MARINER: Combining Generative AI and Bayesian Networks for Reliable and Explainable Nuclear Risk Analysis

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Identification of Use Cases

Nuclear-powered naval platforms and ships rely on highly complex systems whose safe operation requires rigorous risk assessment and informed decision-making under uncertainty. Technical failures, human factors, operational constraints and environmental conditions interact continuously, making conventional approaches insufficient for many safety analyses. Bayesian networks naturally integrate uncertain observations, incomplete evidence and expert judgement into a coherent mathematical framework. This capability is particularly relevant for naval nuclear propulsion, where operational decisions frequently have to be taken before all information becomes available.

Bayesian Networks have become one of the reference technologies for probabilistic risk assessment because they explicitly represent causal relationships and provide mathematically rigorous reasoning under uncertainty while remaining fully explainable and auditable. Recent publications from China, one of the world's leading naval nuclear powers, illustrate this growing interest through the development of Bayesian Network models for the analysis of nuclear accidents in Marine Nuclear Power Plants [1].

BAYESIA has been developing Bayesian Network technologies for more than twenty years and has contributed to their application in industrial risk management, reliability engineering and decision support. Previous work has demonstrated how Bayesian Networks provide a unified framework combining expert knowledge and operational data to support prediction, diagnosis, maintenance and risk assessment within a single probabilistic model [2].

The MARINER project investigates the combined use of Generative AI and Bayesian Networks to accelerate the development of probabilistic models for naval nuclear risk management. The initial phase will be conducted under the Brevet d'Atomicien de la Marine (BATOM), the French Navy's nuclear engineering certification programme, and will primarily consist of a prospective study aimed at identifying potential applications of this approach to defence nuclear safety. This study may lead to the development of a simple, generic demonstrator addressing a specific use case and relying exclusively on non-classified documentation. It is also intended to lay the groundwork for a future final-year Nuclear Engineering project focusing on Severe Accident Mitigation (SAM).

The proposed methodology could eventually support a broader range of operational capabilities, including the dynamic exploitation of operational experience feedback (REX), risk-based maintenance optimization, configuration management, and operational decision

support through continuous assessment of the vessel's risk level and evaluation of alternative courses of action.

Proposed Technical Approach

MARINER combines two complementary Artificial Intelligence paradigms. Each technology compensates for the limitations of the other.

Large Language Models are used during the knowledge engineering phase to analyse technical documentation, identify relevant concepts, extract causal relationships and propose an initial model structure. Rather than acting as decision-making systems, they serve as assistants for knowledge acquisition and model construction. They can rapidly identify entities, events, procedures and potential causal relationships from large document collections, producing an initial draft model that would otherwise require weeks of manual work.

Bayesian Networks then transform this information into explicit probabilistic models that can be reviewed, validated and refined by domain experts. Their mathematical foundations ensure rigorous reasoning under uncertainty while providing complete traceability and explainability of every inference. Every node, dependency and probability distribution remains visible and can be challenged, modified and validated by subject-matter experts before operational use.

The proposed workflow consists of:

1. collecting and analyzing all relevant technical documentation;
2. automatically generating several candidate Bayesian Networks using Generative AI;
3. reviewing, refining and validating the proposed models with nuclear-domain experts;
4. evaluating the resulting Bayesian Network through representative operational decision-support scenarios.

The project starts at TRL 4 and aims to reach TRL 5 through the validation of an operational demonstrator. In parallel, software integration requirements will be defined to facilitate future deployment within naval information systems. The demonstrator will also assess the feasibility of integrating the proposed methodology into future operational decision-support environments.

By combining the productivity of Generative AI with the rigor and transparency of Bayesian reasoning, MARINER aims to significantly reduce the cost and duration of probabilistic model development while preserving the level of confidence required for safety-critical nuclear applications. The project therefore represents an original step towards trustworthy hybrid AI for defence applications, combining the productivity of foundation models with the robustness of probabilistic reasoning.

References

[1] Zhao, F., Shu, R., Xu, S., Zou, S., A Cause Analysis Model of Nuclear Accidents in Marine Nuclear Power Plants Based on the Perspective of a Socio-Technical System, Safety, 2025.

[2] Munteanu, P., Debache, G., Duval, C., Bayesian Networks for Industrial Risk Management, Revue de l'Électricité et de l'Électronique (REE), No. 8, 2008.