System dynamics-based conceptual model for nuclear safety management in nuclear power plants

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Abstract. *The purpose of this paper is to present a model for nuclear safety management in an operational organization of a nuclear power plant, based on the HTOE (human, technology, organization, and environment) framework. The model was developed through a literature review and semi-structured interviews conducted with industry and academic experts. The causal model comprises nine distinct causal loops, each representing a crucial factor in the safety and performance of nuclear power plants. These loops include human reliability of operational and maintenance personnel, the interplay between plant safety and availability, unexpected demands on the shutdown system resulting from technological failures or transient operational states of the reactor, core damage probability, management of human and equipment reliability, safety culture and leadership, reliance on suppliers and the electricity market, and nuclear industry regulation.*

1 Introduction

Nuclear safety management comprises a set of theories and practices adopted and applied by nuclear facilities operating organizations to prevent events that may lead to radiological consequences for workers, the public, and the environment.

In the case of a nuclear power plant operation, the events to prevent are those that lead to reactor core damage and unplanned release of radionuclides (to its containment and to the atmosphere). To prevent this, nuclear power plant operating organizations adopt prevention and safety practices established and required by the regulatory bodies, international organizations, or best practices of the operational experience shared by other organizations. Practices comprise engineering, management, and organizational practices.

In compliance with these practices, the nuclear industry aims to be classified as ultra-safe industry (Amalberti, 2001). This implies that the industry operates with a risk of “$5x10^{-7}$ disastrous accident per safety unit in the system" (Amalberti, 2001). The value obtained by this industry in this risk metric is accompanied by the achievement of an average plant availability of the order of 80%, with an annual global production of electricity (for 2021) of 2653.1 TW.h (around a 10% of the global electricity generated in the world) (IAEA, 2022a).

Given the socio-technical nature of the mentioned practices, the disciplines that contribute with theories or approaches are numerous and from diverse areas of academic knowledge including operational nuclear safety engineering, operations management, equipment reliability, human reliability, process management, and strategic management. This mix of converging specializations determines in practice a very complex system to manage, not only due to the technological complexity of this industry but also due to the diversity of issues that converge in decision-making processes to achieve the organizational objectives.

Considering the above mentioned disciplines involved in the nuclear power plant operation management the challenge is not only to minimize the risk of accidents but also to minimize the unplanned production interruptions due safety issues (Baumont et al., 2000; Meshakti, 2007) and manage the complex relationships between plant performance, safety performance, regulations compliance and business continuity (Hansen & Golay, 1997).

Considering that the main objective of a nuclear power plant operating organization is the safe generation of electrical power we pose as a research question what trade-off dynamics arise in the organization's management to achieve high performance in safety and production simultaneously? There is little research that addresses this problem from a systemic and comprehensive point of view (Acuña et al., 2020).

There is a research opportunity whose challenge lies in systematically integrating and describing how different socio-technical dynamics contribute to achieve the aforementioned performance metrics. Addressing these opportunities would allow the development of new holistic approaches that could assist informed decision-making processes associated with the nuclear safety management of a nuclear power plant operating organization.

This work develops and presents a conceptual and qualitative model of the nuclear safety management dynamics of a generic nuclear power plant operating organization based on system dynamics methodology (Forrester, 1961; Sterman, 2000). The model is based on the MTOE framework of Acuña, Giménez, Caputo, et al. (2021), mapped according to Barbrook-Johnson & Penn (2022) and elaborated based on a literature review and semi-structured interviews with experts of the nuclear industry.

2 Research objectives

The research objectives are the following:

- Establish the basis to understand the general dynamic of the nuclear safety management of a nuclear power plant operation.

> The dynamic hypothesis is "The generation of electrical energy in a safe manner is determined by the interaction of the elements of the human, technological, organizational, and environmental subsystems of a nuclear power plant operating organization NPPOO"

- Develop and present a conceptual and causal model on the management of nuclear safety of a nuclear power plant organization. Develop the model based on the MTOE framework by applying the qualitative methodology of causal loops of systems dynamics.
- Identify the constitutive elements of the model and define their causal relationships to describe the general dynamics of the system qualitatively. Lay the foundations for detailed modeling and quantitative modeling of the system.

3 Methodology and data source

The methodology used corresponds to modeling complex systems through system dynamics (Forrester, 1961), applying the qualitative modeling stage by developing causal loop diagrams according to Sterman (2000).

The nuclear safety management of a nuclear power plant operating organization is modeled based on the MTOE framework (Acuña, Giménez, Caputo, et al., 2021).

For this, a causal loop is modeled based on the scope and possible behavior of each MTOE subsystem. The causal loop was elaborated based on literature review and semi-structured interviews conducted with experts from the nuclear industry (Hernandez Sampieri et al., 2010). The dynamic hypothesis is formulated considering the operational and business aspects of the mentioned type of organization.

For the literature review, as a primary source, papers that studied the nuclear industry and particularly papers that modeled safety management were considered. When a paper that addressed the specific aspect with the aforementioned subject was not found, papers that studied or modeled high-reliability industrial organizations (HRIO) were consulted, adapting their contributions to the specificity of the nuclear industry.

The experts interviewed were nuclear power plant operators, middle managers and managers, regulators, agents from international organizations (International Atomic Energy Agency –IAEA, and World Association of Nuclear operators –WANO) and academics. The questions that guided the semi-structured interviews were:

- From the perspective of your expertise or area, how is the organization's nuclear safety performance affected or improved?
- What agents or elements of your area interact with others? How do they interact with other areas?
- What behaviors can be observed or described from the identified agents or elements?

Also, systems mapping approach of Barbrook-Johnson & Penn (2022) was used to identify the constituent elements of the subsystems of the MTOE framework. This identification is done by breaking down each subsystem into smaller units by applying analytical reduction. Each smaller unit is called a factor. Considering by factor, each unit with a behavior with independent causes of others of the same subsystem. All the processes were supported by the reviewed literature review.

4 Results

4.1 Literature review

4.1.1 Previous system dynamics works on nuclear industry and nuclear power operation

The documents presented in Table 1 were recovered after conducting a bibliographic search using the Scopus academic search engine and the IAEA technical-academic search engine, INIS. The string "system dynamics" AND "nuclear power plant" AND "operation" was used to search in titles, abstracts, or keywords. Twelve works were recovered. Duplicates papers and those related to modeling electrical networks and developing nuclear industry policies were excluded. Nine papers were analyzed to identify the object of analysis, the type of model, and type of publication. Regarding the type of models, a classification was made based on qualitative models (causal loop diagram), quantitative models (Stock and flow diagram), or both (Coyle, 2000).

Table 1 Literature review on system dynamics applied to nuclear industry and nuclear power plant operation.

#	Papers	What models?	Type of models		Published in		
			Qualitative	Quantitative	Journal	Congress	Thesis
1	(Hansen & Golay, 1997)	Neutronics aspects, nuclear power plant construction project and the basic dynamics of a plant's operation.	√	√	√	-	-
2	(Chen, 2005)	Good operating practices of a nuclear power plant.	-	√	-	-	√
3	(Chu, 2006b)	Human error effect on the operation of a nuclear power plant.	-	√	-	-	√

4	(Woo & Kim, 2012)	Risk assessment of a nuclear power plant power uprate.	√	√	√	-	-
5	(Woo & Lee, 2012)	Seismic safety assessment of a nuclear power plant.	√	√	√	-	-
6	(Woo, 2015)	Economics and safety aspects of power uprate of a nuclear power plant.	√	√	√	-	-
7	(El-Sefy et al., 2019)	Thermahidraulics process in the operation of a nuclear power plant.	-	√	√	-	-
8	(Hossen & Hossain, 2021)	Causes of Fukushima Daiichi nuclear power plant unit-1 accident.	√	-	√	-	-
9	(Wu et al., 2022)	Nuclear power plant operators behavior	√	√	√	-	-
		Total	5	7	6	-	2

Given the few previous works, much research has yet to be carried out applying system dynamics to nuclear power plant operations, particularly nuclear safety management. Three papers include models on the operation of a nuclear power plant considering comprehensive operational aspects: Chen (2005), Chu (2006) and Hansen & Golay (1997). It is worth highlighting that the studies conducted by (Chen, 2005), Chu (2006) and Wu et al. (2022) have focused solely on human and technological factors without addressing organizational or environmental aspects. On the other hand, Hansen and Golay (1997) have not modeled organizational factors, and only presented some qualitative aspects regarding the influence of the environment. Furthermore, their plant technological models have very limited details. The remaining five investigations have been dedicated to modeling the physical processes of plant operations (El-sefy et al., 2019; Woo & Kim, 2012), seismic safety evaluations (Woo & Lee, 2012), economic and safety aspects of power uprate of a nuclear power plant (Woo, 2015), and the analysis of the causes of the Fukushima Daiichi accident by Hossen and Hossain (2021).

One aspect to highlight from the literature review is that the qualitative modeling using causal loops (used in five documents) is less used than quantitative modeling (used in seven documents). The recovered documents were published mainly in journals (six papers) and the remaining two in masters and doctoral theses, respectively.

The Table 1 shows a significant research gap in applying system dynamics to the field of nuclear power plant operations, particularly in the context of nuclear safety management. Only a few previous works have explored this area, with limited focus on comprehensive operational aspects.

Overall, the findings highlight the need for further research in applying system dynamics to nuclear safety management, encompassing a comprehensive range of factors and adopting both qualitative and quantitative modeling approaches. The existing studies provide some insights into the operation of nuclear power plants but lack a holistic understanding of organizational and environmental aspects, indicating a potential avenue for future investigations. Moreover, the dominance of quantitative modeling suggests a potential opportunity to explore the application of qualitative modeling techniques, to gain a deeper understanding of the complex dynamics involved in nuclear safety management.

4.1.2 Previous system dynamics works in safety management

As observed in the previous section, the history of the application of SD to the nuclear industry, the operation of nuclear reactors, and the management of their nuclear safety is scarce. In this section, there is a systematic review of the literature regarding safety management modeling based on SD in the conventional industry. This review is relevant not only because of the limited background in the nuclear industry but also because the organization and management in the nuclear industry have some similarities with the process industry (chemical and petrochemical (Hofmann et al., 1995)) and other HRIO (such as aeronautics, military, and aerospace (Amalberti, 2009)). These similarities may be considered as valid for the nuclear industry, when the application of the particular regulatory framework and the management of very specific risks (related to nuclear technology and radiological aspects) are contemplated in its adaptation (Baumont et al., 2000).

The search string “system dynamics” AND “safety management” was used in the abstract, title, and keywords of the Scopus database. A total of fifty-four documents were obtained, and those related to service, health, and arts industries were discarded. Twenty-four documents were described by the type of industry[1], the unit of analysis, the type of model (qualitative, quantitative, or both) and, the publication type (journal, congress or book). Folloqwing Table 2 summarize the analysis.

Table 2 Literature review on system dynamics applied to model safety management in HRIO.

#	Papers	Industry	What models?	Type of model		Published in		
				Qualitative	Quantitative	Journal	Congress	Book
1	(Cooke, 2003a)	Mining	Mining company industrial safety management system.	√	√	√	-	-
2	(Cooke, 2003b)	Generic	Industrial incidents occurrence and an organizational learning system.	√	√	-	√	-
3	(Dulac, Leveson, Zipkin, Cutcher-Gershenfeld, et al., 2005)	Aerospatial	NASA's manned space program and the Columbia accident.	√	√	-	√	-
4	(Cooke & Rohleder, 2006)	Generic	An incident learning system	√	√	√	-	-
5	(W. Zhang et al., 2008)	Aviation	Air control safety management system.	√	√	-	√	-
6	(He, 2010)	Mining	Mining company safety management system.	-	√	√	-	-
7	(He, 2011)					√	-	-
8	(Y. J. Liu et al., 2013)	Mining	Mining company safety management system.	√	-	√	-	-
9	(D. Zhang et al., 2013)	Aviation	Aviation service safety culture.	-	√	√	-	-
10	(Zhou et al., 2014)	Construction	A construction project stakeholder’s behavior.	√	√	-	√	-
11	(R. H. Taylor et al., 2015)	Generic	Organizational and cultural accidents precursors.	√	-	√	-	-
12	(Di Nardo et al., 2016)	Chemical	Process plant safety management system.	√	-	√	-	-
13	(Abniki et al., 2017)	Generic	Performance and safety culture in occupational accidents.	√	√	-	√	-
14	(Baraftabi et al., 2017)	Generic	Occupational health and safety management system.	√	-	-	√	-
15	(C.-Y. Li et al., 2018)	Chemical	Chemical plant safety management system.	-	√	√	-	-

[1] Some papers were classified under the term "generic industry" due to the lack of specificity in production details or technological aspects. Despite that, they are still valuable for this work because they model elements applicable and pertinent to the nuclear industry organizational factors, such as event management and organizational and cultural factors, aspects coincident with the surveyed in (Acuña et al., 2022).

16	(Bastan, Groesser, et al., 2018)	Generic	Safety, occupational health, and accident management system.	√	-	-	√	-
17	(C. Li & Li, 2017)	Chemical	Process industry safety management system.	√	√	-	√	-
18	(Mohammadi et al., 2018)	Construction	Safety archetypes for construction projects.	√	√	-	√	-
19	(Kontogiannis & Boukas, 2019)	Generic	Safety and production management system and its organizational trade-offs.	√	√	-	√	-
20	(Boukas & Kontogiannis, 2019)					-	√	-
21	(Garbolino et al., 2019)	Chemical	Chemical plant and its control system. Technology oriented.	√	√	-	-	√
22	(Bouliz & Garbolino, 2019)	Chemical	Chemical plant safety management activities include human, technological and organizational factors.	√	√	-	-	√
23	(Di Nardo, Madonna, Murino, et al., 2020)	Chemical	Bhopal accident dynamics, including technological, human, organizational and economic factors.	√	√	-	√	-
24	(Di Nardo, Madonna, Gallo, et al., 2020)	Chemical	Plastic production plant operation in a fire risk scenario.	√	√	-	√	-
			Total	21	19	9	13	2

Regarding the industry under study, the documents focus on developing models for the chemical industry (seven papers) and models of the so-called "generic industry" (seven papers).

Regarding the typology of developed models, five papers presented only qualitative models, two developed only quantitative models, and sixteen developed both types of models. The retrieved documents were primarily presented in conferences (thirteen papers), followed by publications in journals (nine papers), and two in book chapters.

One inference that can be drawn from this paragraph is that there is a variety of approaches used in safety management modeling. Some studies focus solely on qualitative models, suggesting a more descriptive or conceptual approach to safety. Other studies focus solely on quantitative models, indicating a more analytical or numerical approach to safety. However, the majority of studies use a combination of both approaches, indicating a tendency to use models that leverage both qualitative and quantitative aspects to understand and improve safety management.

Considering previous research on safety management modeling in the HRIO industries when modeling safety management in the nuclear industry could be pertinent due to the shared elements and the absence of nuclear safety management research applying system dynamics, as mentioned in section 4.1.1. Both type of industries deal with hazardous industrial elements and processes, where errors or incidents can have severe implications for human safety and the environment. Additionally, they are subject to strict regulations and standards to uphold safety in their operations. Also HRIO industries must implement robust safety management systems and risk assessment processes to identify and mitigate potential hazards. They also require a strong safety culture, where training, technical competence, and risk awareness are crucial in preventing incidents.

It is important to note that while there are specific differences between the two industries, such as the characteristics and effects of the materials used, the general principles of safety management are transferable and can enhance the modeling of nuclear safety management.

The modeling work in safety management within the chemical (seven documents) or generic industry (six) can help establish conceptual frameworks that are applicable and relevant to the nuclear industry models.

4.2 MTOE framework bases and conceptual dynamics for modeling

The MTOE framework is a specific framework for the modeling of nuclear safety management of a nuclear power plant organization. This framework states that the nuclear safety management of an operating organization is determined by the interaction of four subsystems: the human factors subsystem, the technological subsystem, the organizational subsystem and the environment subsystem.

The MTOE framework proposes the integration of the dynamics of the subsystems mentioned above depending on the actions and decisions taken by its elements or agents. Table 3 shows the scope and detail of the elements and agents behaviors considered for the model. This detail was elaborated based on literature review.

For practical implications of this paper, the MTOE framework is renamed into HTOE (human, technological, organizational, and environmental).

Table 3 HTOE subsystems scope and their behaviors consider in the model. Based on (Acuña, Giménez, Caputo, et al., 2021) and literature review.

HTOE Subsystem		Scope	Behaviors consider to model	
#	Name		Description	References
H	Human	Operators and maintenance personnel human actions and decisions.	Behavior of individuals who operate or maintain the plant: human actions and decisions	(Fernandes et al., 2020; IAEA, 2001a; Meshakti, 2007; Morais et al., 2018)
T	Technological	Reactor normal operation, and safety systems and components: technological actions	Behavior of technological and physical systems: availability for technological actions (for active systems).	(Acuña, Giménez, Sánchez, et al., 2021; IAEA, 2007, 2014; Lipár, 2012; Sui et al., 2018)
O	Organizational	Human decisions of the people who provide support to the operation and management of the plant.	Behavior of organizational factors: human actions and decisions associated with the programs and processes of the safety management system and safety culture program.	(Acuña et al., 2022; Ghosh & Apostolakis, 2005; Hyvärinen et al., 2022; IAEA, 2022b; INSAG, 2017; Jacobs et al., 1992; Young, 2017)
E	Environmental	Decisions related to external market agents or entities that are in contact with the organization managers.	Behavior of regulatory and market factors: human decisions associated with regulators, international organizations and market agents.	(IAEA, 2001b, 2022b; INSAG, 2017; Vaurio, 1998)

4.3 Dynamic hypothesis and conceptual model description

Based on the identification of the behaviors of the agents and elements identified and presented in Table 3, the dynamic hypothesis for modeling is postulated as: "The generation of electrical energy in a safe manner is determined by the interaction of the elements of the human, technological, organizational, and environmental subsystems of a nuclear power plant operating organization."

The dynamic hypothesis is based on the main management objective of an operative nuclear power plant: the safe generation of electrical energy. In other words, the generation of electrical energy prevents those events that make the plant unavailable or damage the reactor core. Considering the premise of the HTOE (that the interaction of its four subsystems determines the nuclear safety management of an operating organization), the dynamic hypothesis of the model is defined as "the generation of electrical energy in a safe manner is determined by the interaction of the elements of human, technological, organizational and environmental subsystems".

Subsequently, taking into account the scope of the HTOE subsystems and the overarching modeling hypothesis, the interactions and potential interfaces among the agents and elements of these subsystems were elucidated. This survey was conducted by identifying documents incorporating relevant safety requirements from the International Atomic Energy Agency (IAEA), as well as conducting interviews with subject matter experts. Drawing upon the insights garnered from this investigation and substantiated by pertinent literature, the following interactions and interfaces were discerned:

- The environmental subsystem interacts with the organizational subsystem through documented requirements, event reports, and resource demand and provision requests (IAEA, 2016b requirements 5) and (IAEA, 2016c requirements 5 and 6).
- The organizational subsystem interacts with the human and technological subsystems.
    - It interacts with the human subsystem through safety management processes and programs related to human performance and continuous improvement (IAEA, 2016b requirements 12, 14) and (IAEA, 2016d requirements 2, 5 and 7).
    - It interacts with the technological subsystem through organization management processes and programs related to plant asset management, including normal operation or safety systems and components (IAEA, 2016b requirement 1) and (IAEA, 2016d requirements 14 and 31).

As a result of analyzing the mentioned requirements, the interview answers, considering the systems thinking approach applied to the nuclear industry (Wahlström, 2018), as well as the experience of a part of the research team in the nuclear field, Figure 1 has been developed. This figure illustrates the macro-interactions and interfaces of the HTOE subsystems in a diagram.

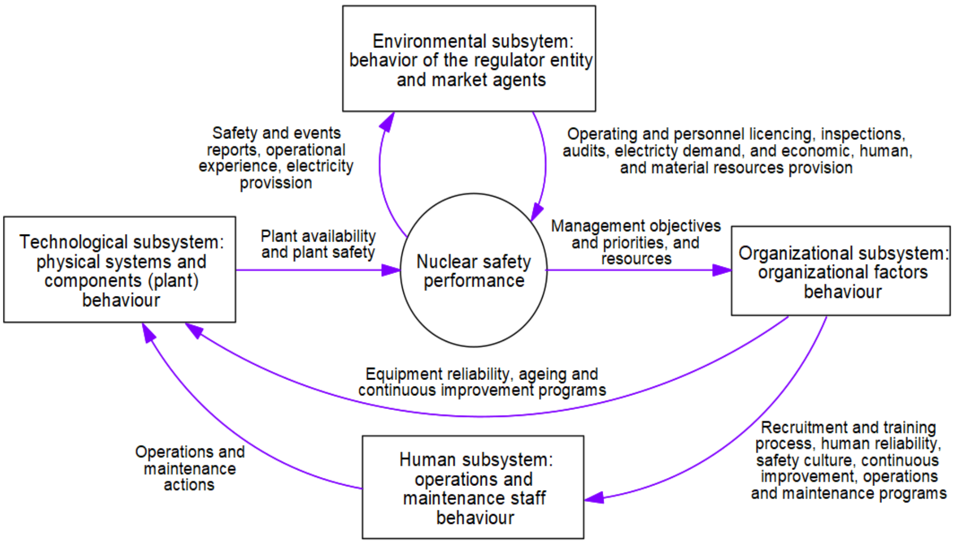

Figure 1 Interactions and interfaces between the subsystems of the HTOE. Source: developed by the authors.

4.4 Causal Loop diagram

In this section, the results of developing the causal loop diagram are presented.

Based on the collected and postulated elements presented in Table 3 and Figure 1, each HTOE subsystem was further disaggregated into smaller units to facilitate the analysis and approach to the overall system behavior. These units were called factors. The identification or definition of each factor aims to disaggregate the constituent elements of each subsystem. In addition, this identification and definition aims to disaggregate the behavior of the constituent elements of each subsystem. This step was necessary to facilitate the identification of the dynamics to be modeled. For this nine factors were identified supported in literature review and the findings of the previous expert interviews:

- The Human subsystem was broken down into two factors: HF1 (human factor 1) human error probability during reactor maintenance activities and HF2 human error probability during reactor maintenance activities.
- The technological subsystem was broken down into two factors: TF1 (technological factor 1) normal operation systems availability and, TF2 safety systems availability.
- The organizational subsystem was broken down into two factors: OF1 (organizational factor 1) Safety culture and leadership level in the organization and, OF2 management processes and programs effectiveness.
- The environmental subsystem was broken down into three factors: EF1 (environmental factor 1) compliance with the regulatory framework requirements and international organizations' recommendations, EF2 electricity market demand and requirements and, EF3 human resources and materials availability in market.

Next, in Table 4, the definitions, research sources (literature or expert interviews), and literature background of their modeling with system dynamics for the proposed factors are presented.

Table 4 HTOE subsystems factors identification and its consideration for the model

HTOE subsystems		**Constitutive factors of the subsystems**			**Research source**		**Literature background of their modeling with system dynamics**
#	**Name**	**Code**	**Factor**	**Definition**	**Literature**	**Expert interviews**[2]	
H	Human	HF1	Human error probability during reactor maintenance activities.	Human error effect of the plant maintenance activities.	√	√	(Bouliz & Garbolino, 2019; Chu, 2006b)
		HF2	Human error probability during reactor operation.	Human error effect on the operation of the reactor.	√	√	(Chu, 2006b; J. Liu et al., 2021)
T	Technological	TF1	Normal operation systems availability	Effect of system failures in plant availability.	√	-	(Bouliz & Garbolino, 2019; Chen, 2005; Chu, 2006a; Garbolino et al.,

[2] In this section, the responses obtained from the semi-structured interviews with experts were also used.

							2019; Kontogiannis & Boukas, 2019)
		TF2	Safety systems availability	Effect of safety system failures in plant safety.	√	√	(Acuña, Giménez, Sánchez, et al., 2021; Hossen & Hossain, 2021)
O	Organizational	OF1	Safety culture and leadership level in the organization	Effect of organizational practices to promote and sustain levels of safety culture following world best practices and to promote priority and commitment to safety.	√	√	(Dulac, Leveson, Zipkin, Friedenthal, et al., 2005)
		OF2	Management processes and programs effectiveness.	Safety management system processes and safety culture programs efficacy.	√	√	(Bastan, Baraftabi, et al., 2018; Carhart, 2009; Di Nardo et al., 2016; Di Nardo, Madonna, Murino, et al., 2020; Dulac, Leveson, Zipkin, Friedenthal, et al., 2005; Kontogiannis, 2012; Marais et al., 2006)
E	Environmental	EF1	Compliance with the regulatory framework requirements and international organizations' recommendations.	Effect of formal actions of the regulatory body and international organizations on organizational performance (granting licenses, permits, inspections, audits).	√	-	(Carhart, 2009; Carhart & Yearworth, 2010; Kontogiannis, 2012)
		EF2	Electricity market demand and requirements.	Market demand effect on organizational performance.	√	-	(Kontogiannis & Boukas, 2019; Turek, 1995; Woo, 2012)
		EF3	Human resources and materials availability in market.	Human and material resources availability effect for the fulfillment of the objectives of the organization.	√	√	(Cooke, 2003a), (Cooke, 2003b), (Dulac, Leveson, Zipkin, Cutcher-Gershenfeld, et al., 2005), (W. Zhang et al., 2008)

From the identification of the constitutive factors of each system, causal relationships between them were identified.

The information obtained from the interviews played a crucial role in the analysis and modeling of the links between factors, particularly in postulating their polarity and contrasting it with existing literature. During the interviews, a more detailed and contextualized understanding of the factors involved in the studied system, as well as their interactions and relationships, was obtained. The participants provided valuable insights into how they perceive and experience these factors in the specific environment. Based on these interviews, it was possible to identify behavior patterns and trends associated with the factors, which allowed for formulating hypotheses about the direction of their causal relationships. For example, by examining the participants' responses, consistent and recurring connections between certain factors could be identified, suggesting a specific polarity in the links.

However, to ensure the validity and theoretical foundation of these postulations, it was necessary to contrast them with the existing literature. A thorough review of studies, research, and academic works related to the topic was conducted to find evidence and references that supported or refuted the hypotheses. This contrast with the literature was essential to substantiate and strengthen the postulation of the polarity of the links between factors.

Based on the information presented in the previous paragraphs eight causal loops were postulated following the next detail[3,4]:

- For the environmental subsystem three causal loops were postulated, of which one is of the reinforcement type: named “nuclear industry regulations” (coded as EL.R1) and, two are of balance type: named “electricity market dependency” and, “supplier market dependency” (coded as EL.B1 and, EL.B2 respectively).
- For the organizational subsystem three causal loops were postulated, one of the reinforcement type: named “safety management system” (coded as OL.R1) and, two of balance type: named “safety culture and leadership management” and, “human resources development” (coded as OL.B1 and OL.B2 respectively).
- For the human subsystem one causal loop of balance type was postulated: named “human reliability” (coded as HL.B1).
- For the technological subsystem one causal loop of balance type one causal loop of balance type was postulated: named “systems plant availability” (coded as TL.B1)

Furthermore, in order to link the causal loops postulated and demonstrate ways of specifying the dynamics of the model, key performance indicators (KPI) are included in the modeling of the mentioned causal loops. KPI1: Electricity generation load factor” (for availability performance) and KPI2: “Core damage probability” (for safety performance).

- KPI1: “Electricity generation load factor”: This performance indicator is postulated as a business continuity merit figure that reflects the combination of nuclear safety performance and availability performance.
- KP2: “Core damage probability”: This performance indicator is postulated as a nuclear safety merit figure that reflects the combination of the probability of failure of the technological factors, considering the probability of human error (human factors) and the probability of organizational failure or error (organizational factors).

The inclusion of these key performance indicators in the causal diagram helps to better understand the interaction between different factors and components in nuclear safety management.

Firstly, the "Electricity safe generation performance" represents the primary objective of a nuclear power plant: to generate electricity safely and reliably. By including this indicator in the causal diagram, it becomes possible to analyze how different factors and elements within the nuclear safety system directly or indirectly affect the safe generation of electricity.

Secondly, the "core damage probability" is critical in nuclear safety management as it represents the risk of a catastrophic event such as core meltdown. This indicator reflects the integrity of the reactor core and the effectiveness of the barriers and safeguards designed to prevent severe accidents. By including this indicator in the causal diagram,

[3] More detail, like definitions and dynamics descriptions of each causal loop can be found in Table 5.

[4] Graphical representation can be found in Figure 2.

it becomes possible to identify the various causes that could increase or decrease the probability of core damage, such as cooling system failures, human errors, or weaknesses in safety protocols.

Figure 2 shows a diagram with the causal loop and key performance indicators. Furthermore, following Figure 2, Table 5 and Table 6 with details of the causal loop, its factors and the balance or reinforcement loops are presented. Table 5 presents an organized, comprehensive and structured overview of the identified causal loops. A unique coding has been assigned to each causal loop to facilitate its identification and referencing. Furthermore, a descriptive denomination has been provided for each loop, enabling a clear and concise understanding of the analyzed topic or phenomenon.

Each causal loop has also been precisely defined, offering a clear understanding of its purpose and scope. These definitions help establish the boundaries and nature of each causal loop, thereby facilitating the analysis and interpretation of results. Additionally, a description of the dynamics represented by each causal loop in the diagram has been included.

This description outlines how the factors interact within each loop and how the flow of causality occurs among them. This information is crucial for understanding the cause-and-effect relationships present in the studied system.

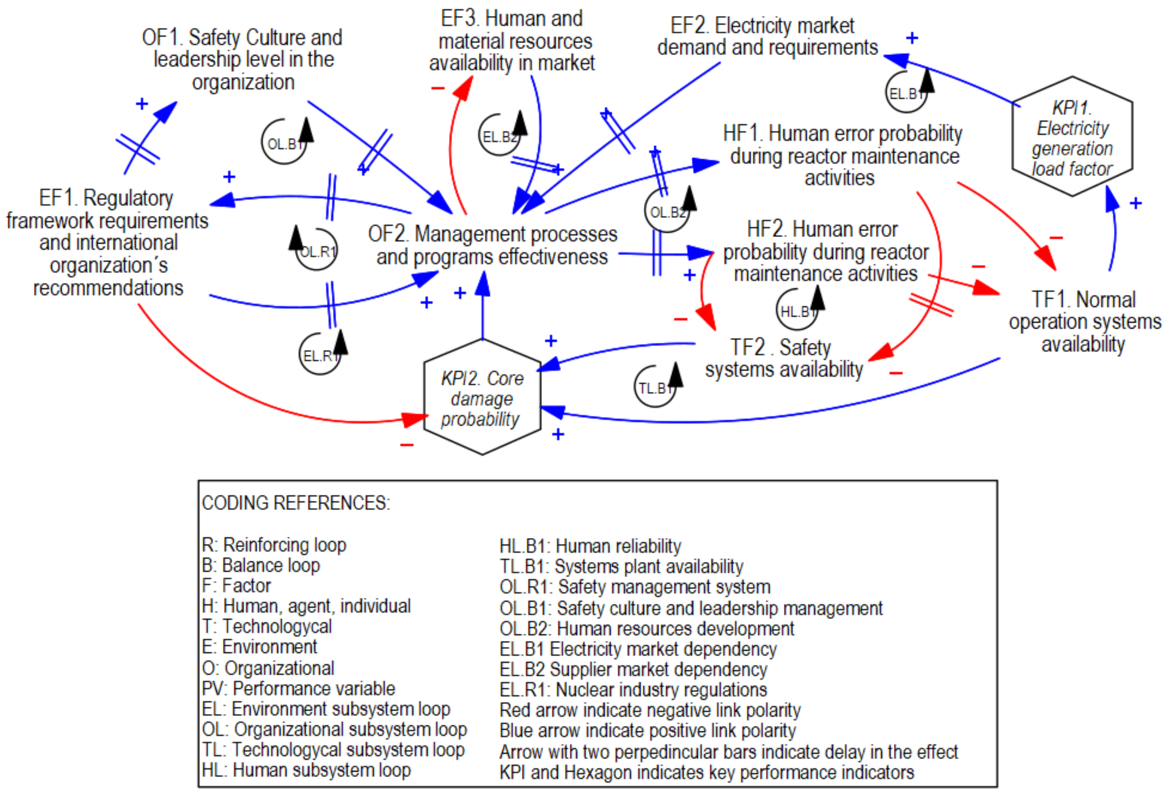

Figure 2 Causal model proposed for nuclear safety management of a nuclear power plant operation dynamics. Source: developed by the authors.

As mentioned earlier, the detailed information regarding Figure 2 is presented in Table 5 below.

Table 5 Causal loops denomination, definitions and description of the dynamics they represent.

HTOE subsystem	Causal loops			
	Code	Denomination	Definitions	Description of the dynamics they represent.
Environmental	EL.R1 (environmental loop, type reinforcement[5] nº 1)	Nuclear industry regulations	The actions and decisions of the national regulator, the nuclear industry international organizations (IAEA, WANO mainly) and the NPPOO to establish, monitor, and comply with safety standards.	The regulatory body establishes safety requirements and standards that organizations must comply with. When the organization achieves good safety performance and successfully meets these requirements, positive feedback is created. Successful compliance can lead to positive recognition from the regulator, reinforcing ongoing compliance and safety performance. Furthermore, good safety performance can generate trust in regulatory authorities and the public. This can lead to increased acceptance and support of the regulator, as well as the implementation of even stronger safety measures. In turn, this reinforces compliance and safety performance, creating a cycle of continuous improvement.
	EL.B1 (environmental loop, type balance nº 1)	Electricity market dependency	The actions and decisions of the wholesale electricity market and the NPPOO to demand and supply electricity.	The demand for electrical energy imposes pressure on the nuclear power plant to generate the required amount of electricity reliably. The nuclear power plant must ensure safe operation and compliance with established safety standards to ensure a reliable supply of energy to meet market demand. If the nuclear power plant fails to meet the demand due to safety issues, maintenance, or any other reason, there can be negative consequences. This may include the need to rely on other sources of energy, such as backup power plants, which can incur additional costs and logistical challenges. It can also affect the stability of the electrical supply and the trust in the nuclear power plant as a reliable energy source. Therefore, there is a negative feedback loop in case the nuclear power plant fails to meet the demand due to safety issues. This creates pressure to maintain high safety standards and ensure regulatory compliance in order to maintain continuous operation and meet the electrical energy demand of the market.
	EL.B2 (environmental loop, type balance nº 2)	Supplier market dependency	The actions and decisions of the supplier market agents (employment, materials and, services market) and the NPPOO.	If an organization has poor safety performance, it can generate concerns in the resource provider market. Suppliers may be hesitant to associate with an organization that does not meet the required safety standards, which can limit access to key resources. Additionally, if a serious safety-related incident occurs, suppliers may face regulatory or reputation pressures by being associated with the organization. This can lead to a reduction in resource availability and an increase in costs associated with resource acquisition.

[5] It is important to note that the loop between the regulator and safety performance may also involve elements of balancing loops. While there is positive feedback that reinforces compliance and safety performance, there may also be elements of negative feedback in the form of penalties or withdrawal of the reactor's operating license in case of serious non-compliance.

Organizational	OL.B1 (organizational loop, type balance nº 1)	Safety culture and leadership management	The actions and decisions taken by NPPOO regarding the development and sustainability of individuals behavior related to safety and the commitment to it.	A high level of safety culture and leadership can contribute to improved safety performance. When there is a strong safety culture and committed leadership, safe practices are promoted, active employee participation in safety is encouraged, and clear standards and expectations are established. This can result in greater adherence to safety protocols, increased identification and prevention of risks, and a decrease in safety incidents. In turn, improved safety performance reinforces the safety culture and leadership. When safety efforts lead to positive outcomes, such as a reduction in accidents or incidents, the importance of safety culture and committed leadership is reinforced. This further strengthens adherence to safety principles, trust in leadership, and belief in the effectiveness of safety measures. In this positive reinforcing loop, higher safety performance drives a stronger safety culture, and in turn, a stronger safety culture contributes to improved safety performance. It is important for organizations to recognize this loop and actively work to strengthen both their safety culture and safety performance to create a cycle of continuous improvement.
	OL.B2 (organizational loop, type balance nº 2)	Human resources development	The actions and decisions taken about training and recruitment qualified staff to perform operations and maintenance, managerial and support activities.	The effectiveness of training, education, and human reliability programs has a positive impact on nuclear safety by reducing the probability of human error in maintenance and operations. These programs enhance workers' understanding and knowledge, develop technical skills, improve decision-making, and foster a safety culture. By having better-informed, competent, and safety-committed workers, human errors are minimized, and a safe environment is promoted in the nuclear power plant.
	OL.R1 (organizational loop, type reinforcement nº 1)	Safety management system	The decisions about the safety management system processes and programs taken by the managerial and support staff.	Good safety performance demonstrates the effectiveness of the management system, validating and supporting its approach. The organization can recognize successful practices and use the data and information obtained from performance to improve and strengthen its safety management system. Conversely, the safety management system influences safety performance. An effective management system provides the tools and mechanisms to identify areas for improvement and take corrective actions, as well as manage unwanted events. Through proper risk management, proactive management of radiological hazards can be achieved. The results of safety performance could be used to evaluate and adjust the management system, while improvements in the management system translate into better safety performance.

Human	HL.B1 (human loop, type balance nº1)	Human reliability	The maintenance and operation actions carried out by the operations and maintenance groups within the framework of maintenance and operation programs.	When human reliability in operation and maintenance is high, human errors are reduced, and potential failures are minimized. This contributes to increased safety and prevention of incidents or accidents in the nuclear reactor. Safe and incident-free operation results in better performance of the safety management system. However, if failures in human reliability occur, such as errors or negligence in operation or maintenance, incidents or accidents can occur. These incidents or accidents generate negative feedback and demand the implementation of corrective actions, such as investigations, additional training, or changes in procedures. The implementation of these corrective actions reinforces the importance of human reliability and promotes greater attention to and compliance with safety practices. It is important to note that the existence of corrective maintenance and unplanned plant shutdowns can impact this causal loop. Corrective maintenance and unplanned shutdowns can be indicators of lower levels of human reliability or a less effective safety management system. These disruptions can trigger the need for improvements in human reliability as well as the safety management system through the identification of deficiencies and the implementation of corrective measures.
Technological	TL.B1 (technological loop, type balance nº 1)	Systems plant availability	The actions (passive or active) taken (automatically or manually) by the nuclear reactor normal operation systems and, safety systems.	When the normal operation systems are available and functioning correctly, the plant has higher availability for safe power generation. These normal operation systems include components such as turbines, generators, control systems, and cooling systems, among others. If these systems are in good condition and operate smoothly, the plant can operate efficiently and safely. On the other hand, the availability of safety systems is essential to ensure safety in power generation. These systems include protection systems and accident mitigation systems, such as emergency cooling systems and containment systems. When the safety systems are available and functioning correctly, risks are reduced, and the plant's safety is improved. However, if the availability of normal operation systems decreases due to failures or breakdowns, the availability of the plant for safe power generation is compromised. This can be due to unplanned shutdowns or the need for corrective maintenance in the normal operation systems. A decrease in the availability of these systems can negatively affect the plant's capacity to generate power safely and efficiently. Similarly, if the availability of safety systems decreases due to failures or breakdowns, the plant's safety is compromised. This can be due to the need for repairs or corrective maintenance in the safety systems, which can lead to unplanned shutdowns or a reduction in the ability to respond to potential accidents. It is important to address and improve both the availability of normal operation systems and the availability of safety systems to maintain a balanced loop and ensure safe and reliable power generation in the nuclear reactor

For more precisions about Figure 2, next the Table 6 offers a detailed description of the information related to causal loops, including the causal relationships between factors, references to literature that support the causality, and the postulated mode of behavior for each loop. This information was supported the development of the mentioned Figure its causal loops, in determining the polarity between factors, identifying delays between cause and effect, and in the postulation of the behavior of each loop.

The table is structured with several columns that effectively organize the provided information. The first column, labeled "Loop Number," assigns a unique numerical identifier to each causal loop, allowing for easy reference and identification. The second column, titled "Factors," lists the factors involved in each causal loop. These factors represent the variables or elements that interact within the loop and contribute to the cause-and-effect relationships being studied.

The third column, titled "Causal Relationships," provides detailed descriptions of the causal relationships between the factors within each loop. This column explains how changes or variations in one factor can impact other factors in the loop, establishing a cause-and-effect connection. It elucidates the specific dynamics and interactions between the factors.

The fourth column, labeled "References," includes citations to relevant literature or sources that discuss the causality of the relationships within the loops. These references serve as supporting evidence for the proposed causal relationships and offer additional insights into the dynamics being studied. They provide a basis for the established connections and contribute to the overall understanding of the system.

Lastly, the "Postulated Behavior" column describes the anticipated mode of behavior or expected dynamics for each causal loop. This information is derived from the literature references and represents the predicted behavior of the system under study based on the identified causal relationships. It provides an insight into how the system is expected to respond and behave in various scenarios.

By organizing the information in this table, the relationships between factors, supporting literature references, and postulated behavior for each causal loop are presented in a clear and systematic manner. This allows for comprehensive analysis, discussion, and future research in the field of study. Furthermore, the table enhances the interpretability and reproducibility of the study. By providing a concise and standardized format for describing each causal loop, it enables researchers and stakeholders to grasp the key concepts and relationships quickly. This enhances the overall clarity and transparency of the research findings.

Table 6 Causal relationships between each factor of each loop, references in the literature regarding its causality and postulated mode of behavior.

HTOE subsystem	Causal Loop			Causal relationship between factors	Effect asynchrony	References in the literature regarding its causality	Postulated mode of behavior according (Sterman, 2000)
	Code	Denomination	Type				
Human	HL.B1	Human reliability	Balance	HF1 (-) TF1 and, TF2	√	(Chen, 2005; Chu, 2006b; Pyy, 2001; Rasmussen, 1997; Zarei et al., 2021a, 2022, Vaurio, 1998)	S-shaped growth: Human performance will grow to achieve values close to industry standards. That value will be achieved due to the processes and programs of management of training, learning, human reliability, continuous improvement, and the implementation of the best operational practices of the industry.
				HF2 (-) TF1	√	(Guedes Soares, 2002; IAEA, 2022b; Khorshidi et al., 2015; NRC, 1983, 2007; Okoh & Haugen, 2014; C. Taylor, 2017; Zarei et al., 2021a) and (IAEA, 2006, 2014; INSAG, 1999; OECD, 2020; Schnuerer, 2009)	
				HF2 (-) TF2	-		
Technological	TL.B1	System plant availability		HF1 (-) TF1	-		Goal seeking: The performance in safety and availability of the plant will grow, seeking to reach the maximum values in the industry. This will be due to the growth in the performance of the human and organizational factors in line with compliance with the regulatory framework. Plant reliability and safety will be affected by human errors in operations and maintenance actions and organizational processes deficiencies.
				HF1 (-) TF2	√		
				TF1 (+) KP2	-		
				TF2 (+) KP2	-		
				HF2 (-) TF1	-		
				HF2 (-) TF2	-		
Organizational	OL.B1	Safety culture and leadership management		EF1 (+) OF1	√	(Gracia et al., 2020; IAEA, 2016a; Martinez-Córcoles, 2012)	S-shaped growth: Safety culture and leadership organization level will grow to achieve values close to industry standards. That value will be achieved due to the processes and programs of management safety culture. Safety culture and leadership level will vary based on the organization staff.
				OF1 (+) OF2	√		
				OF2 (+) EF1	√		
	OL.B2	Human resources development		OF2 (+) HF1 and, HF2	√	(Acuña, 2017; Acuña et al., 2019, 2022; Baraftabi et al., 2017; Cooke, 2003a, 2003b; Dulac, Leveson, Zipkin, Cutcher-Gershenfeld, et al., 2005; Reiman et al., 2007)	Goal seeking: A gradual reduction in the probability of human error is expected as system improvements are implemented, generating positive feedback that reinforces training and development efforts. However, there is a limit to the reduction, and a balance will be reached between improvement efforts and the results achieved.
				HF1 (+) TF1 and, TF2	-		
				HF2 (+) TF1 and, TF2			
				TF1 and TF2 (+) KPI2			
				KPI2 (+) OF2			

	OL.R1	Safety management system	Reinforcement	EF1 (+) OF2	√	(IAEA, 2001b, 2008; Lipár, 2012)	S-shaped growth: The management processes and programs efficacy will grow to achieve maximum value possible according the available of resources and the trade-off management priorities. That value will be achieved due to the processes and programs of management of training, learning, human reliability, continuous improvement, and the implementation of the best operational practices of the industry.
				OF2 (+) EF1	√	(Guedes Soares, 2002; IAEA, 2022b; Khorshidi et al., 2015; NRC, 1983, 2007; Okoh & Haugen, 2014; C. Taylor, 2017; Zarei et al., 2021a) (IAEA, 2001b, 2005, 2016; Lipár, 2012; Y. Liu & Wu, 2006; Wahlström, 2018)	
Environmental	EL.R1	Nuclear industry regulations		EF1 (+) OF2	√	(Aoki & Rothwell, 2013; Ghosh & Apostolakis, 2005; Grote, 2012; Himanen et al., 2012; Nukusheva et al., 2021; Pettersen et al., 2017; Rehani, 2011; Yin & Zou, 2021)	Goal seeking: The regulatory body will adopt the best international practices and the state of the art of academic knowledge in nuclear safety, establishing these as compliance objectives for regulated nuclear power plants.
				EF1 (-) KPI2	√		
				KPI2 (+) OF2	-		
	EL.B1	Electricity market dependency	Balance	OF2 (+) HF1	√	(Chia et al., 2015; Woo & Kim, 2012) (Ho et al., 2019; Woo & Kim, 2012)	Growth with overshoot: Nuclear power plants as base-type power generation plants will meet the demand of the electricity market stably. During the first years of operation, the energy generated will be increased until the nominal design capacity is reached. Once the generation has stabilized close to said capacity, this amount will vary with the nuclear safety performance of the facility.
				HF1 (-) TF1	-		
				TF1 (+) KP1	-		
				KP1 (+) EF2	-		
				EF2 (+) OF2	√		
	EL.B2	Supplier market dependency		EF3 (+) OF2	√	(Fernandes et al., 2020; IAEA, 2001b; Park et al., 2020; Peralta-argomeda et al., 2016; Salazar, 2002; Zarei et al., 2022)	Oscillation according the human and material resources availability in the market.
				OF2 (-) EF3	-	(Rasmussen, 1997; Zarei et al., 2021b, 2022)	

4.5 Analysis of the dynamics

From a general perspective, the model of nuclear safety management for operational organizations of nuclear power plants demonstrates a predominance of balancing loops driving system dynamics, with six such loops at play. These loops are counteracted by two reinforcing loops. The EL.R1 loop, associated with regulatory compliance and recommendations from regulatory bodies, and the OL.R1 loop, related to the safety management system and its programs, contribute to maintaining equilibrium within the system. However, the growth of these loops is constrained by the OL.B1 loop, linked to the organization's safety culture and leadership, and the EL.B2 loop, influenced by the availability of market resources.

In addition to emphasizing the importance of maintaining equilibrium, the presence of balancing loops highlights the significance of a robust safety culture and effective leadership in promoting a safe operating environment. The OL.R1 loop, focused on the safety management system, ensures the implementation of necessary processes and programs for effective risk mitigation. Similarly, the EL.R1 loop, centered on regulatory compliance, guides the organization in adhering to industry standards and upholding a high level of safety performance.

Conversely, the reinforcing loops within the model emphasize areas where positive feedback can amplify or reinforce certain behaviors. The OL.B1 loop, influenced by the organization's safety culture and leadership, plays a crucial role in strengthening positive safety behaviors. Effective leadership and a strong safety culture lead to improved safety performance, further enhancing the safety management system. Likewise, the EL.B2 loop, dependent on market resources, reinforces positive behaviors by ensuring sufficient resource allocation for safety initiatives. This positive feedback loop results in continued improvements in safety outcomes through an increased emphasis on safety culture and resource allocation.

Furthermore, the balance loops in the environment subsystem, specifically EL.B1 and EL.B2, induce disequilibrium in the OL.B1 and OL.B2 loops due to the trade-offs between safety and production. Acting as the primary regulator of this disequilibrium, the EL.R1 loop operates with a strong focus on safety performance objectives. Consequently, achieving safe operation of a nuclear power plant relies on appropriate operational conditions, effective plant maintenance, and proficient management of organizational processes in compliance with regulatory frameworks.

Consideration of delays within the system, as described by Seivatici et al. (2002), highlights the time-dependent nature of decision-making processes and their impact on organizational behavior. Strategic decision-making, involving long-term priorities set by top managers, requires a longer timeframe for changes to manifest. In contrast, tactical and operational decision-making by middle managers has an immediate influence on organizational priorities. Recognizing these delays is crucial for developing effective strategies that drive positive changes in safety management practices and align organizational goals with safety objectives.

Within the context of the model of nuclear safety management described, it is crucial to recognize that the factors encompassed by the model can be broken down into smaller components to represent micro behaviors within each loop. This process of disaggregation is highly significant as it allows for the formulation of stock and flow diagrams and the definition of equations, thereby enabling a more comprehensive understanding of the intricacies of the system dynamics and interactions.

The disaggregation of factors within the model of nuclear safety management allows for a more nuanced and detailed examination of the system dynamics and interactions. This analytical approach, employing stock and flow diagrams and defining equations, enhances our understanding of how each component within a loop contributes to the overall behavior of the system. Ultimately, this deeper understanding facilitates the development of more effective strategies and interventions to promote safety and align organizational goals with safety objectives.

4.6 Expected model macro behavior

Based on the level of conceptual detail presented, it is expected that the overall behavior of the model, specifically in terms of KPIs, will exhibit an S-shaped growth pattern with overshoot according to Sterman (2000), as illustrated in Figure 3.

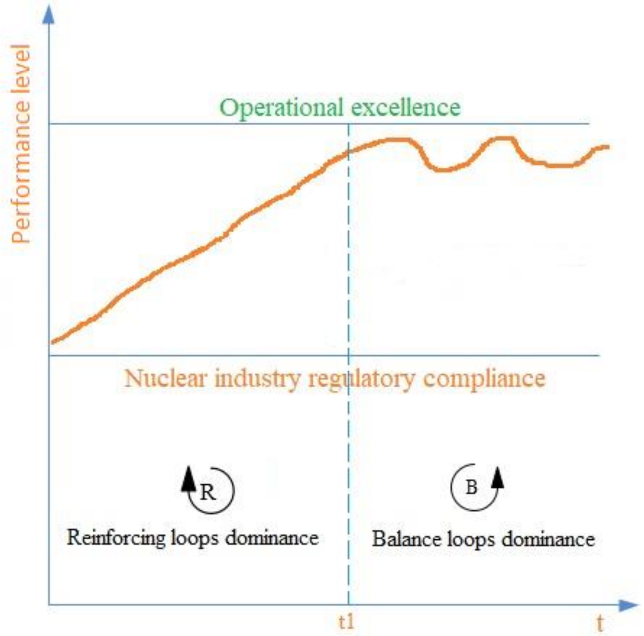

Figure 3 Model macro behavior expected

This expectation is grounded on the assumption that in the early stages of the dynamics, particularly at t=0, the reinforcing loops (EL.R1 and OL.R1) would dominate over the balancing loops (EL.B1, EL.B2, OL.B1, OL.B2, HL.B1, and TL.B1). This inference is supported by the understanding that compliance with the regulatory framework establishes a solid foundation of support and acceptability for achieving a high level of performance, as evidenced by industry statistics. Additionally, the continuous adherence to safety requirements and recommendations from international organizations, as well as the exchange and adoption of best operational practices, serve as ongoing drivers towards the implementation of practices that foster operational excellence.

As time progresses, it is expected that the dynamics of the model will gradually shift towards a predominance of balancing loops, particularly driven by the HL.B1 and TL.B1 loops (resulting from human errors and technological system failures) triggered by organizational deficiencies (OL.B2 loop). These balancing loops act as buffers or trade-offs between safety and production pressures.

However, it is important to acknowledge that the behavior of the system can be influenced by various factors, and the presented model serves as a simplified representation of the complex dynamics at play. Further research and refinement are necessary to capture the full complexity and intricacies of the system dynamics.

It is important to note that the model's predictions and outcomes are contingent upon the assumptions and limitations inherent in the model's design and scope. Factors such as organizational culture, resource allocation, and external influences may interact with and impact the dynamics of the model in ways that are not fully captured within its simplified representation.

5 Conclusions

The development process of the presented causal model has provided a foundation for enhancing the understanding of the overall dynamics of nuclear safety management in the operation of a nuclear power plant. The regulatory framework and international organizations have emerged as pivotal drivers for implementing nuclear safety requirements within the operating organization. Additionally, external factors such as the electricity market and resource availability exert significant influence on achieving safety goals.

Human errors and technological failures must be effectively managed through the implementation of management system processes and programs aimed at minimizing their impact and recurrence. Continuous improvement tools play a crucial role in the correction and prevention of the occurrence and recurrence of such incidents. However, organizational factors exhibit delays in the manifestation of their effects, introducing asynchrony between cause and effect. This disconnect slows down the seamless integration of operational resolutions, addressing root causes, and facilitating organizational learning to prevent future events. Nevertheless, the notable achievements of the nuclear industry in attaining high levels of performance underscore the effectiveness of these organizational mechanisms.

In summary, the causal model development process has shed light on the systemic dynamics of nuclear safety management in nuclear power plant operations. It has highlighted the importance of regulatory frameworks, international organizations, external determinants, and organizational factors in shaping safety outcomes. Effective management of human errors, technological failures, and continuous improvement processes contributes to maintaining high levels of performance. However, addressing the delays associated with organizational factors remains a challenge, necessitating a closer integration of operational resolutions, root cause analysis, and organizational learning.

5.1 Conceptual model limitations

Despite its potential usefulness, the model presented has certain limitations. For example, the model is based on a simplified representation of the complex dynamics involved in the nuclear safety management reality. The model assumes that the loops interact in a simple way, which may not always be the case in reality. Additionally, the model does not take into account all possible factors that may affect the behavior of the system, such as changes in the organizational structure or more external factors like political ones more beyond the control of the organization and the industry.

Moreover, the model relies on assumptions and generalizations that may not hold true in specific contexts. For instance, the assumption that compliance with regulatory frameworks ensures a high level of performance may not always be accurate, as some organizations may engage in regulatory capture or engage in other forms of non-compliance. Finally, the model is only as good as the data used to calibrate it, and the accuracy of the model's predictions depends on the quality and relevance of the input data.

In conclusion, while the model presented provides valuable insights into the behavior of the nuclear safety system, it is important to recognize its limitations and use it as a tool to guide decision-making rather than relying on it exclusively. Future research can explore ways to improve the model by incorporating additional factors and validating its predictions using real-world data.

5.2 Future Research

Building upon the findings and conceptual bases established in this study, there are several potential avenues for future research. One area of focus could be the development of detailed causal models that delve deeper into the specific factors influencing nuclear safety management in the operation of a nuclear power plant. These models could incorporate a more comprehensive understanding of the interdependencies and feedback loops within the system, allowing for a more nuanced analysis of the dynamics at play.

In complementation future research could involve the application of Forrester models, to further explore the complex dynamics of nuclear safety management. Forrester models provide a quantitative approach to modeling dynamic systems and can offer insights into the potential impacts of different policy interventions and management strategies.

Additionally, simulation models can be employed to simulate various scenarios and assess the effectiveness of different safety measures and protocols. Simulation models enable researchers to test different strategies, evaluate their outcomes, and identify areas for improvement in the management of nuclear safety.

By further investigating these areas, researchers can enhance our understanding of the intricate causal relationships and dynamics within nuclear safety management. This knowledge can contribute to the development of more robust and effective strategies for ensuring safe and reliable operations in nuclear power plants.

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