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Integrating RAMI into risk-informed decision-making for nuclear facilities

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Operation of nuclear facilities requires the highest standards of risk management, where safety-related decisions must be rigorously justified, transparent, and auditable. However, the risk measures applied in decision-making for complex nuclear systems and processes are inherently heterogeneous and subject to uncertainty. Moreover, the long-term operation of the nuclear facilities must ensure economic viability at an acceptable level, which should be integrated into the decision-making process without compromising safety. Therefore, non-routine decisions concerning nuclear facilities typically extend beyond deterministic and probabilistic safety studies. They may involve additional factors such as economic indicators, security aspects, and societal concerns. Addressing such a broad range of issues requires a complex multi-attribute decision-making procedure. In response to this need, the Integrated Risk-Informed Decision-Making (IRIDM) framework was developed by the International Atomic Energy Agency. IRIDM provides a structured approach in which diverse aspects (deterministic and probabilistic safety assessment, standards and good practices, operational experience, human and organizational issues, security aspects, and socio-economic factors), represented by different risk metrics, are systematically evaluated and integrated into the risk-informed decision-making process. This work aims to extend the IRIDM framework by incorporating lifetime characteristics of the Reliability, Availability, Maintainability, and Inspectability (RAMI). Complementing the conventional Probabilistic Safety Assessment (PSA), which quantifies the accident scenarios leading to core damage and radiological releases, the integration of RAMI parameters provides broader insights into the probabilistic aspects. It captures scenarios that increase the forced outage rate without directly challenging safety and are therefore not addressed in PSA. The integration of RAMI into the IRIDM framework is presented and discussed in the context of real decision-making processes on the MARIA research reactor, operated by the Polish National Centre for Nuclear Research. The concept proposed herein is, however, broadly applicable within the nuclear industry to improve risk management processes.

Keywords: IRIDM, IRISC, IRDA, RAMI, MARIA.

1. Introduction

Risk management in the nuclear energy sector is particularly challenging, as it involves balancing multiple, often competing, attributes, including the highest safety requirements, compliance with national and international standards, operational performance, and economic constraints.

The traditional deterministic methods, based on conservative assumptions and the defense-in-depth principle, have provided a strong foundation for nuclear safety. However, deterministic criteria cannot fully characterize the relative importance of different safety matters or determine priorities of various safety improvements.

Over the last decades, Probabilistic Safety Assessment (PSA) has matured into a commonly accepted method that complements deterministic analyses by providing quantitative insights into accident sequences and risk contributors.

The integration of deterministic methods and probabilistic insights reflects the concept of the risk-informed regulation of nuclear facilities, promoted by the International Atomic Energy Agency (IAEA 2005). However, the non-routine decisions concerning nuclear facilities typically extend beyond deterministic and probabilistic safety studies, involving additional factors such as economic indicators, security aspects, societal concerns, and more. In response to this need, a multi-attribute framework of the Integrated Risk-Informed Decision-Making (IRIDM) for nuclear facilities has been developed (IAEA 2011).

In parallel, methods for optimizing RAMI (Reliability, Availability, Maintainability, and Inspectability) have been widely applied in the nuclear sector to support design improvements, ageing management, maintenance planning, and operational efficiency.

Although RAMI aspects are closely linked to both safety and performance, they are often considered implicitly or addressed quantitatively through engineering judgement in risk-informed decision-making processes or incorporated within static PSA models (event trees and fault trees).

This work aims to demonstrate how RAMI parameters can be explicitly integrated into the IRIDM process by considering the entire facility lifetime, rather than focusing on system reliability limited to short-term response to initiating events. Intermediate advancements in this direction have already been achieved through the development of the Integrated Risk-Informed Safety Classification (IRISC) approach (Kałowski and Kowal 2023) and the Integrated Reliability Data Aggregation (IRDA) procedure (Kałowski et al. 2025) for the MARIA research reactor. Both these concepts are based on equipment reliability data derived from long-term reactor operation. However, they have primarily been used to support traditional (static) PSA models. This approach extends these efforts by incorporating the long-term RAMI simulation results into the IRIDM framework across the entire facility lifecycle.

2. The IAEA framework for IRIDM

Following the principles and main objectives of the IRIDM approach, the IAEA has developed a common implementation framework intended for application by Member States. This framework encompasses the identification of inputs relevant to decision-making process and their prioritization according to the level of risk (IAEA 2011). The decision options are then evaluated in terms of optimization of these aspects, namely compliance with standards and good practices, lessons learned from operating experience, results of deterministic and probabilistic studies, economic insights, etc. The aim of this activity is to choose the option that solves the specified issue with minimal risk.

The early IRIDM concept was constrained by the lack of well-defined methodology for the assessment and integration of individual inputs corresponding to qualitatively different types or risk. This deficiency has been addressed in the newest guidance through the use of the Value Tree Analysis (VTA) methods (IAEA 2020).

The remaining gap in the IRIDM framework is that probabilistic insights are limited to typical PSA results, including Core Damage Frequency (CFD), Large Early Release Frequency (LERF), and the risk of potential radiation doses. All these metrics are primarily related to severe accident sequences. Consequently, their absolute values are extremely low and typically exhibit only minor variations when the rational decision options are evaluated. Moreover, the impact of the considered decision options on normal facility operation is not reflected in probabilistic metrics.

By complementing traditional PSA metrics, the inclusion of RAMI parameters into the IRIDM framework enables a comprehensive assessment of the impacts of decision options on both safety and operational performance.

3. Integrating RAMI into the IRIDM process

Two main aspects are important for integrating RAMI parameters into the IRIDM process. First, the algorithm for calculating RAMI parameters must ensure their applicability in comparing the considered decision options. Second, the RAMI parameters must be appropriately incorporated into the general framework of IRIDM, alongside many other inputs. The former can be achieved through the application of the Integrated Multi-model Simulation (IMS) (Kowal, 2022), whereas the latter can be accomplished using Value Tree Analysis (VTA) (Borysiewicz et al., 2015).

The lifetime simulation of RAMI parameters remains the central part of the concept proposed in this article. It aims to establish digital twin models of engineered systems that capture their long-term RAMI characteristics. In this approach, models for individual components and failure modes are subsequently integrated into reliability-oriented logical structures according to their functional relation (e.g., Dynamic Fault Trees or Reliability Block Diagrams). These reliability structures are further expanded by incorporating probabilistic models of events that are typically not included in static fault trees, such as the scheduled preventive maintenance, refueling outages, forced outages due to equipment failures, corrective maintenance aimed at the system restoration, initiating events challenging the reactor safety, and safety system failures that may affect the facility's capability in the accident prevention and mitigation. All such events are parameterized using statistical variables described by probability density functions (PDFs). This enables the lifetime simulation of the system behavior under dynamically changing conditions, while comparing various models (corresponding to decision options) based on the same dataset.

The algorithm for the integrated multi-model simulation of RAMI is shown in Fig. 1. It uses three logical loops: (1) Sampling loop is to access each failure mode i, for which the failure rate (λ_i) and repair time (τ_i) are sampled from the PDFs, each time the loop passes; (2) Simulation loop is executed N times for each time point t to execute in parallel the calculation of RAMI parameters for k decision options based on the common dataset, so that the simulation results create a matrix of size N x k; and (3) Time loop is executed for t changing from 0 to T (the facility lifetime) with a predefined step Δt.

The reliability of individual components can be expressed by exponential or Weibull function:

$$R^{(i)}_{Exp.} = e^{-\lambda_i t} \text{ or } R^{(i)}_{Weib.}(t) = e^{-(t/\eta_i)^{\beta_i}}, \quad (1)$$

where: β and η are, respectively, shape and scale parameters. In both cases the uncertainty of λ_i can be defined by gamma distribution function:

$$f^{(i)}_{Gamma}(\lambda_i) = \frac{1}{\Gamma(k_i)\theta_i^{\,k_i}} \lambda_i^{k_i-1} e^{-\lambda_i/\theta_i}, \quad (2)$$

where: k_i is a shape, and θ_i is a scale parameter. Finally, the operational availability ($A_{oper.}$) and the forced outage rate (FOR) are calculated as:

$$A_{oper.} = \frac{SH}{SH+FOH+PMH} \text{ and } FOR = \frac{FOH}{SH+FOH}, \quad (3)$$

where: SH is the sum of all service hours of the plant during its lifetime, FOH is the sum of all forced outage hours, and PMH is the total time spent for refueling and preventive maintenance.

When the RAMI models corresponding to the considered decision options are quantified, the results must be appropriately incorporated into the IRIDM framework, alongside many other inputs, including the key results of Deterministic Safety Analysis (DSA), Probabilistic Safety Assessment (PSA), economic factors and more. The VTA is one of the methods for supporting this process (Borysiewicz et al., 2015). A generic value tree diagram illustrating the integration of RAMI into the IRIDM process is presented in Fig. 2, where k decision options are evaluated by DSA, PSA, etc.

In this approach, all the decision options are scored using the following formula:

$$S_k = \sum_i W_i \sum_j A_{ij} \cdot s_{ijk}, \quad (4)$$

where: W_i is the weighting factor of input i, A_{ij} is the weighting factor the attribute j of input i, while s_{ikj} factor describes how the implementation of option k would affect the attribute j of input i.

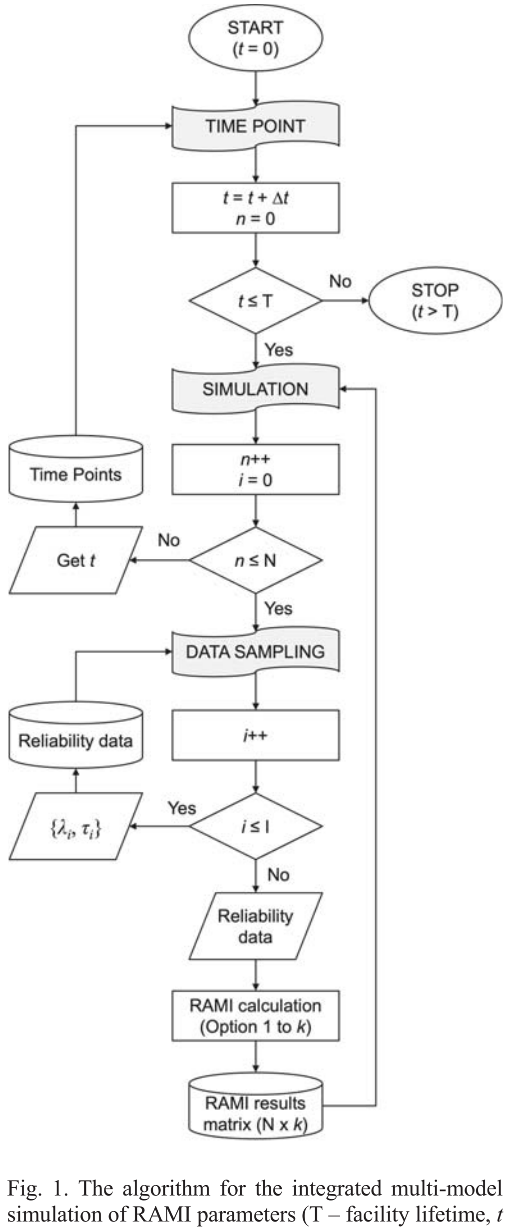

Fig. 1. The algorithm for the integrated multi-model simulation of RAMI parameters (T – facility lifetime, t – current time point, Δt – time step, N – number of simulation runs, n – current simulation run, I – number of failure modes considered in the RAMI models, λ_i – frequency of failure mode i-th, τ_i – restoration time for failure mode i-th, k – number of potential decision options considered and evaluated within the IRIDM process).

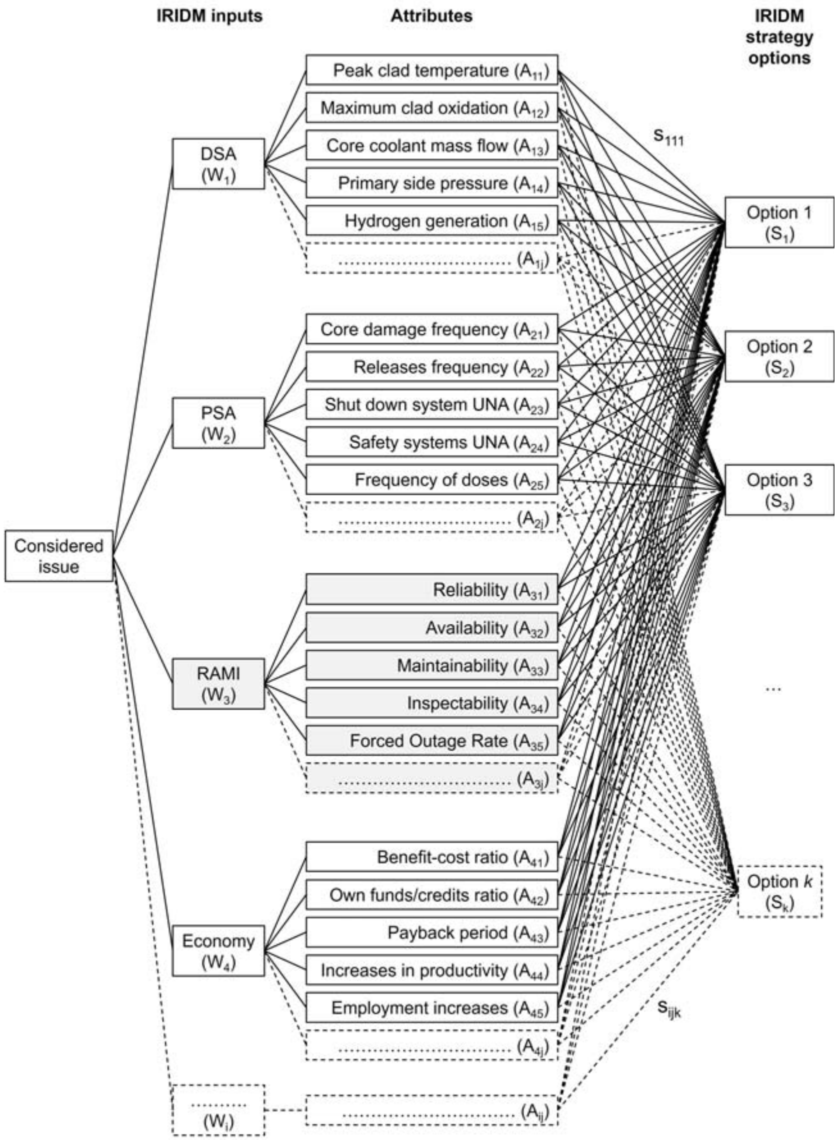

Fig. 2. A generic value tree diagram integrating RAMI into risk-informed decision-making on nuclear facilities.

4. Lessons from the MARIA research reactor

The implementation of the RAMI attributes into the IRIDM process has been considered under the real-case decision-making activities at the MARIA research reactor operated by the Polish National Centre for Nuclear Research (NCBJ).

MARIA is a unique water- and beryllium-moderated, water-cooled, pool-type reactor with a nominal thermal power of 30 MW. Designed as a highly flexible and multipurpose facility, the reactor features pressurized fuel channels with concentric multi-tube fuel element assemblies.

It is equipped with the vertical irradiation positions and horizontal neutron beam channels enabling a wide range of both experimental and commercial activities, including production of radionuclides, novel materials, fuel testing, and neutron beam experiments (Migdal et al. 2021).

Recently, a new neutron facility has been designed and constructed as part of the MARIA Neutron Laboratory (MNL) to support research applications across a broad range of disciplines, including biology, chemistry, and medicine. The main objective of this infrastructure is, however, to generate a neutron beam appropriate for the research on the Boron Neutron Capture Therapy (BNCT) – irradiation of the glioblastoma cancer tumors (Michaś-Majewska et al. 2025).

The IRIDM framework was applied to the MARIA reactor for the first time to optimize the fuel conversion procedure. This aimed to replace high-enriched uranium (HEU) fuel, containing 36% U-235, with low-enriched uranium (LEU) fuel containing 17% U-235, to satisfy the Global Threat Reduction Initiative (GTRI) (Borysiewicz et al. 2015). Subsequently, the concept of risk-informed decision-making has been extended and applied to the safety classification process of the reactor systems, structures, and components (SSC) (Kałowski and Kowal 2023). The impact of equipment reliability on safety classification results has been further investigated (Kałowski et al. 2025), thereby supporting the need for integrating RAMI into the IRIDM process.

As demonstrated during the fuel conversion process, the integration of probabilistic insights, primarily related to initiating event frequencies and safety system performance, enabled decision makers to compare the alternative solutions in a consistent risk-informed manner. This process, however, was strongly driven by safety aspects. Therefore, the probabilistic attributes of IRIDM included core damage probability, radiological release frequency, and quantitative estimates of risk associated with the potential radiation doses. Although the long-term reliable operation of the reactor was considered within the economic part of the IRIDM framework, explicit calculations of the facility's availability and forced outage rates for alternative solutions were not performed.

Applying the IRIDM approach to the safety classification of MARIA systems, structures, and components resulted in the development of the Integrated Risk-Informed Safety Classification (IRISC) procedure. In this concept, Probabilistic Safety Assessment (PSA) models were applied to determine the frequency of activation of safety functions and to support the assignment of SSC safety classes in conjunction with deterministic consequence analyses. The key methodological challenge was that multiple initiating events may trigger activation of safety functions in research reactors. This may result in cumulative effects that are not adequately captured when initiating events are analyzed independently. Moreover, safety-important SSCs can be used continuously during the normal reactor operation rather than being activated on demand following initiating events. This aspect directly links the long-term reliability and availability of the SSCs to their functional importance in accident prevention and mitigation throughout the facility life cycle.

The most recent extension of this work (Kałowski et al. 2025) explicitly addressed the importance of equipment reliability data and its uncertainty in the classification procedure. By analyzing operational data from more than two decades of the MARIA reactor exploitation, it was demonstrated that the component reliability estimates can differ significantly depending on whether generic databases, site-specific data, or integrated data sources are used. The proposed Integrated Reliability Data Aggregation (IRDA) approach enables the combination of multiple data sources by using Bayesian updating, Monte Carlo sampling, and multi-criteria weighting techniques. This allows reliability inputs to be treated as dynamic quantities reflecting ageing, maintenance efficiency, and operational modes characteristics, rather than as fixed values.

While reliability data were initially treated as static, the experience gained during this work demonstrated both the importance and feasibility of accounting for the long-term characteristics of SSCs. This approach is particularly relevant, but not limited, to research reactors, which are often characterized by extended operational lifetimes, unique installations for production and research, and multiple modernization phases. The MARIA case studies discussed in this article demonstrate that, although changes in equipment reliability do not necessarily determine the final decision, they significantly enhance risk characterization of the considered options by providing insights that extend beyond conventional PSA measures.

The experience gained from implementing the risk-informed approach in the safety-related decision-making at the MARIA research reactor supports the integration of the lifetime RAMI parameters as explicit inputs into future IRIDM processes. Moreover, this approach is broadly applicable beyond research reactors and may be used across the nuclear industry to enhance risk management in existing nuclear power plants as well as in newly developed nuclear technologies.

5. Summary and conclusions

This paper proposes a structured approach for incorporating RAMI parameters into the IAEA framework for integrated risk-informed decision-making process applied to nuclear facilities. By explicitly embedding RAMI attributes within the IRIDM procedure, safety-related decisions that require the multi-criteria evaluation of various solutions can more comprehensively account for system performance, equipment degradation, as well as long-term operational and maintenance characteristics over the facility life cycle.

The proposed integration of RAMI indices does not require any fundamental changes to the existing framework of IRIDM. The extension builds on its inherent flexibility by enriching the set of indicators used to quantify the decision options. The lessons from to the MARIA reactor operation illustrate the practical benefits of this approach, including improved transparency of the process, more balanced trade-off assessment, and the robustness of implemented solutions.

The implementation of IRIDM within the MARIA reactor decision-making processes has gradually evolved from a conceptual framework into a comprehensive approach that supports risk management throughout the facility's entire life cycle. Initially, IRIDM was employed to support strategic decisions related to the conversion of reactor core from high- to low-enriched uranium fuel due to the non-proliferation objectives. This required multiple criteria to be jointly considered in a consistent manner, including safety margins, operational performance, security, and regulatory compliance. Subsequently, the IRIDM approach was further developed and applied to the safety classification process of systems, structures, and components of the MARIA reactor. The analysis revealed that the long-term equipment reliability may influence the safety-related decision-making process and, therefore, should be incorporated into the framework of IRIDM.

As a continuation of these efforts, further research may focus on standardizing the RAMI indicators within the IRIDM framework and on developing quantitative methods for integrating RAMI with probabilistic and deterministic safety studies. Moreover, while the explicit integration of RAMI parameters into IRIDM enhances holistic and sustainable risk management of nuclear facilities, their impact on final decision-making warrants further investigation, including uncertainty assessment, sensitivity analysis, and the effectiveness of the simulation algorithms.

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