Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

doi: 10.3850/978-981-18-8071-1_P486-cd

Nuclear safety management: A detailed causal model of nuclear power plant operation based on system dynamics

Acuña, Santiago Gregorio

Nuclear Safety Department, Atomic Energy National Commission, Argentina. gregorioacuna@cab.cnea.gov.ar

Giménez, Marcelo Oscar

Nuclear Safety Department, Atomic Energy National Commission, Argentina. gimenez@cab.cnea.gov.ar

Sánchez, Marisa Analía

Departamento Ciencias de la Administración, Universidad Nacional del Sur, Argentina. mas@uns.edu.ar

Di Nardo, Mario

Università degli Studi di Napoli Federico II, Italy. mario.dinardo@unina.it

Madsen, Dag Øivind

Department of Business, Marketing and Law, University of South-Eastern Norway, Norway. dag.oivind.madsen@usn.no

Abstract: This paper presents a qualitative model based on system dynamics methodology to investigate the management of nuclear safety and availability in the operation of a nuclear power plant. By integrating human, technological, organizational, and environmental factors, the model aims to understand the complex dynamics that influence the prevention of nuclear accidents and the safe generation of electricity. Drawing on previous research, a literature review, and interviews with nuclear industry experts, the model identifies two causal reinforcement loops and six causal balance loops that capture the effective management of nuclear safety within power plant organizations. These findings offer valuable insights into the intricate dynamics of nuclear power plant operation, providing a comprehensive understanding of the factors that contribute to accident prevention. Furthermore, the analysis reveals potential tensions and trade-offs between nuclear safety and the electricity generation load factor. Balancing the pursuit of high availability with the imperative of maintaining safety poses significant challenges. The model sheds light on the interplay between these factors, offering insights into the dynamic trade-offs and emphasizing the need for careful decision-making and risk management strategies. Understanding and effectively managing these tensions and trade-offs are crucial for nuclear power plant operators. By leveraging the insights from this model, organizations can enhance their safety practices, optimize operational decisions, and proactively mitigate risks. This research contributes to the broader understanding of nuclear power plant operation dynamics and provides valuable guidance for maintaining a high nuclear safety and electricity generation performance.

Keywords: nuclear safety management, nuclear power plant, system dynamics.

1. Introduction

The study of nuclear power plant safety management is of utmost importance due to the potential risks and consequences associated with nuclear energy. Traditionally, the factors influencing safety management have been studied in isolation, without considering their interconnectedness and integration into a systemic framework. This novel approach, as highlighted by NEA (2022) and Waterson et al. (2022), recognizes the need to understand the interactions and interdependencies among the factors that ensure effective safety management.

The work of Acuña, Giménez, and Sánchez (2023a) addresses this gap by presenting a system dynamics conceptual model that captures the dynamics of the various factors involved in nuclear safety management. By utilizing the technique of system dynamics, the model provides a comprehensive and holistic understanding of the complex dynamics at play

within the nuclear power plant operating organization environment.
This research contributes to the field of nuclear safety management by offering a detailed causal model that considers the interplay of factors such as human, technological, organizational and environmental ones. The utilization of causal loops enables the identification of feedback mechanisms and the examination of the system's behavior over time. By adopting a systems thinking perspective, this study enhances our understanding of nuclear safety management and provides insights for improving the overall safety performance of nuclear power plants. The model explores the dynamics of the tradeoffs between nuclear safety and availability for electricity generation in a nuclear power plant. Achieving and maintaining high performance in nuclear safety is of paramount importance to prevent accidents and protect the integrity of the reactor core. However, it is equally crucial to ensure the availability and efficient generation of electricity to meet the energy demands of society.

2. Methodology and tools used.

The methodology applied utilizes a qualitative approach based on Sterman (2000) causal loop diagram development. Additionally, systems mapping approach technique, as outlined by Barbrook-Johnson and Penn (2022), is used to identify causal elements within the model.
Each conceptual causal loop from Acuña, Giménez, and Sánchez's (2023a) model is broken down into smaller causal units based on the postulated behavior. This breakdown is supported by a literature review and semi-structured interviews with nuclear industry experts, including operators, managers, regulators, and academics. For detailed interview questions, please refer to https://tinyurl.com/48f67rst.
VENSIM PLE+ software is employed for graphical representation of the causal diagrams, following Sterman's (2000) notation guidelines.

3. Conceptual model developed in previous works

The conceptual model by Acuña, Giménez, and Sánchez (2023a) proposes the following hypothesis: "the safe generation of electrical energy is determined by the interaction of human, technological, organizational, and environmental subsystems." Eight causal loops were developed (see Fig. 1) to model these subsystems presented in Acuña et al (2021) (see details in Table 1). Also two key performance indicators (KPI) were identified to represent the integrated system behaviour: core damage probability (for nuclear safety performance) and electricity generation load factor (for availability performance).

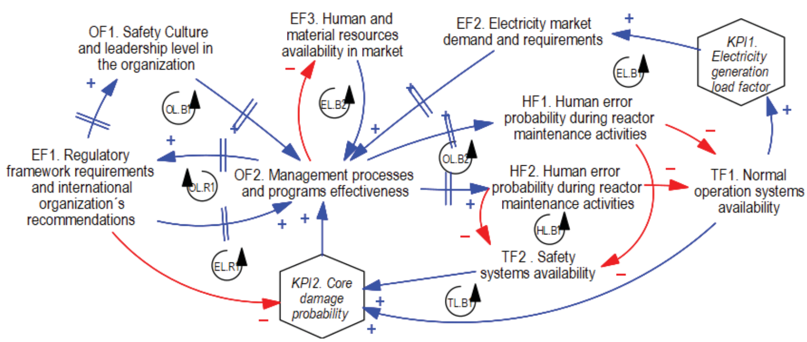

Fig. 1 Conceptual causal model. Source: Acuña, Giménez and Sánchez (2023a)

Table 1 Conceptual model developed in previous works. Source: Acuña, Giménez and Sánchez (2023a)

Subsystems	Causal loops	Denomination	Comprises a set of actions and decisions regarding
Environmental	EL.R1	Nuclear industry regulations	National regulator, the nuclear industry international organizations (International Atomic Energy Agency - IAEA, World Association of Nuclear Operators – WANO mainly) and the nuclear reactor operating organization (NROO) to establish, monitor, and comply with safety standards.

	EL.B1	Electricity market dependency	The wholesale electricity market and the NROO to demand and supply electricity.
	EL.B2	Supplier market dependency	The supplier market agents (employment, materials and, services market) and the NROO.
Organizational	OL.B1	Safety culture and leadership	The development and sustainability of individual's behaviour related to safety and the commitment to it.
	OL.B2	Human resources development	Training and recruitment of qualified staff to perform operations, maintenance, managerial and support activities.
	OL.R1	Safety Management System	The safety management system processes and programmes taken by the managerial and support staff.
Human	HL.B1	Human reliability	The plant operation carried out by operations and maintenance staff.
Technological	TL.B1	Systems plant availability	A set of actions (passive or active) taken (automatically or manually) by the nuclear reactor normal operation systems and, safety systems.

4. Results

In this section, we present the outcomes of the modeling process and demonstrate its alignment with the underlying framework that serves as the foundation for its architecture. The conceptual causal loops introduced earlier are meticulously analyzed and deconstructed into their constituent causal elements, allowing for a comprehensive understanding of the dynamic behavior within each loop. This breakdown enables us to trace the causal relationships and interactions that drive the system dynamics, shedding light on the intricate mechanisms at play. By dissecting these causal elements, we gain insights into the underlying factors and feedback loops that influence the behavior of the system, facilitating a deeper exploration of its complexity. Through this detailed examination, we enhance our understanding of the intricate dynamics within each conceptual causal loop and further establish the traceability of the model to the overarching framework. For more details, please see Fig. 2.

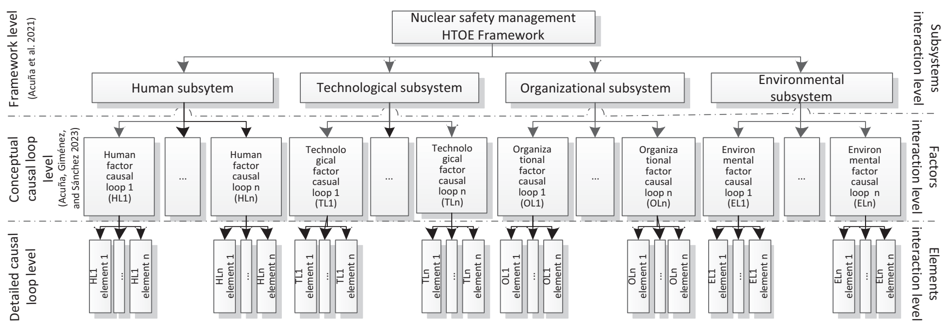

Fig. 2 Model architecture and traceability. Note: This paper aboard the "detailed causal loop level".

4.1. *Environmental causal loops*

The detail of three conceptual causal loops is developed: EL.R1 nuclear industry regulations, EL.B1 electricity market dependency and EL.B2 supplier market dependency.

4.1.1. *Nuclear industry regulations causal loop*

This section addresses modelling a distinctive feature of the nuclear industry, its high level of regulation, and external control. Based on the archetype of goal seeking of Sterman (2000) the causal loop developed models the nuclear power plant compliance of the mentioned requirements. Please see dynamics details in Fig. 33.

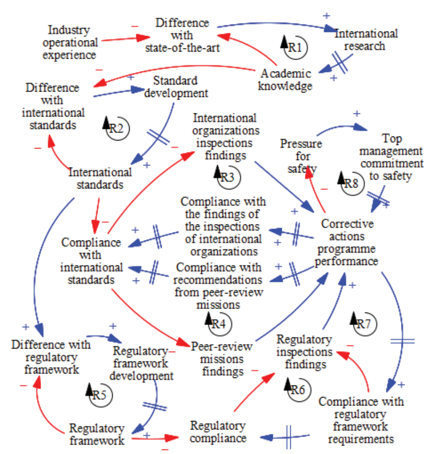

Fig. 3 EL.R1 Nuclear industry regulations causal loop.

Nuclear activities are controlled by national regulatory bodies and international organizations. Regulatory bodies have authority over permits and licenses based on national laws, while international organizations develops standards and conduct inspections according to international agreements. This ensures continuous pursuit of operational excellence through various control and verification measures. Loops R1, R2, and R5 represent the processes of development, updating, and compliance verification with nuclear safety requirements, primarily informed by industry operational experience and the latest academic knowledge. Conversely, loops R3, R4, R6, and R7 demonstrate how the operating organization incorporates necessary corrective actions to meet those requirements, based on regulator or international organization inspections and peer reviews.

4.1.2. *Electricity market dependency causal loop*

In this section, we model another environmental factor that influences the overall behavior of the model: the interaction between the operating organization of the nuclear power plant and the electricity market. It is important to note that nuclear power plants are considered base generators, similar to hydroelectric and thermal plants. Therefore, the detailed modeling of the conceptual causal loop EL.B1 follows the archetype of goal-seeking behavior. The availability and generation of other base plants, as well as the historical availability of the specific nuclear power plant under analysis, determine the goal for plant availability and generation. Therefore, the EL.B1 loop is broken down into a single balance loop (B1). Please see dynamics details in Fig. 4.

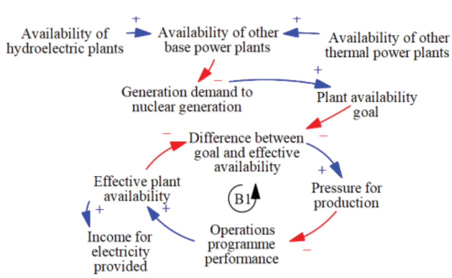

Fig. 4 EL.B1 Electricity market dependency causal loop.

4.1.3. *Supplier market dependency causal loop*

The EL.B1 causal loop establishes that the plant's availability and generation goals determine the need for material and human resources. Following Sterman's goal-seeking model (2000), the developed causal loop represents the resource acquisition process based on the discrepancy between staffing capabilities (refer to IAEA 2023) and material inventory (refer to IAEA, 2016a), influenced by budget availability (as shown in causal loops B2 and B4). Additionally, the budget availability is influenced by the economic income obtained in the previous production cycle. Please see dynamics details in Fig. 5.

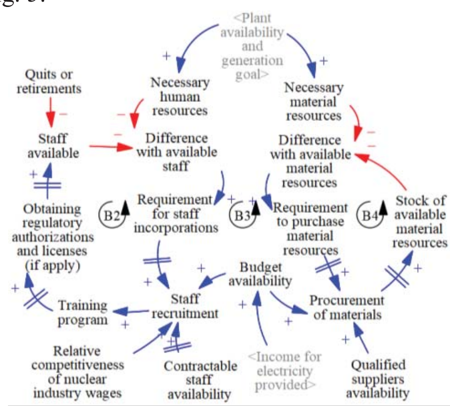

Fig. 5 EL.B2 Supplier market dependency causal loop.

4.2. *Organizational causal loops*

Three conceptual causal loops are detailed: OL.B1 (safety culture and leadership), OL.B2 (human resources development) and OL.R1 (safety management system). This model section does not provide a specific detailed modeling of the OL.B2 causal loop because its dynamics was included in EL.B2 causal loop.

4.2.1. *Safety culture and leadership management causal loop*

This section models how the organization's safety culture programme influences staff behavior. The aim is to adopt industry-best safety practices (Rollenhagen and Wahlström, 2007). The OL.B1 loop exhibits goal-seeking behaviour, because the organization assesses its safety culture performance against international best practices through self-assessments and independent reviews (R9 loop) (IAEA, 2016b; Nelson, 2010). The differences between the organization safety culture performance and the international best practices states pressure for safety that pushes the commitment to safety, leadership practices and decisions to drive safety that improves safety climate and staff commitment to safety (refers to Acuña, Giménez, and Sánchez (2023b)). Please see dynamics details in Fig. 6.

Fig. 6 OL.B1 Safety culture and leadership causal loop.

4.2.2. *Safety management system process and programmes causal loop*

This section details the OL.R1 causal loop, addressing the key elements of continuous improvement management identified by IAEA (2006). Three balanced causal loops are utilized: event management process (B7), corrective actions programme (B8), and its restrictions (B9). Please see dynamics details in Fig. 7.

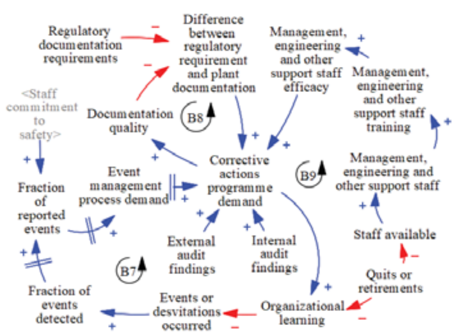

Fig. 7 OL.B2 Management system causal loop.

In Fig. 7, the B7 causal loop models the event management process, encompassing the detection and reporting of safety-significant deviations or operational events, and the organizational learning associated with event prevention (Baumont et al., 2000; Di Nardo et al., 2016; Vital T., 2021). The B8 loop captures the dynamics of the corrective actions programme, involving audit programmes and documentation management (Paradies, 2007). In the B9 loop, the effectiveness of the corrective action programme is considered, with the main determining factor being the efficacy of support staff (engineering, management, etc.), as postulated by Paradies and Skompski (2002).

4.3. *Human causal loop – Human reliability causal loop*

The detailed conceptual causal loop of HL.B1 delves into the crucial role of human factors, specifically focusing on human reliability management. The carefully constructed causal loops provide a comprehensive model for effectively managing human reliability among operators and maintenance personnel. These loops acknowledge the significant impact of performance shaping factors (PFS) on the probability of human error, as demonstrated in B10, B11, B12, and B13 loops. For further insights, consult the works of Di Nardo et al. (2015), Park, Jung, and Kim (2020), and Liu et al. (2021). It is pertinent to clarify that the dynamics of the PFS come from the detail causal loops of the conceptual causal loops (EL.B2, OL.B1 and, OL.R1).

Please see HL.B1 dynamics details in Fig. 8.

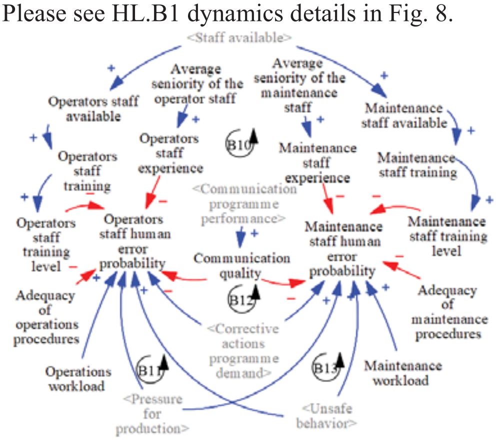

Fig. 8 HL.B1 Human reliability management causal loop.

4.4. *Technological causal loop - Systems plant availability causal loop*

This section provides a detailed breakdown of the TL.B1 causal loop into three balanced causal loops: B14, B15, and B16. Causal loop B14 explores the impact of operational performance on reactor availability. Causal loop B15 examines the connection between the human reliability (described in the HL.B1 causal loop) and system failures, as well as the performance of the systems reliability programme. Causal loop B16 illustrates the causal relationship between human error probability in operations and maintenance and the occurrence of transient states and unplanned SCRAM events (Chen, 2005).

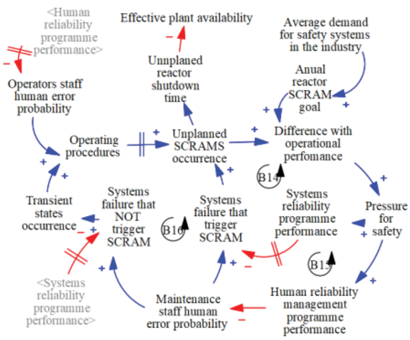

Fig. 9 TL.B1 Systems plant availability causal loop.

4.5. System key performance indicators

In this section, the model postulates the convergence of the dynamics presented previously in the two (KPI) resulting feedback within the system.

Firstly, we provide an analysis of the "electricity generation load factor" key performance indicator is examined, taking into account the influence of regulatory and international standards, as well as the occurrence of unplanned SCRAM events. This provides a comprehensive perspective on ensuring safe electricity generation. Please see details in Fig. 10.

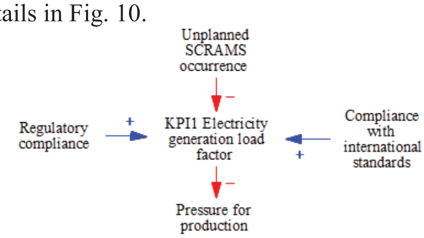

Fig. 10 Electricity safe generation performance.

Following the "core damage probability" KPI is detailed. In addition to the conventional approach (as described by Beutler et al., 2001, and Chen, 2005), our proposal takes into account the influence of organizational performance on the impact of technology failures that compromise safety barriers and human errors that pose challenges to these barriers (refer to Fig. 10). Organizational performance, represented in the model by the safety culture programme performance and safety management performence (sintetized in the corrective actions programme performance and human reliability programme performance), is hypothesized to amplify or mitigate the effects of technological failures and human errors. The model incorporates organizational performance, enhancing the understanding of core damage probability and highlighting the interplay between technology, human factors, and organizational factors in nuclear plant safety presented in previous causal loops. Please see details in Fig. 11.

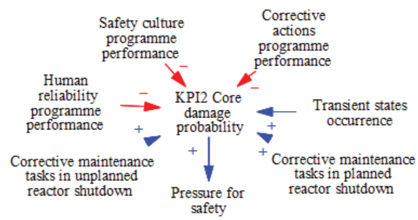

Fig. 11 Core damage frequency.

By taking into account the impact of regulatory and international standards, the research underscores the significance of adhering to these guidelines to ensure the secure generation of electricity.

Moreover, in line with WANO's operational nuclear safety performance indicators (see (WANO 2020)), the study acknowledges the importance of unplanned SCRAMS events, which entail the abrupt shutdown of a reactor. By integrating the consequences of these events into the performance variable, the research emphasizes the necessity for effective measures to handle and mitigate such incidents. This encompasses the maintenance and enhancement of the reliability and functionality of safety systems and processes to guarantee the safe generation of electricity.

5. Conclusions

A detailed causal model was presented to explore nuclear safety management in the operation of a nuclear power plant. The model highlighted the significance of loops related to regulatory compliance, verification processes (inspections and audits), safety management systems, and continuous improvement programs in reinforcing nuclear safety and facilitating its management.

Taking a broader perspective, it can be inferred that the nuclear industry's safety levels are not solely reliant on robust technological design and system reliability. Solid organizational and institutional mechanisms, coupled with constant monitoring, play a crucial role in enhancing nuclear safety performance. The model also underscores the dependency of nuclear power plants on highly specialized staff, whose replacement is not immediate due to labor market constraints and the time required for training.

The model reveals a relationship between the key performance indicators "core damage probability" and "electricity generation load factor" in nuclear power plants, highlighting a trade-off between safety and availability in electricity generation. the core damage probability KPI focuses on evaluating the nuclear power plant safety and represents the likelihood of events that could cause damage the reactor core. Its objective is to minimize risks and ensure that necessary measures are taken to prevent core damage.

On the other hand, the electricity generation load factor KPI emphasizes operational efficiency and maximizing electricity production. It measures the proportion of a nuclear plant's total generation capacity effectively utilized over a specific period. A high load factor indicates efficient operation and high performance in electricity generation.

However, there exists an inherent trade-off between these two KPIs. In some cases, maximizing the electricity generation load factor may require more intensive operations, which can increase the risk of accidents or situations that could compromise plant safety and consequently raise the core damage probability. Conversely, solely focusing on minimizing core damage probability may lead to a reduction in the electricity generation load factor due to more stringent safety measures and operational limitations.

The strength of this research lies in its comprehensive and systemic approach, integrating various elements such as human factors, technology, organization, and the environment to prevent core damage and ensure safe electricity generation. However, it is important to acknowledge the limitations of this study. The qualitative approach employed may not capture the full complexity of system dynamics. Additionally, other crucial aspects of nuclear safety management, such as plant modifications and fuel management are not analyzed.

Future research could benefit from incorporating quantitative analysis methods to enhance the understanding of nuclear safety management.

Acknowledgement

The authors of this paper thank all the nuclear industry experts (nuclear reactors operators, managers, and support staff, regulators and, IAEA and WANO officers) who participated in the interviews. The authors also thank the M.Sc. Mariela Grinberg for her expert comments to improve this work.

References

Acuña, G., Giménez M., and Sánchez M. (2020). “Nuclear Safety Management after Fukushima Accident . A Systematic and Critical Review of the State of the Art.” In International Conference of Production Research. Bahía Blanca, 9, 10 y 11 de Diciembre., 1–15.

Acuña, G., M. Giménez, and Sánchez M. (2023a). “System dynamics-based conceptual model for nuclear safety management in nuclear power plants.” In Procedings of the 2023 System Dynamics Conference - Chicago USA.

Acuña, G., Giménez M., Caputo, M., and Sánchez M. (2021) A framework to understand and model the dynamics of safety management in the operation of a nuclear reactor. In proceedings of “The 15th International Congress of the International Radiation Protection Association” – Bahía Blanca, Argentina

Acuña, G., Giménez M., and Sánchez M. (2023b). “Safety Culture and Nuclear Safety Management . Analysis of the Relationships of Its Variables through a Bibliographic Review and AHP.” In Proceedings of the 33rd European Conference On Safety And Reliability (ESREL) 3rd September – 8th September 2023, 1–8. Southampton, England: Research Publishing Services, Singapore.

Barbrook-Johnson, P., and Penn A. (2022). Systems Mapping. How to Build and Use Causal Models of Systems. First edit. Cham, Switzerland: Palgrave Macmillan Cham. https://doi.org/10.1007/978-3-031-01919-7_2.

Baumont, G., F. Ménage, J. R. Schneiter, A. Spurgin, and A. Vogel. (2000). “Quantifying Human and Organizational Factors in Accident Management Using Decision Trees: The HORAAM Method.”

Reliability Engineering and System Safety 70 (2): 113–24. https://doi.org/10.1016/S0951-8320(00)00051-X.

Beutler, R, G Schoen, R Schulz, and K Theiss. (2001). "Risk-Based Analysis of Operational Events for Swiss Nuclear Power Plants." In OECD/NEA Workshop on Precursor Analysis 28 – 30 March 2001, Brussels, Belgium, 1–11.

Chen, Haibo. (2005). "Identification of Good Practices in the Operation of Nuclear Power Plant. Ph. D. in Nuclear Science and Engineering Thesis." Massachusetts Institute of Technology.

Di Nardo M., Madonna M., Santillo L. (2016) "Safety Management System: a system dynamics approach to manage risks in a process plant". International Review on Modelling and Simulations, Vol. 9, N. 4.

Di Nardo M., Gallo M., Madonna M., Santillo L. (2015). "A Conceptual Model of Human Behaviour in Socio-technical Systems" In: Fujita, H., Guizzi, G. (eds) Intelligent Software Methodologies, Tools and Techniques. SoMeT 2015. Communications in Computer and Information Science, vol 532. Springer, Cham. https://doi.org/10.1007/978-3-319-22689-7_46

IAEA (2006). "IAEA-TECDOC-1491 Management of Continual Improvement for Facilities and Activities. A Structured Approach." Vienna, Austria.

IAEA (2016a). "IAEA Nuclear Energy Series No. NP-T3.21 Procurement Engineering and Supply Chain Guidelines in Support of Operation and Maintenance of Nuclear Facilities." Vienna, Austria. http://www.iaea.org/books.

IAEA (2016b). "IAEA Safety Report Series No. 83 - Performing Safety Culture Self-Assessments." Vienna, Austria. www.iaea.org/books.

IAEA (2023). "IAEA Nuclear Energy Series NG-G-2.1 Rev.1 Managing Human Resources in the Field of Nuclear Energy." IAEA Nuclear Energy Series NG-G-2.1 Rev.1. Vol. 4. Vienna, Austria.

Liu, Jianqiao, Yanhua Zou, Wei Wang, Li Zhang, Xueyang Liu, Qianqiao Ding, Zhuomin Qin, and Marko Čepin. 2021. "Analysis of Dependencies among Performance Shaping Factors in Human Reliability Analysis Based on a System Dynamics Approach." Reliability Engineering and System Safety 215 (June). https://doi.org/10.1016/j.ress.2021.107890.

NEA. (2022). "Human and Organisational Performance in Nuclear Installations."

Nelson, W.R. (2010). "Building and Assessing an Effective Safety and Performance Culture." In 10th International Conference on Probabilistic Safety Assessment and Management 2010, PSAM 2010, 3:2103–11.

Paradies, Mark. (2007). "Improving an Existing Root Cause Analysis and Corrective Action Programme." IEEE Conference on Human Factors and Power Plants, 75–77. https://doi.org/10.1109/HFPP.2007.4413183.

Paradies, Mark, and Ed Skompski. (2002). "Why People Don't Develop Effective Corrective Actions." IEEE Conference on Human Factors and Power Plants, 218–22. https://doi.org/10.1109/hfpp.2002.1042828.

Park, Jooyoung, Wondea Jung, and Jonghyun Kim. (2020). "Inter-Relationships between Performance Shaping Factors for Human Reliability Analysis of Nuclear Power Plants." Nuclear Engineering and Technology 52 (1): 87–100. https://doi.org/10.1016/j.net.2019.07.004.

Rollenhagen, C., and Wahlström B. (2007). "Management Systems and Safety Culture; Reflections and Suggestions for Research." IEEE Conference on Human Factors and Power Plants, no. May 2017: 145–48. https://doi.org/10.1109/HFPP.2007.4413196.

Sterman, J. (2000). Business Dynamics. Systems Thinking and Modeling for a Complex World. Business Dynamics. Systems Thinking and Modeling for a Complex World. First edit. New York, USA: Mc Graw Hill. https://doi.org/10.4324/9781351152723-7.

Vital, Richard Brandão Nogueira, Jefferson Borges Araujo, and Tatiane Melo Vital. (2021). "Nuclear Power Plants Event Classification Based on International Reporting System (IRS)." Brazilian Journal of Radiation Sciences 8 (3A). https://doi.org/10.15392/bjrs.v8i3a.1282.

Wahlström, B. (2018). "Systemic Thinking in Support of Safety Management in Nuclear Power Plants." Safety Science 109: 201–18. https://doi.org/10.1016/j.ssci.2018.06.001.

Waterson, P., R. Hamer, T. Jun, and A. Teperi. (2022). "Applying Adaptive Safety-Based Methods to a Real-World Nuclear Operational Event Applying Adaptive Safety-Based Methods to a Real-World Nuclear Operational Event." SSRN Electronic Journal, no. Janaury 2022: 47. https://doi.org/10.2139/ssrn.4202072.

WANO (2020) "Performance Indicators 2020.", World Association of Nuclear Operators.