Similarly to the first example, Table 4 shows how the RAW value of feature A changes with reducing the risk through the same five cases shown in Table 3. This time it can be seen that, as the overall risk decreases, the RAW of the feature A in the case of the strategy I decreases also, whereas at strategy II it increases again. As the risk is reduced by 25%, the RAW of A increases by some 33%. The reason is the same as in the previous case, only that this time the feature A is not a single line of defense on its own: it is only a part of it. The observation, again, indicates that the risk is not well balanced. It is again mentioned that the same risk impact is at strategy I obtained with additional feature R which has relatively low reliability (failure probabilities in the range from 0.5 through 0.9).

Table 3: Second Example – Five Cases of Reduced Risk

Case	$P(B)_{fin}$	$P(R) = q_I$	$P_{II}(A) = q_{II}$
a	0.019	0.9	0.009
b	0.018	0.8	0.008
c	0.017	0.7	0.007
d	0.016	0.6	0.006
e	0.015	0.5	0.005

Table 4: Second Example – RAW Values in Five Cases Considered

Case	$I_{RAW,I}(A)$	$I_{RAW,II}(A)$
a	47.89	52.63
b	45.00	55.56
c	41.76	58.82
d	38.13	62.50
e	34.00	66.67

5 CONCLUSION

Basic theoretical relation between the RAW and the RRW importance measures was discussed, together with some of its direct implications on risk considerations. In this context, the two basic strategies were discussed for reducing the risk of the facility with respect to particular safety feature by controlling (decreasing) the RRW of considered feature: 1) decreasing the RRW with failure probability kept at the same level, and 2) decreasing the RRW by decreasing the failure probability. It was shown that in the first case the RAW of the considered feature decreases while in the second case it can also increase, depending on the role the considered safety feature has in the facility's configuration. This means that although the overall risk is reduced, the risk profile may become unbalanced in the sense that there is over-reliance on the high reliability / availability of the considered feature *A*.

Even the simplistic examples which were discussed point to the importance of diversification of safety functions. Additional diverse (alternative) features may even not necessarily have particularly high reliability.

In this simple exercise no attempt was made to address the common cause failure potential, but it is considered that it would only strengthen the conclusions.

In some cases, it may be easier to introduce an alternative success path with flexible or/and movable equipment with relaxed safety classification requirements than to demonstrate that certain risk target is achieved through improved testing, inspection, maintenance or quality assurance strategies.

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