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Methodology for Risk Assessment of Blackout on Maritime Nuclear Power Plants

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Nuclear power can contribute significantly to maritime transport. However, the economical and the regulatory issues intimidate the deployment of nuclear powered commercial shipping. There are several discussions to present the economic feasibility of marine based small modular reactors, but country neutral methods to demonstrate acceptable level of risk to worldwide regulatory bodies still not consolidated. This work proposes a methodology for risk assessment, based on risk informed approach, which enables the country neutral review of safety reports and permits to explore the state-of-art on reliability best estimate modelling, including system reconfigurations, human intervention and permissibility of short outage periods. The methodology is applied on a simplified case study of power loss accident of a hypothetical light water reactor with two loops. The methodology estimates a station blackout probability of 5.4 x 10^{-6} reactor.year. Probabilistic safety analysis using combinatorial models like fault tree results in a station blackout probability of 1.53 x 10^{-4} reactor.year. These results encourage to enjoy the opportunity of establishment of new method for reviewing safety reports to complement the systems design approach of *"redundancy, segregation and independency"* with *"maintainability, maintenance and operational procedures"* approach, reducing capital costs and keeping safety.

Keywords: Nuclear Power, Maritime transport, Risk Assessment, Country Neutral Method, Hypothetical Case Study, Station Blackout.

1. Introduction

The nuclear power generation is stable in terms of availability and cost when compared to other renewable energy sources, and relatively cheap. It also presents historically fewer accidents, environmental disasters and human health problems. Several studies emphasize the use of nuclear energy to reduce climate change and environmental impacts Hong (2013, 2014a, b, 2015).

A Maritime transport is a major source of air pollution Gravina (2012) and accounts for 95% of international maritime trade (Royal Academy of Engineering (2013). An alternative to fossil fuels is nuclear power for merchant ships propulsion, especially for large container ships with shaft power in range of 60 to 80MW Freire and Andrade (2019). Given the relevance of maritime transport and the advantages of nuclear power, it is natural the idea of using a nuclear power to propel merchant ships, a solution widely used in military vessels. Hass (2014) presented two major issues for the deployment of nuclear powered commercial shipping, the economical and the safety and regulatory issues.

In recent years, there has been widespread interest in Small Modular Reactors (SMR). SMRs offer the advantage of lower initial capital investment and scalability. Carlson et al. (2011) studied the nuclear propulsion for different ships and the maximum installed power has been estimated in 78MWe for an ultra large crude carrier with capacity over 1,000,000 deadweight tonnage at a speed of 16 knots. Hirdaris (2014a) also investigated the practical marine applications for small modular reactors. Freire and Andrade (2019) discussed the economic feasibility of Nuclear Power Plants (NPP) for merchant ships, proposing an economically competitive solution of nuclear power for their propulsion. Those are some of the discussions to present the economic feasibility of marine applications of SMR, however nuclear powered ships will not be deployed if the acceptable level of safety cannot be demonstrated to nuclear regulatory bodies worldwide.

The design of nuclear safety systems is based on several safety criteria and demonstration that the plant performs the safety functions in front of design based events pre-established. A SMR have different risk profile from NPP Travis (2019), especially mobile SMR with quite lower radiological inventory. (Prochazkova et al. 2021) shows SMR risk sources and indicate risk based method for design of such plants. Risk-informed approach enables design decisions driven by the risk level, comprehending exhaustive probabilistic analysis. A trustworthy and worldwide auditable method to analyse probabilistic analysis are key features for risk-informed approach successfulness, in special for maritime context.

Probability combinatorial models like fault tree and/or event tree are consolidated method used on probabilistic analysis, but are based on static basic events and do not consider complex scenarios of dynamic reliability, leading to conservative results. The Markov Chains have been used for system states orientation modelling. However, modelling larger systems directly on their states is cumbersome and difficult to audit. A formal method to define the states diagram is necessary. The system modelling through Petri Nets (PN) provides several characteristics to ensure model verification, such as net properties verification, invariants analysis, reachability graph, simulation, etc.

This work proposes to largely apply the reliability and maintainability studies on the design of safety systems, what certainly provide insights to decrease the risk. The probability quantification of scenarios involving reconfigurations and human intervention could only be obtained through state oriented system modelling. The formal demonstration of model correctness is obtained by application of Generalized Stochastic Petri Nets (GSPN), a Markovian class of Petri Nets where analytical and numerical steady state and transitory analysis still relatively simple, and profits the modelling formalism. In fact, GSPN has been considered the ideal trade-off between modelling powerful and quantitative analysis simplicity. Shukla and Arul (2020) used monte carlo simulation to quantify probabilities of PN, but simulation of really low probability event are cumbersome and challenging to perform parametric and sensitivity analysis.

To be clear, this work does not propose to substitute the safety design criteria and licensing methods of nuclear installations, but foment the application of state of art of reliability and maintenance engineering on the safety analysis. The maintenance engineering aspects must be deeply explored, since it can contribute significantly on risk. Level of reparability is explored by Souza and Gabe (2017) and demonstrated that repairs can increase significantly reliability on redundant systems. Actions performed by crew has been valorously implemented on Dynamic Probabilistic Safety Assessment (PSA) software platform of (Diaconeasa and Mosleh, 2018). Disregarding a possibility of repairing failed equipment during an accident scenario leads to a conservative estimate (Bouissou et al., 2020). The feasibility to perform some repairs is usually questioned on safety analysis reviews. Therefore, a maintenance task analysis is necessary to identify resources necessary to perform repairs, and the feasibility to perform them.

As tangible results of application of modelling by GSPN is the simplification of design by possibility of decreasing redundancy level, based on risk decision making. It could reflect in reduction of capital costs, since safety would also be demonstrable by reconfigurations, human intervention and permissibility of short outage periods. A risk-based safety demonstration would also alleviate certain economic burdens of implement some safety design criteria. Moreover, safety systems design simplification is important to nuclear power on commercial shipping, because the marine context impose several constraints in term of level of redundancy of safety systems and integration of passive safety features.

The power loss accident on marine based SMR has a different risk profile from large-scale land based reactors. Light Water Reactor (LWR) accidents like large and medium Loss-of-Coolant Accident (LOCA), interfacing-system LOCA, steam generator tube rupture, and a set of transients, coming from traditional safety analysis, can be replicated to marine context considering the scale factors and some context specificities. Station Blackout (SBO) accident, the most core damage contributor in reactor up to *Generation III*, has been chosen as case study. This accident sequence permits to explore risk-informed approach through best-estimate dynamic reliability modelling, taking into account the reconfigurations, human intervention and permissibility of short outage periods.

To illustrate the application of the methodology proposed, the blackout risk is analysed on a hypothetical *Generation III* marine based reactor, with two loops and active safety systems with level 2 of redundancy.

Section 2 presents the proposed methodology for blackout risk assessment. The main input data necessary, processes and results, illustrated through a flowchart. Section 3 performs the risk assessment on a hypothetical marine NPP. It describes in a detailed way the input data, hypothesis and activities, always exemplifying it based on the case study.

The Section 4 presents the results and discussions and Section 5 shows the conclusion.

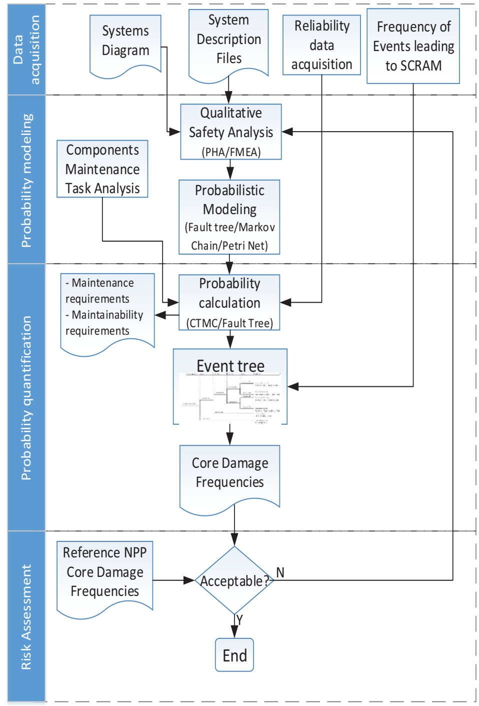

Fig. 1. Methodology for Risk Assessment on Maritime Nuclear Power Plants.

2. Method

The Figure 1 shows the methodology flowchart providing a macroscopic overview of the activities.

The methodology proposed for obtain a risk assessment of NPP is also applicable on early design phases. The data and the methods are discussed on the following subsection.

2.1. Data Acquisition

The system design data adopted on the definition of risk level are the ones necessary to enable probabilistic analysis, usually coherent with a preliminary design phase. Detailed data of components reliability and frequency of initiating event are usually acquired from generic data bases on early design phases, and gradually replaced by supplier information and detailed studies results. In the study of blackout, emergency electric sources nominal power, diesel generator auxiliary systems architecture and safety system power consumption are examples of information relevant to draft probabilistic models.

2.2. Probability Modeling

The probability analysis can involve several tools for probability evaluation, since the most typical, like event tree, up to state of art on dynamic reliability calculation by Markov chains.

A qualitative safety analysis is recommended to identify hazards and related safety functions. It also identifies several procedures and corrective measures. Those insights are important to ensure good modeling. This step is part of the methodology mainly to identify features not evident, like components behavioral interdependencies, system reconfigurations, repairs and operational procedures, etc.

A maintenance task analysis is proposed to verify the related resources necessary to perform repairs, and the feasibility to perform them on accidental scenarios.

The use of Petri nets (PN) to model system reliability is not a recent idea. Schneeweiss (2001) shows many models of reliability through PN in a didactic way. (Dosda and Brandeletb, 2021) reinforced currently the advantages of use on PN to overcome limitation of static reliability.

Starting the modelling by PN enable the formalism and analysis to ensure model correctness. When a PN model is adequately constructed, the system states can be obtained through the reachability graph analysis. Model the reliability of large system directly on its Markov chain is laborious and error-prone. Therefore, each time complex scenarios not modelled by combinatorial models like fault tree, a system reliability model through PN is recommended. There are a package of properties and analyses to be performed on a petri net to formally ensure model correctness and performance measuring.

The Stochastic Petri Nets (SPN) is a petri net where each transition has a firing delay probabilistically distributed. GSPN is characterized due to its capacity to accept two types of transition, timed exponential and immediate, this last used to represent a logical control and action that delay is negligible, expanding the representativeness capability of a SPN. Wider classes of SPN can model other types of transitions firing delays, such as deterministic or generally distributed firing delays. However, the stochastic process behind wider SPN classes are non-Markovian, which is solved by discrete time approximation of the stochastic behavior process of the marking process Horváth et al (2001). This solution cannot by simple calculated analytically or numerically and is usually solved by computational tools. Therefore, non-Markovian Stochastic Petri Nets (NMSPN) turns the analytical solution presented hereinafter impossible. Monte Carlo simulation on event with quite low probability are challenging and usually avoided. It is preferably to kept simply using an approximation where deterministic of other than exponential distribution firing delays are approximated by exponential distributed firing delays and ensuring the applicability of stochastic Markovian process.

2.3. Probability Quantification

The reachability graph is isomorph to a Markov chain. In other words, when all firing delays are exponential distributed, the stochastic process behind the Petri Net is a Markovian process, and the performance or quantitative analysis of SPNs can be carried out straightforwardly by analysing the corresponding Markovian process. The Markov chain state space is obtained by the reachability graph of the PN with initial marking M_0. The transition rate from state M_i to state M_j is given by

$$q_{ij} = \begin{cases} \sum_{k \in H_{ij}} I_k \\ -\sum_{k \in H_i} I_k \end{cases} \quad (1)$$

H_i is the group of all transitions enabled by the M_i marking,

H_{ij} is the group of all transitions enabled by the M_i marking, whose firing leads to M_j marking.

Supposing an ergodic chain, where the initial marking can be recovered for any state of the reachability graph, i.e. a cycling net free of traps and deadlocks, the steady state probability vector $\pi = (\pi_1\ \pi_2 \ldots \pi_s)$, where “s” is the number of states, can be calculated, through the resolution of the following equations,

$$\pi * Q = 0 \quad (2)$$

$$\sum_i \pi_i = 1 \quad (3)$$

Q is the transition matrix.

The steady state probability vector represents the probability to the system is find on each state. Associating the probabilities of all states that presents the system available, the system availability can be found.

A small modification to transitory analysis, is that q_{ij} is equal to 1-q_i. An initial state probability vector π_0 must be introduced. $\pi(t)$ represents the instantaneous state probability vector. The time dependent behaviour of the Continuous Transition Markov Chain (CTMC) can be described using the Kolmogorov differential equation

$$\dot{\pi}(t) = \pi(t)Q \quad (4)$$

The instantaneous availability of the system can be found by the same association described previously. The transient solution demands interactive calculation to find each next instantaneous state probability vector. The transient analysis has not the constraint of cycling nets, and supports absorbing states, i.e. deadlocks. Therefore, the system reliability can be calculated as the association of all states instantaneous probability that represents system free of failures, i.e. the probability of be out of absorbing states representing system in failure.

2.4. Risk Assessment

With the results of probability calculation, and the results of consequence, the risk of a marine NPP is raised. In the lack of normative base for mobile NPP, the risk level raised can be compared to operating references of NPP, in order to be sure that the level of risk is acceptable.

In the case of an unacceptable level of blackout risk, several options can be explored, being preferably to explore options in maintenance and reliability engineering (i.e. increase of equipment reliability or repair capacity) instead of design modifications.

3. Case Study

In order to consolidate the methodology presented on previous section, data for a hypothetical marine NPP is estimated from a mix of sources. In despite of results does not represents a specific plant, they demonstrate how to apply the proposed methodology.

The methodology is applied to assess the frequency of core damage due to blackout accident. It permits to explore the state-of-art on dynamic reliability best estimate modeling. Blackout on marine SMR unpowered by passive heat removal is a key safety issue due to inexistence of offsite power at sea and reduced quantity of Diesel-Generators for accident management.

Figure 2 presents the architecture of the hypothetical marine based reactor electric power system with level two of redundancy.

An important feature on the electrical power system of Figure 2 compared to land based NPP is the presence of Station Batteries. These batteries are dimensioned to support safety-related functions to achieve and maintain safe shutdown at short term.

This solution is suitable to mobile SMR because it:

- Provide uninterruptable power supply to smoothly reduce transient involving reactor trip
- Contribute on diversity safety principle providing another emergency power source technology than diesel-generators

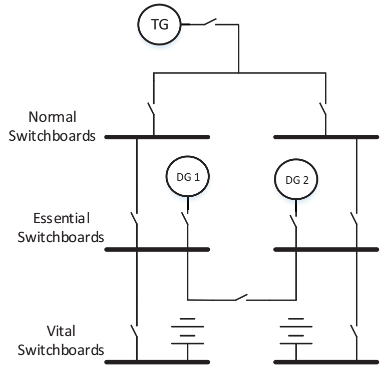

Fig. 2. Hypothetical marine based reactor electric power system.

- Cope with recommendations of post-Fukushima to maintain as much as reasonable safety-related functions on SBO scenarios

In this case, during batteries autonomy to supply safety-related electrical buses, a temporary redundancy to Diesel-Generators are ensured. Moreover, possibility to recover at least one Diesel-Generator while batteries supply power constitutes an important accident management procedure. Core damage due to blackout scenario does not take place while the batteries have energy. To estimate the probability to be in power outage involves system reconfiguration due to standby redundancy. The GSPN of figure 3 was used to model the probability to be at power outage, i.e. the unavailability of all power sources. Batteries are considered to be recharged when at least one Diesel-Generator is available.

The boundness and liveness of PN of Figure 3 are ensured, the mandatory characteristics calculate availability by steady-state analysis of Bause and Kritzinger (2013). The place invariants of Figure 3 PN demonstrate the model correctness,

$$\begin{cases} M(Bat\_power) + M(PowerOutage) = 1 \\ M(DG\_stb) + M(DG\_oper) + M(DG\_unavail) = 2 \end{cases} \quad (4)$$

After a PN modelling and properties analysis, the reachability graph can be draft. This analysis consists in drawn a schematic of system states and transitions between them. The reachability graph of Figure 3 is shown on Figure 4. In addition , another calculation method is redrawn

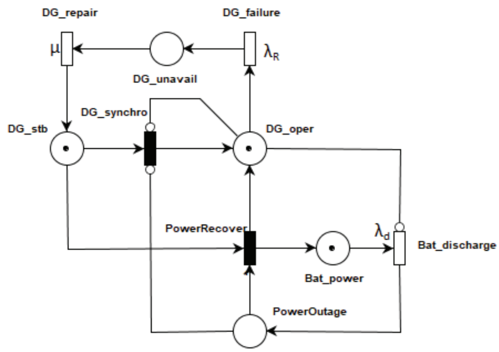

Fig. 3. GSPN for availability calculation of emergency electric power system.

reachability graph removing the vanish states. It results in the reduced reachability graph, that is isomorph to the Markov Chain of the stochastic process behind the PN of Figure 3. Afterwards, steady state and transitory analysis of CTMC can be applied.

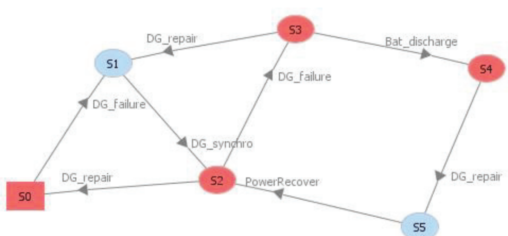

Fig. 4. Reachability graph of the GSPN of Figure 3.

The contribution of battery to power outage likelihood reduction cannot be modelled by fault trees. The battery provides a temporary redundancy up to its depletion and is recovered when recharged by a Diesel-Generator. This demands state orientation. Moreover, there is no gates for standby redundancy.

A more realistic scenario must include the limitation on diesel-generators and auxiliary system reparability. Crew account only with resources available on board. Moreover, accidental scenario could also impose constraints on repairs. Maintenance limitations of accidental scenarios on a ship at sea are characteristics of Partially Repairable System (PRS). Souza and Gabe (2017) proposes to consider repair on reliability, since short time repairs are feasible on many scenarios including accidental ones. Fault Trees are able to model repairs, but calculate failure to operate probability of repairable stand-by redundant system is a example of feature to encourage the use of GSPN. The Figure 5 shows the GSPN to model reliability of the PRS of Figure 2.

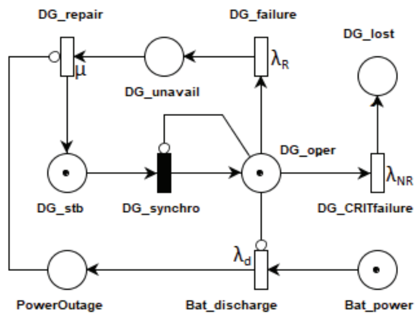

Fig. 5. GSPN to reliability calculation of emergency electric power system.

The boundness of PN of Figure 4 is ensured. Since the PN models reliability, the system is composed by some absorbing states and liveness is not reached. In this case, only transient analysis is possible. The place invariants of Figure 4 PN below emphasize the model correctness,

$$\begin{cases} M(Bat\_power) + M(PowerOutage) = 1 \\ M(DG\_stb) + M(DG\_lost) + M(DG\_oper) + M(DG\_unavail) = 2 \end{cases} \quad (5)$$

The reachability graph of Figure 4 is shown on Figure 5. It is necessary to remove the vanish states, resulting in the reduced reachability graph, that is isomorph to the Markov Chain of the stochastic process of Figure 4 PN.

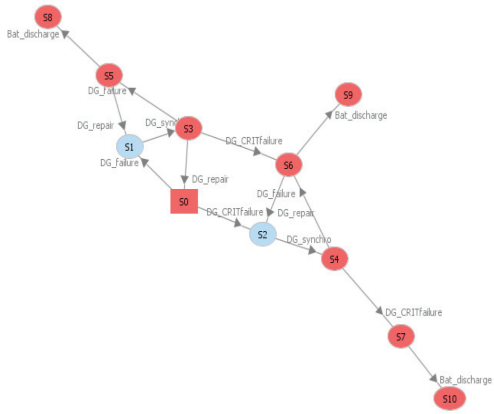

Fig. 6. Reachability graph of the GSPN of Figure 5.

The Markovian transition matrix Q of reduced reachability graph is

$$Q = \begin{vmatrix} 1-(\lambda_R+\lambda_{NR})\Delta T & \mu\Delta T & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_R\Delta T & 1-(\lambda_R+\lambda_{NR}+\lambda_d)\Delta T & 0 & \mu\Delta T & 0 & 0 & 0 & 0 & 0 \\ \lambda_{NR}\Delta T & 0 & 1-(\lambda_R+\lambda_{NR})\Delta T & 0 & \mu\Delta T & 0 & 0 & 0 & 0 \\ 0 & \lambda_R\Delta T & 0 & 1-(\mu+\lambda_d)\Delta T & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_{NR}\Delta T & \lambda_R\Delta T & 0 & 1-(\mu+\lambda_d)\Delta T & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_{NR}\Delta T & 0 & 0 & 1-\lambda_d\Delta T & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_d\Delta T & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_d\Delta T & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_d\Delta T & 0 & 0 & 1 \end{vmatrix}$$

A transient analysis is performed through the iterative resolution of Kolmogorov differential equation. In addition to the fault tree limitations to model battery redundancy and standby reconfigurations, the reliability of redundant repairable systems cannot be calculated by combinatorial models, as explained by Souza and Gabe (2017).

4. Results and Discussions

The Petri nets models of Figure 3 and Figure 5 are used to calculate unavailability and failure probability, respectively, of the redundant safety-related Diesel-Generators and Station Batteries. The reliability data used to quantify the results are shown in Table 1.

Table 1. Reliability data used by Souza and Gabe (2017).

Data	Value	Unit
$MTBF_{DG}$	2545	h
$MTTR_{DG\_global}$	12	h
Repair Rate	0.85	
$MTTR_{DG\_short\_repair}$	5	h
Battery Autonomy	12	h

The reliability data of Table 1 is also applied on the availability and failure probability calculation of an usual fault tree of redundant diesel-generator, in order to compare results calculated on such consolidated modelling tool.

The battery reliability modelling considers $R_{bat}(t) = 1$ for $0 < t \leq T_{autonomy}$ and $R_{bat}(t) = 0$ for $t > T_{autonomy}$. The DG auxiliaries' equivalent failure rate and reparability factor are included on DG reliability data.

The steady state analysis of Figure 3 calculates the probability to be at state S_4, i.e. $P(S_4)$, which represents the average number of tokens in the place *Power Outage*.

The critical failures are the non-repairable failures. The unreliability has been obtained by the probability of reach the states S_8, S_9 and S_{10}. It resulted in a probability to fall into the absorbing states that represents power blackout in an analysis time frame of 336 hours.

The Table 2 shows the results of Petri Nets compared to Fault Tree, modeling unavailability and failure probability.

Table 2. Results of unavailability and failure probability.

Model	Results	Method
Unavailability – Fault Tree	7.52×10^{-6}	Analytical
Unavailability – Petri Net (Figure 3)	2.78×10^{-6}	Analytical/ Numerical
Failure Probability – Fault Tree	1.53×10^{-2}	Analytical
Failure Probability – Fault Tree	1.25×10^{-3}	Monte Carlo (repairs account on reliability)
Failure Probability – Petri Net (Figure 3)	5.42×10^{-4}	Analytical/ Numerical

To obtain the probability to reach Blackout or to be in blackout, the results of Table 2 must be multiplied by the frequency of occurrence of normal power loss. Long term of normal power loss is considered part of design basis events. Such events have an annual occurrence frequency estimated in an order of 10^{-2} events/reactor.year.

5. Conclusions

This work indicated the GSPN as ideal class of Petri Nets to complement the PSA, when combinatorial models are insufficient. The proposed methods are intending to demonstrate level of risk to worldwide regulatory bodies through a country neutral method, which easy audits through Petri Nets properties verification, invariants analysis, reachability graph, simulation, etc. Moreover, this method explores the state-of-art on reliability best estimate modelling, including system reconfigurations, human intervention and permissibility of short outage periods.

The proposed methodology is applied on a simplified case study of power loss accident of a hypothetical marine based SMR electric power system, and shown results encourage to complement the systems design approach of “redundancy, segregation and independency” with “maintainability, maintenance and operational procedures” approach, reducing capital costs and keeping safety with lower levels of redundancy equal to 2.

The key features of the method support complex risk analysis of Maritime Nuclear Power Plants, and encourage the deployment of nuclear powered commercial shipping. However, it is recognized that the demonstration of method success demands the application on a complete PSA of a specific design, to confirm the insights and contribution highlighted.

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