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Significance of Multi-Component Risk Importance Measures in Risk-Informed Design of I&C Systems

Rahman Khalil ur [a, b], Kyungho Jin[a], Moath kassim [a], Gyunyoung Heo [a*]
[a]*Kyung Hee Univ., Yongin-si, Gyeonggi-do, 446-701, Korea*
[b] *Pakistan Nuclear Regulatory Authority (PNRA), G-8/1, Islamabad(44000), Pakistan.*
[*]*Corresponding author: gheo@khu.ac.kr*

1. Introduction

In the recent decades, methodologies for risk-informed decision making and design approaches have been tested and applied in various industries. The principal driving force for risk assessment applications is the need to optimize or prioritize objects for betterment of plant systems, operations, safety management and preventive or corrective maintenance activities [1]. Vaurio highlighted in his study that application of risk informed approaches have rewarded improved economy and effective use of resources while maintaining or improving safety as an outcome [2]. He further highlighted that risk based optimization and cost reduction is becoming a common practice at nuclear power plants and explained the case study of risk application in Loviisa NPS (unit 1) for cost reduction due internal flood caused by a pipe break in a cable room in the control building. The internal flooding event called UJFLOOD caused 48% of the total (CDF). Author discussed the various options of core damage frequency (CDF)-cost for reducing risk due to this event.

Several methods have even been established to the level of Regulatory Guides in nuclear industry for application of risk for plant-specific changes to the licensing basis [3], in service testing [4], technical specifications [5] and in-service inspection of piping [6]. There are a several proposed applications of the risk informed in regulatory process. One major activity of these risk applications is to find either the ranking or the categorization of structures, systems and components (SSCs) with respect to their risk-significance, or with respect to their safety-significance [7]. A distinction is made between ranking and categorization. The purpose of ranking is generally to arrange items in order of increasing or decreasing importance. The purpose of categorization, on the other hand, is to allocate these items into two or more groups, according to some preset guidelines or criteria. Another distinction is made between risk significance and safety significance. Depending on the application, it may be appropriate to categorize or rank SSCs with respect to risk-significance, or with respect to safety-significance. In the next section, we propose definitions of risk-significance and safety-significance as applied to SSCs.

Rahman & Heo [8] proposed a probabilistic design and optimization approach for instrumentation & control (I&C) systems of research reactors, to remove over conservatism, based on risk importance, availability criteria and cost. They concluded that design cost of I&C architectures can be reduced up to 30–40% by using this approach. They used risk importance measures of each component and module in I&C system in order to optimize it with respect to cost and attain high level of safety and availability. The authors implemented risk reduction worth (RRW) and risk achievement worth (RAW) indices, among many importance measures, which has been recommended by Vasseur and Llory [9] as a merit of PSA along with core damage frequency and large early release frequency. American Society of Mechanical Engineers (ASME) provides criteria for these indices based on single component, which does not fulfill the need of risk based design. Additional criteria for multi-components, diverse & redundant ones performing same function in system, is required in order to attain the objective of risk based optimized design of I&C systems.

In this article, a need for an additional risk importance measure has been highlighted for multi-components because single component risk importance measure keep shifting from one component to other component when system is modified to reduce risk for particular component. For explanation, let's consider three components A, B and C in a certain system. If we make a system configuration-I and analyze, component A is returned as one of the highest risk sensitive component. In order to reduce risk due to this component, we formulate configuration-II by considering the risk feedback in configuration-I. In new system configuration, component C appears as high risk contributing component with the fact that configuration-II has high availability than configuration-I. This cycle keeps on and there is no stop limit or criteria to decide which level of availability or which configuration is best. The details for the need of multi-component risk importance have been discussed in succeeding headings.

2. Risk Importance: A Risk Informed Design Metric

The use of importance measures to analyze Probabilistic Safety Assessment (PSA) results to find applications, design modifications and test & maintenance schedule have studied by most of nuclear power plant utilities and researches. The applications of risk insights based on probabilistic analysis are determined and are being implemented in various industries such as nuclear facilities, aviation specially space shuttles, chemical, railways and marine. The risk analysis terms have various nomenclatures such as quantitative risk assessment (QRA), probabilistic safety assessment (PSA) and probabilistic risk analysis

(PRA) being used synonymously in various industries. In nuclear industry, the initial PSA study had been performed in WASH-1400 [10] for risk assessment due to potential accidents in U.S. commercial nuclear power plants in 1975.Therefore, PSA and risk applications have gained much significance in nuclear industry, as it has ability to find the detail insight of failures, combinations of failures in sequences and many other reliability features. Probabilistic analysis has ability to provide [11] (a) information related to intersystem dependencies and potential common cause failures (CCFs) associated with them (b) various design options and risk associated with them and (c) risk and sensitivity measures of system structure and components (SSCs).

M.C Cheok et al. [7] mentioned that commonly used risk importance measures such as Fussell-Vesely (FV), Risk Reduction Worth (RRW) and Risk Achievement Worth (RAW) are relatively gross measures of the importance of a basic event and they have the following shortcomings:

① the measure changes in risk and the importance of basic events only at the maxima (0,1) of the defined range of probability and

② These measures do not consider the credible (uncertainty) range for the basic event probability.

They further highlighted the following issues:

- there is no simple relationship between importance measures evaluated at the single component level and those evaluated at the level of a group of components;
- Hence these importance measures are not realistic measures of the sensitivity of the overall risk to parameter value changes; and,
- Importance measures do not typically take into account parameter uncertainties which raise the question of the robustness of conclusions drawn from importance analyses.

Therefore, an alternative measure of importance capable of changing to event probabilities is essential to be determined. They developed two curves are for events contained in the Surry Individual Plant Examination (IPE). Figure 3 shows the risk importance curve for an event which has a relatively low Risk Achievement Worth and a relatively large Risk Reduction Worth as compared to the criteria presented in NUMARC 93-011. The NUMARC 93-01 criterion for the RRW (and FV) importance is exceeded when the slope of the event risk importance curve is greater than that of the enveloping curve. Figure 4 shows the risk importance curve for an event which has a large Risk Achievement Worth and a relatively small Risk Reduction Worth. The NUMARC 93-01 criterion 8 for the RAW is exceeded when the risk ratio (y-axis value) at the right-hand side endpoint of the risk importance curve (at $P_{i.n}$ = 1) exceeds a value of two. It is important to note that

R_0 = base (reference) case overall model risk.

$R_{i,n}$ = the model risk with a new value for the probability of basic event i;

$P_{i,n}$ = the probability of basic event i at its new value.

In order to see the effect that how risk importance varies and shifts from one system configuration to other configuration. I&C architectures have been developed and analyzed using Bayesian network starting from architecture I (Figure 1) to architecture IV (Table 1). The sensitivity of constituent components and modules such as Pressure/level Transmitter (PT), Analog Input (AI), Digital Input (DI), Bi-stable Processor (PB), Coincidence Processor (CP), Digital Output (DO), Shunt Circuit (ST), Under Voltage circuitry (UV), Circuit Breaker (CB) and secondary circuit breaker (SCB) has been determined and demonstrated in Figure 2.

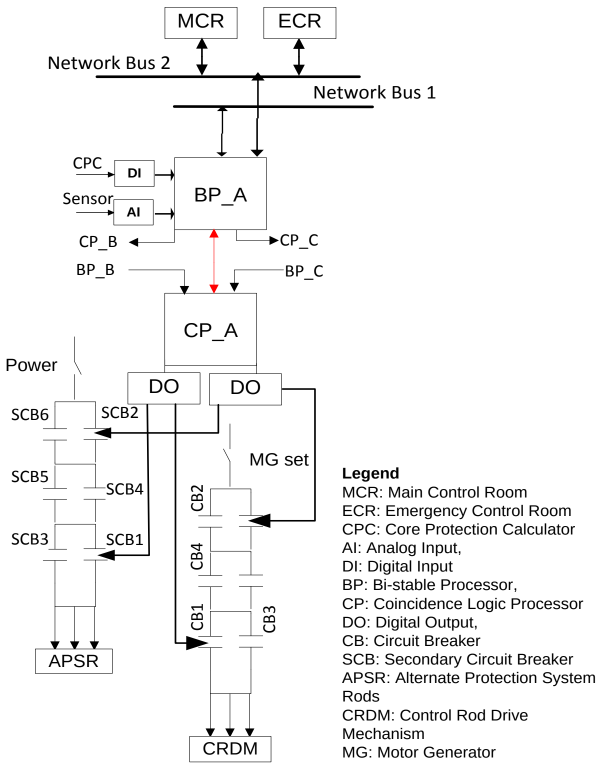

Figure 1: RPS Architecture I configuration [12]

In Figure 2, CP and DO appear as high risk sensitive when compared to ASME risk significance criteria. According to this criterion, components having RRW index less than 1.005 are either having no impact or very low effect in overall risk of system. In order to reduce risk contribution of CP, architecture III has been formulated by adding redundancy and diversity in CP. The results show that system attained relatively high availability but DO appeared as one of highest risk contributing component.

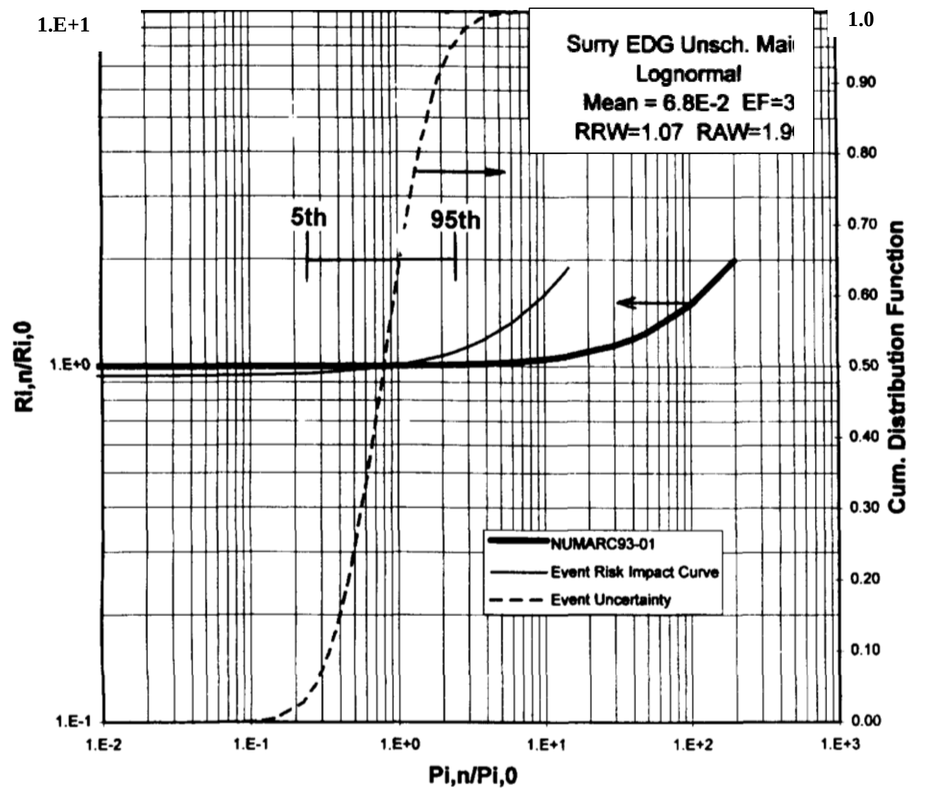

Figure 2: Risk Impact Curve-High RRW and Low RAW indices [7]

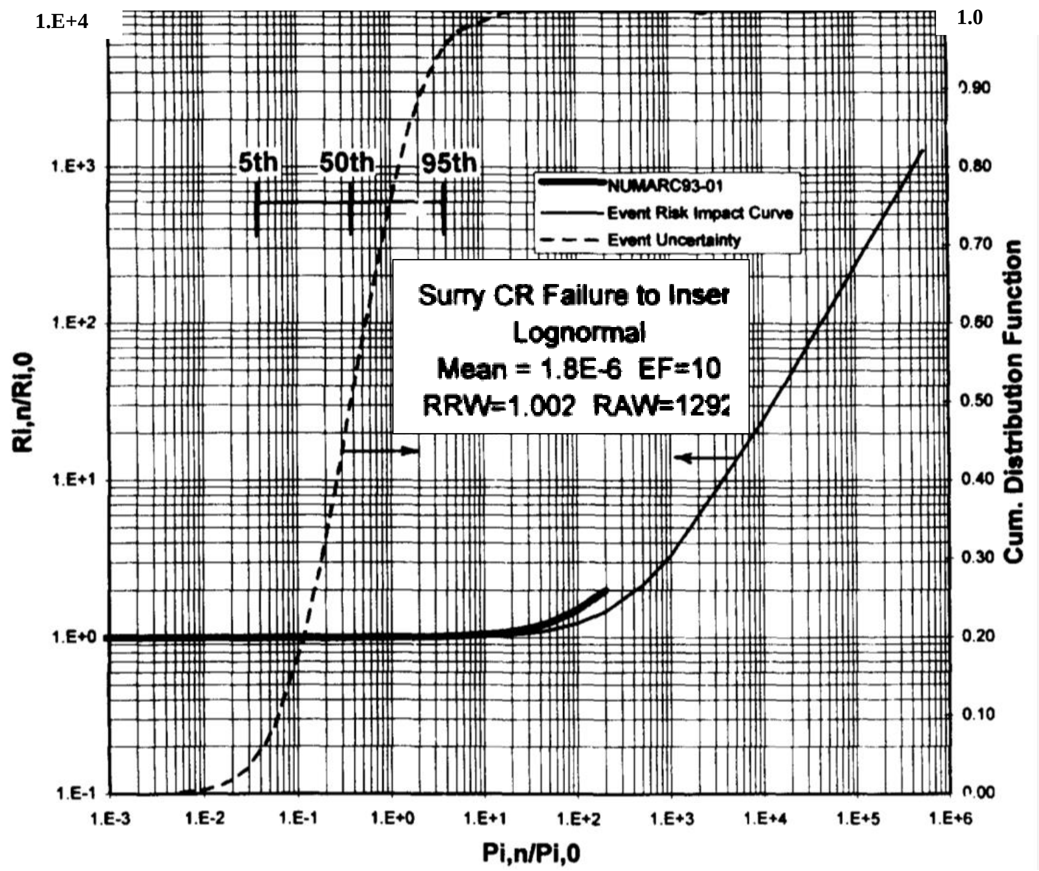

Figure 3: Risk Impact Curve-High RAW and Low RRW indices [7]

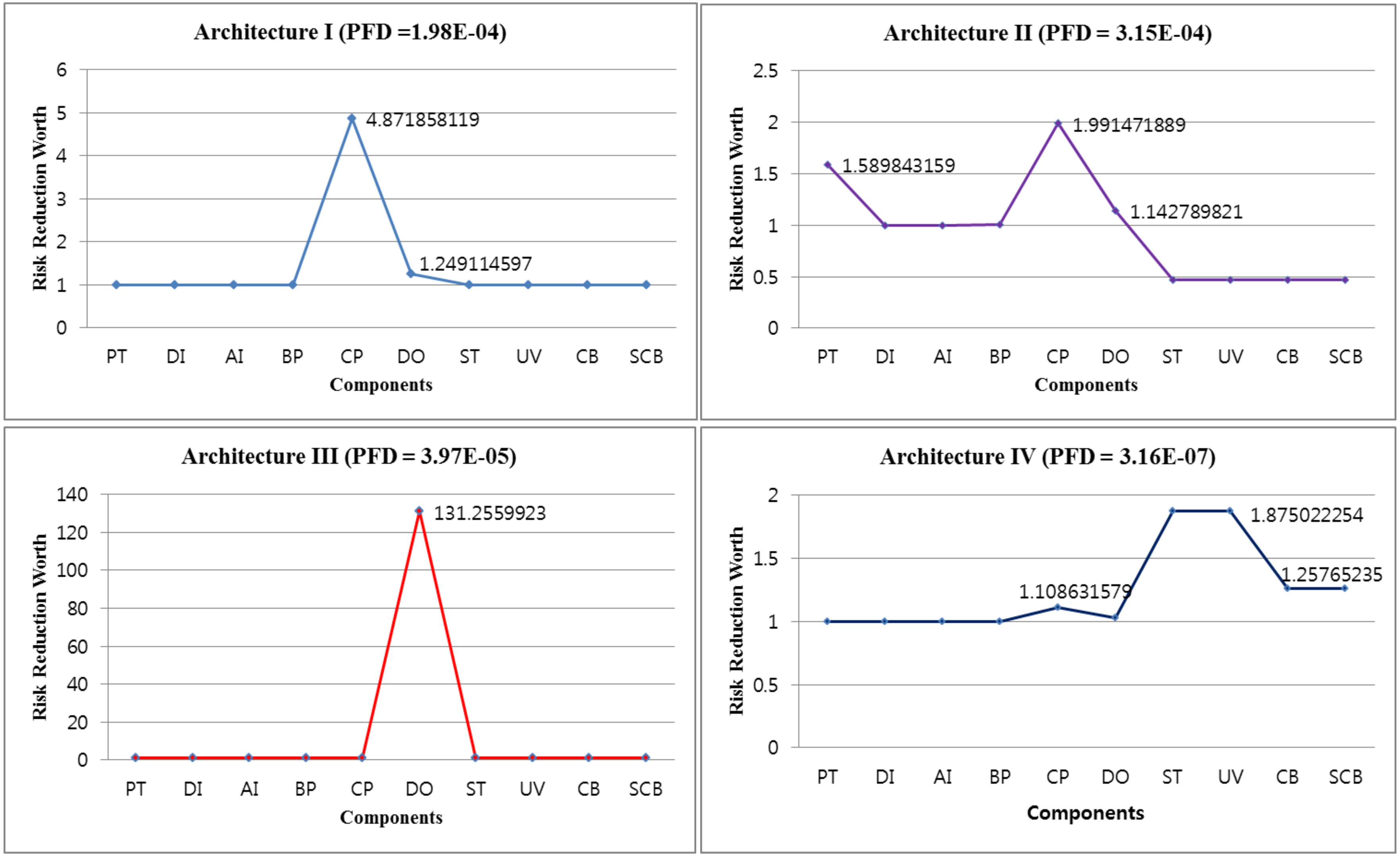

Figure 4: Shifting of component(s) importance from architecture I to architecture IV

Similarly if we add dual redundancy in BP, CP and DO in architecture IV, system attains high availability among all design but yet another side effect happens. The components which were not sensitive in previous designs such as ST/UV and CB/SCB are now significant risk contributors. With single component sensitivity index, such cycle will keep on and there is will be no limit to stop. Therefore a multi-component risk importance measure and criteria on combination of risk importance measures such as (RRW, RAW) must be defined. These will help the designers to use them as decision tool for optimization and high level of safety.

Table 1: I&C architecture configurations composition

Components/modules	Architecture Configurations			
	I	**II**	**III**	**IV**
Bi-stable Processor	1	2	1	2
Coincidence Processor	1	1	2	2
Digital Output	1	1	1	2

3. Conclusions and Recommendations

Based on the aforementioned discussion and feedback, it can be concluded that single component risk index cannot be used for risk based design and optimization because it is a relative measure to system Probability of Failure on Demand (PFD) and strongly dependent on component failure probability or rate. Therefore the followings are being recommended for risk applications in design, decision and optimization:

a) Two risk importance measures such as RRW_j (i=1) and RRW_j ($i \geq 2$) should be determined. Whereas RRW_j (i=1) and RRW_j ($i \geq 2$) are risk reduction worths for single (i shows number of component) and multiple component(s) (j is category of component);
b) To take the decision on risk significance of component(s), we have to consider the difference between RRW_j (i=1) and RRW_j ($i \geq 3$). If the difference between these two is not large for a certain component, then the component(s) is not high risk sensitive. Alternatively, a very small fraction of risk reduction would happen by implementing a large resource, hence making design expensive.
c) A criterion on combination of risk importance measures such as (RRW, RAW) must be defined and verified. What happens when component has high RRW & low RAW and vice versa.

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