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Understanding and enhancing nuclear safety culture in nuclear power plants through a quantitative system dynamics model

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Abstract: This study presents a quantitative system dynamics model developed to understand and enhance nuclear safety culture and operational performance in nuclear power plants. The model employs causal loop diagrams and stock-and-flow diagrams, created using Vensim PLE+ software, to capture and simulate the complex interactions that define safety culture dynamics. Recognizing the fundamental role of organizational culture in maintaining nuclear safety, the model incorporates key elements such as leadership, risk perception, continuous improvement, internal communication, and the commitment of management and personnel. Through an extensive literature review and expert consultations, the research integrates critical variables into the model, grounded in frameworks from the International Atomic Energy Agency (IAEA) and the World Association of Nuclear Operators (WANO). Simulating a decade of safety culture management dynamics, the model reveals the impact of management strategies, demonstrating the effectiveness of continuous improvement initiatives and proactive leadership in enhancing safety outcomes. Stress tests conducted under extreme scenarios validated the model's robustness, reaffirming its applicability in safeguarding safety culture under intensified production pressures. The findings provide actionable insights for nuclear safety professionals and decision-makers, promoting environments that support safety-focused practices. This model serves as a comprehensive tool to advance safety culture in nuclear operations, offering valuable perspectives for both theoretical discourse and practical nuclear safety management.

Keywords: safety management, nuclear power plants, safety culture, quantitative model, causal loop diagram and stock-and-flow diagrams, VENSIM PLE+ software.

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Comprendiendo y mejorando la cultura de seguridad nuclear en centrales nucleares a través de un modelo dinámico cuantitativo de sistemas

Resumen: Este estudio presenta un modelo dinámico cuantitativo de sistemas desarrollado para mejorar la cultura de seguridad nuclear y el desempeño operativo en plantas de energía nuclear. El modelo emplea diagramas de bucles causales y diagramas de stock y flujo, creados utilizando el software Vensim PLE+, para capturar y simular las complejas interacciones que definen la dinámica de la cultura de seguridad. Reconociendo el papel fundamental de la cultura organizacional en el mantenimiento de la seguridad nuclear, el modelo incorpora elementos clave como liderazgo, percepción del riesgo, mejora continua, comunicación interna y el compromiso de la gerencia y el personal. A través de una extensa revisión de literatura y consultas con expertos, la investigación integra variables críticas en el modelo, fundamentadas en marcos proporcionados por la Agencia Internacional de Energía Atómica (IAEA) y la Asociación Mundial de Operadores Nucleares (WANO). Al simular una década de dinámicas de gestión de la cultura de seguridad, el modelo revela el impacto de las estrategias de gestión, demostrando la efectividad de las iniciativas de mejora continua y el liderazgo proactivo en la mejora de los resultados de seguridad. Pruebas de estrés fueron realizadas al modelo bajo escenarios extremos que validaron la robustez del modelo, reafirmando su aplicabilidad para salvaguardar la cultura de seguridad bajo presiones de producción intensificadas. Los hallazgos proporcionan conocimientos prácticos para profesionales de la seguridad nuclear y tomadores de decisiones, promoviendo entornos que apoyen prácticas enfocadas en la seguridad. Este modelo sirve como una herramienta integral para avanzar en la cultura de seguridad en las operaciones nucleares, ofreciendo perspectivas valiosas tanto para el discurso teórico como para la gestión práctica de la seguridad nuclear.

Palabras-clave: gestión de la seguridad, central nuclear, cultura de seguridad, modelo cuantitativo, diagrama de bucles causales y diagramas de stock y flujo, software VENSIM PLE+.

1. INTRODUCTION

Emphasizing a robust nuclear safety culture is essential in preventing accidents and ensuring the safe expansion of nuclear power technology [1]. The operational integrity of nuclear power plants hinges significantly on a comprehensive understanding and management of safety culture [2]. Nuclear safety culture is a crucial element in the operation of nuclear facilities to prevent catastrophic accidents. It is widely acknowledged as a critical tool for enhancing safety at nuclear energy facilities [3]. It encompasses organizational and individual characteristics that prioritize safety issues [4]. Strengthening safety culture not only enhances safety but also contributes to the overall organizational management [5]. The association between safety culture and incidents in nuclear power plants highlights the necessity for effective plans to enhance safety culture [6]. Historically, the nuclear industry has witnessed catastrophic failures where lapses in safety culture played a pivotal role [7], [8]. In response, regulatory bodies and research institutions have underscored the importance of an ingrained safety culture as a cornerstone of nuclear safety [9], [10]. Despite this recognition, the dynamic and complex nature of safety culture, especially in the context of nuclear power plant operations, remains challenging to quantify and model systematically.

Numerous studies have been conducted to explore the role of safety culture in enhancing nuclear safety. In [1] the authors conducted an exhaustive review exploring the symbiotic relationship between human factors, safety culture, and their impact on both organizational and individual performance within nuclear power plants and found out that these elements were important in shaping a resilient safety culture within nuclear setups. [11] Explored the group model approach to delineate the relationship between safety culture components and safety performance factors. By utilizing system dynamics to accommodate the complexity of safety management, their findings suggest that safety culture at the tactical (middle management) and operational levels significantly enhances organizational safety performance more effectively than at the strategic (top management) level. [12] evaluated how nuclear safety culture is applied and legislated in fission and fusion nuclear technologies, using the Czech Republic and the ITER project as case studies, to highlight cross-technology safety practices and legislative adaptations. It was discovered that the implementation of nuclear safety culture principles significantly enhances safety protocols across both fission and fusion technologies, with legislative adaptations and organizational practices evolving in response to technological advancements and historical safety insights. [13] developed and applied the Design for Integrated Safety Culture (DISC) framework for evaluating organizational safety potential in nuclear and healthcare domains, using case studies to demonstrate the framework's utility in practice. [14] Developed and validated a multi-method safety culture assessment approach for nuclear power plants, utilizing Schein's culture model to explore deeper cultural levels, which demonstrated adequate validity in enhancing understanding of cultural dynamics and their impact on safety performance across two German nuclear power plants. However, the study lacked a quantitative, dynamic simulation aspect that could model the interactions among various factors influencing safety culture and predict the impact of management strategies on nuclear safety culture over time. The researchers of [15] conducted a study to identify and rank the key elements of safety culture in nuclear reactor operating organizations, utilizing a systematic literature review and the Analytical Hierarchy Process (AHP). Their findings highlight top management leadership, communication management, safety climate, and hazard and risk analysis as crucial components, with leadership actions identified as the most significant in achieving nuclear safety goals.

Previous research highlights the positive impact of safety culture on safety performance, but the mechanisms underlying this relationship in nuclear power plants remain unclear. Existing studies mainly rely on qualitative analyses, leaving a gap in quantitative modeling to explore the complex dynamics of safety culture. This paper addresses the gap by developing a system dynamics model to quantitatively assess how key safety culture factors—like leadership, risk perception, and communication—affect operational performance and safety outcomes in nuclear facilities.

The model aims to predict the long-term impacts of interventions and guide strategic decision-making. It is grounded in a thorough literature review, expert consultations, and established frameworks from the IAEA and WANO, ensuring relevance to industry challenges. This research contributes to academic understanding and practical management by identifying leverage points for effective interventions, offering a comprehensive tool to enhance safety culture and operational performance in nuclear power plants.

2. MATERIALS AND METHODS

This study employed a system dynamics methodology, originally developed by [16] and expanded through the advancements of [17]. This approach enabled the creation of a quantitative model using causal loop diagrams and stock-and-flow diagrams, developed with VENSIM PLE+ software. The model provides a comprehensive analysis of nuclear safety culture in nuclear power plant operations, integrating qualitative and quantitative methods.

The model's development began with an extensive literature review of academic studies applying system dynamics to safety culture and management, including works by [18], [19], and [20]. Additionally, documents from the International Atomic Energy Agency (IAEA) and the World Association of Nuclear Operators (WANO) were reviewed to incorporate regulatory requirements, best practices, and recommendations essential for cultivating a robust nuclear safety culture.

Building on the conceptual framework outlined by [21], safety culture variables were further refined and integrated as detailed in [15]. This foundation ensured the model aligned with both academic research and industry standards.

Expert interviews played a critical role in identifying variables, causal relationships, and data essential for modeling safety culture dynamics. Participants included operators, managers, regulators, and academics from the nuclear industry. The interviews revealed key factors influencing safety culture, their organizational interactions, and practices that either support or challenge its improvement. Metrics for assessing safety culture effectiveness and their applications in decision-making were also identified. These insights shaped a model that reflects real-world dynamics and offers actionable recommendations.

3. RESULTS AND DISCUSSIONS

3.1. Dynamic hypothesis and simplifying assumptions of the model

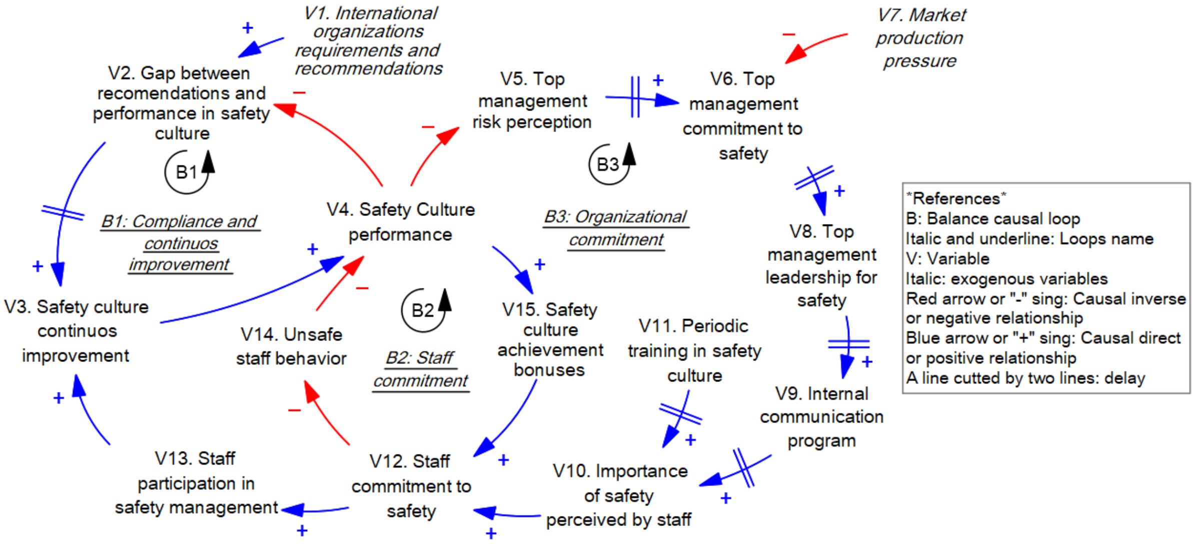
Based on the IAEA and WANO approaches [22] and [23] the following dynamic hypothesis is proposed: "The management approach based on continuous improvement, combined with active leadership from the organization's top management, will result in higher safety culture performance."

The model incorporates simplifying assumptions to focus on key aspects of organizational safety behavior, avoiding excessive complexity and ensuring controllability under predictable conditions. It assumes homogeneity in personnel characteristics, with all employees sharing uniform interest and responsibility regardless of role or experience. Additionally, safety practices and communication programs are considered to improve continuously without interruptions, excluding factors such as fatigue or staff turnover.

3.2. Safey culture causal loop diagram and its description

The causal loop diagram is based on the safety compliance archetype [24], organized around three balancing loops that illustrate key interactions shaping safety culture in nuclear power plants. Adherence to strict international and national safety standards ensures compliance, fostering a robust safety culture (see Figure 1).

Figure 1: Causal loop of safety culture within nuclear power plant operating organizations.



Source: authors' development

The causal loops in Figure 1 highlight key interactions shaping safety culture. It can be observed that B1 (Compliance and Continuous Improvement loop) illustrates how international recommendations drive continuous improvement to close the gap between required and actual safety culture performance, aligning the organization with global standards. B2 (Staff Commitment loop) demonstrates how unsafe behaviors can harm safety culture performance, while improvements lead to recognition of performance, encouraging greater staff participation in safety management. Lastly, B3 (Organizational Commitment loop) underscores the role of top management's risk perception in strengthening safety leadership and staff training, enhancing safety culture, while balancing production pressure, which can weaken these efforts.

3.3. Elicited and proposed variables

The variables of the model elicited in the interviews are presented and detailed, providing a comprehensive overview of the proposed key factors under consideration in the model. Also, literature references about its causal relationships are presented (see Table 1).

Table 1 : List of elicited and proposed variables

#	VARIABLE	REPRESENTS	CAUSAL RELATION	LITERATURE REFERENCE
V1	International organizations requirements and recommendations	Requirements, guidelines, and suggestions from international organizations on safety culture practices.	V1(+)V2	[22], [31]
V2	Difference between recommendations and performance in safety culture	The gap between international safety culture recommendations and actual organizational performance.	V2(+,//)V3	[22], [31]
V3	Safety culture continuous improvement	Ongoing efforts to enhance safety culture through continuous refinement of processes, attitudes, and behaviors.	V3(+)V4	[11], [18], [22], [32], [33], [34]
V4	Safety culture performance	The organization's effectiveness in embedding and practicing safety culture values across all levels.	V4(-,//)V2 V4(-)V5 V4(+)V15	
V5	Top management risk perception	Top management's awareness and understanding of safety risks, hazards, and vulnerabilities.	V5(+,//)V6	[27]
V6	Top management commitment to safety	Top management's commitment to prioritizing and promoting safety through actions, policies, and decisions.	V6(+,//)V8	[26]
V7	Market production pressure	Market-driven pressures on production targets that influence safety-related decision-making and practices.	V7(-)V6	[25], [26]
V8	Top management leadership for safety	Top management's proactive efforts to set goals, establish standards, and foster a safety-focused climate.	V8(+,//)V9	[22], [29] [35], [36]
V9	Internal communication program	A structured internal communication system to share safety information.	V9(+,//)10	[15], [37]
V10	Importance of safety perceived by staff	Staff's perception of safety as a priority and their awareness of its significance in their work.	V10(+,//)V12	[15], [37]
V11	Periodic training in safety culture	Regularly scheduled programs to enhance staff awareness, knowledge, and skills related to safety culture principles and practices.	V11(+,//)V10	[22]
V12	Staff commitment to safety	Employees' adherence to guidelines and active participation in safety activities.	V12(-)V13 V12(+)V14	[26]
V13	Unsafe staff behavior	Actions by employees that deviate from safety expectative, increasing risks and compromising safety.	V13(+)V3	[11]

#	VARIABLE	REPRESENTS	CAUSAL RELATION	LITERATURE REFERENCE
V14	Staff participation in safety management	Staff involvement in safety initiatives, such as hazard reporting, suggesting improvements, and contributing to safety processes.	V14(+)V3	[38]
V15	Safety culture achievement bonuses	Incentives given to staff for actively promoting and maintaining a strong safety culture within the organization.	V15(+)V12	[38]

Note : + signifies a positive relationship, - a negative relationship, and // represents a time delay.

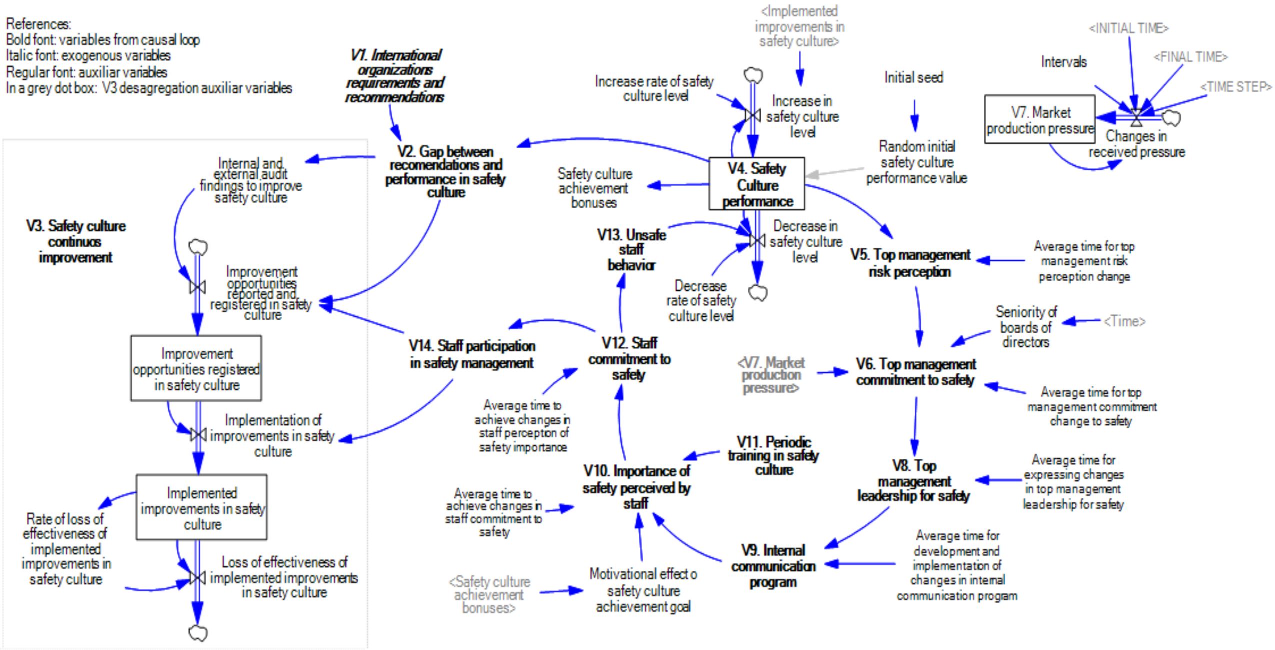
3.4. Model expected behavior

The model predicts gradual improvements in safety culture driven by addressing gaps between safety recommendations and performance, fostering continuous improvement. Strong leadership, active engagement, and robust risk perception from senior management are expected to enhance organizational safety culture. Improved internal communication and heightened staff awareness of safety's importance should boost participation in safety management and adherence to safe practices. While excessive production pressure may weaken safety culture, maintaining a balance between safety priorities and production goals can mitigate unsafe behaviors and uphold standards. Collectively, these dynamics contribute to a safer, risk-preventive organizational culture through effective leadership, communication, and employee commitment.

3.5. Stock and flow diagram

Using the causal loop described earlier, the stocks and flows diagram was developed, identifying stock variables such as the safety culture continuous improvement process, safety culture performance, and market production pressure (see Figure 2).

Figure 2 : Stocks and flows diagram of safety culture within nuclear power plant operating organizations



Source: Authors development.

The system dynamics model employs a stock-and-flow architecture and model like central stocks, variables V4 and V3, that accumulate changes influenced by flows driven by other variables. Additionally, the model incorporates time delays, such as V5 to V12, which influence the pace and sustainability of safety culture dynamics. The equations corresponding to the variables have been carefully developed and implemented using VENSIM PLE+, ensuring accurate representation of the underlying dynamics and relationships within the system being modeled (See Table 2).

Table 2 : List of functions

#	Function or Value	Initial Value
V1	1	1
V2	V1-V4	-
V3.1	V3.3-V3.4	1
V3.2	V3.4-V3.5	10
V3.3	INTEGER(IF THEN ELSE(V2>0.5,integer(1),integer(1)*0.5))	-

#	Function or Value	Initial Value
V3.4	IF THEN ELSE(V3.1> 0, IF THEN ELSE(0 <= V14 :AND: V14 < 0.3, PULSE TRAIN(0, 1, 365, 3650), IF THEN ELSE(0.3 <= V14:AND: V14 < 0.7, PULSE TRAIN(0, 1, 180, 3650), PULSE TRAIN(0, 1, 45, 3650) * 2)), 0)	-
V3.5	IF THEN ELSE(V3.2>0,V3.6,0)	-
V3.6	PULSE TRAIN(365, 1 , 365 , 3650)*V3.2*0.1	-
V4	INTEG (V4.3-V4.1, 0.78)	0.75
V4.1	IF THEN ELSE(V4<0,0,V13*V4.2)	-
V4.2	0.0001	-
V4.3	IF THEN ELSE(V4>1,0,V3.2/10*V4.4)	-
V4.4	0.0001	-
V5	DELAY1(V4, Average time for top management risk perception change)	-
V6	DELAY1(V5*(EXP(-2*V7)),Average time for top management commitment change to safety)	-
V7	INTEG (V7.1, 0.2)	0.2
V7.1	PULSE TRAIN(INITIAL TIME+Intervals, TIME STEP, Intervals, FINAL TIME)*(RANDOM PINK NOISE(0.3,0.05, 365, 0)-V7)/TIME STEP	-
V8	DELAY1(V6, Average time for expressing changes in top management leadership for safety)	-
V9	DELAY1(V8, Average time for development and implementation of changes in internal communication program)	-
V10	DELAY1(V9, Average time to achieve changes in staff commitment to safety)+V11	-
V11	PULSE TRAIN(0, 90 , 180 , 3650)*RANDOM PINK NOISE(0.02,0.01, 365, 1234)	-
V12	DELAY1(V10, Average time to achieve changes in staff perception of safety importance)	-
V13	1-V12	-
V14	V12	-
V15	IF THEN ELSE((DELAY1(V4, 365))<V4,1,0)	-

Some additional auxiliary variables to those presented in the causal loop diagram were elicited in the experts interviews and are described next in see Table 3.

Table 3 : List of auxiliary variables

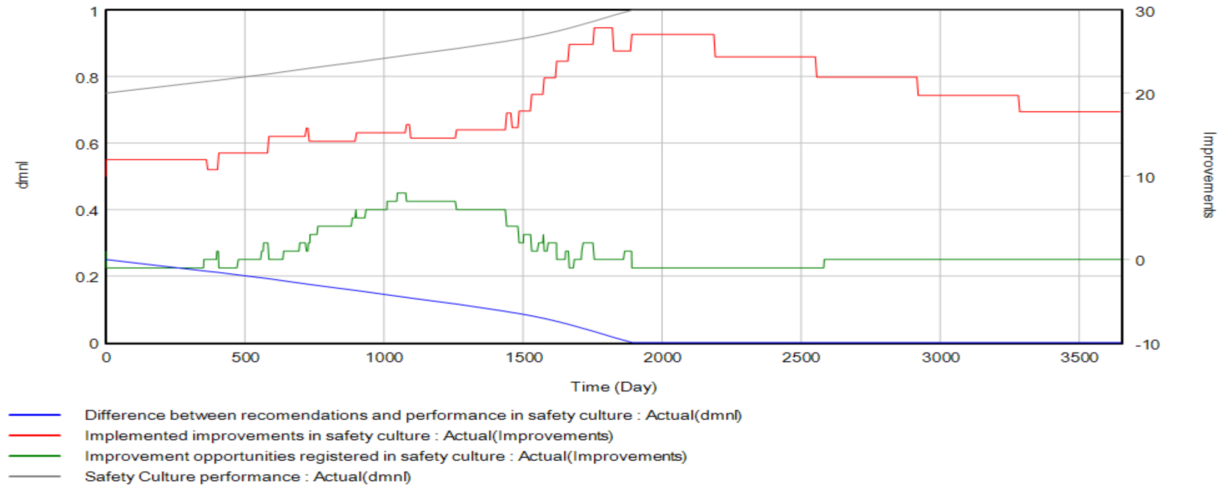
#	AUXILIAR VARIABLE	REPRESENTS	VALUE [days]
1	Findings to improve Safety Culture	The insights derived from spontaneous staff reports or audit reports that have the potential to enhance the safety culture performance.	Random integer value between (0, 1)
2	Average time for development and implementation of changes in internal communication program	The typical time required to develop and put into practice modifications in the internal communication strategy.	60
3	Average time for senior management commitment change to safety	The typical time needed for senior management to transition or alter their commitment to safety within the organization.	60
4	Average time for senior management risk perception change	The typical time for senior management to adjust or modify their perception of risks related to safety.	90
5	Average time for expressing changes in senior management leadership for safety	The typical time taken to articulate changes in senior management's leadership approach towards safety.	180
6	Average time to achieve changes in staff commitment to safety	The typical time required by staff members to modify their commitment to safety within the organization.	30
7	Average time to achieve changes in staff perception of safety importance	The typical time observed in the field for staff to adjust their perception regarding the importance of safety.	30

Table 3 provides a set of auxiliary variables that introduce a temporal dimension to the safety culture dynamics model. These variables conceptually represent the time required for critical processes, such as organizational adjustments, staff behavioral changes, and leadership transformations, to take effect. By integrating these delays, the model highlights the inherent inertia within organizational systems and emphasizes the gradual nature of cultural shifts.

3.6. Simulation results

This section presents and compares ten years of simulation results for a nuclear plant's operation with the expected behaviors outlined earlier. Figure 3 illustrates the findings on safety culture continuous improvement.

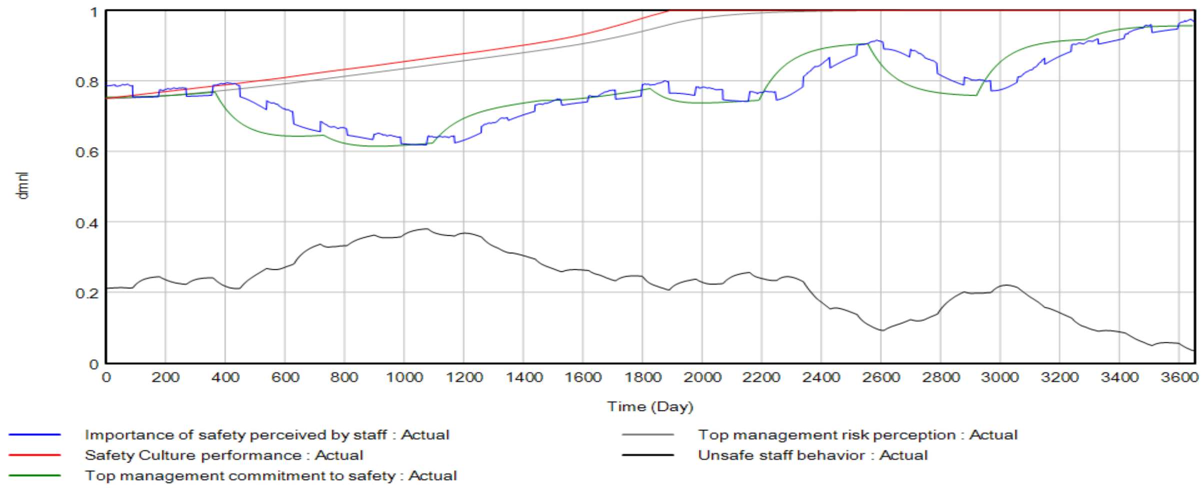
Figure 3 : Results regarding expected behavior 1



Source: authors' development

After 1,500 days of operation, safety culture improvements accelerate significantly as the implementation of improvement measures becomes more rigorous, bridging gaps between safety recommendations and performance. This milestone highlights the critical role of continuous improvement in strengthening safety practices, especially during later operational stages. Figure 4 next presents results on senior management commitment and influence.

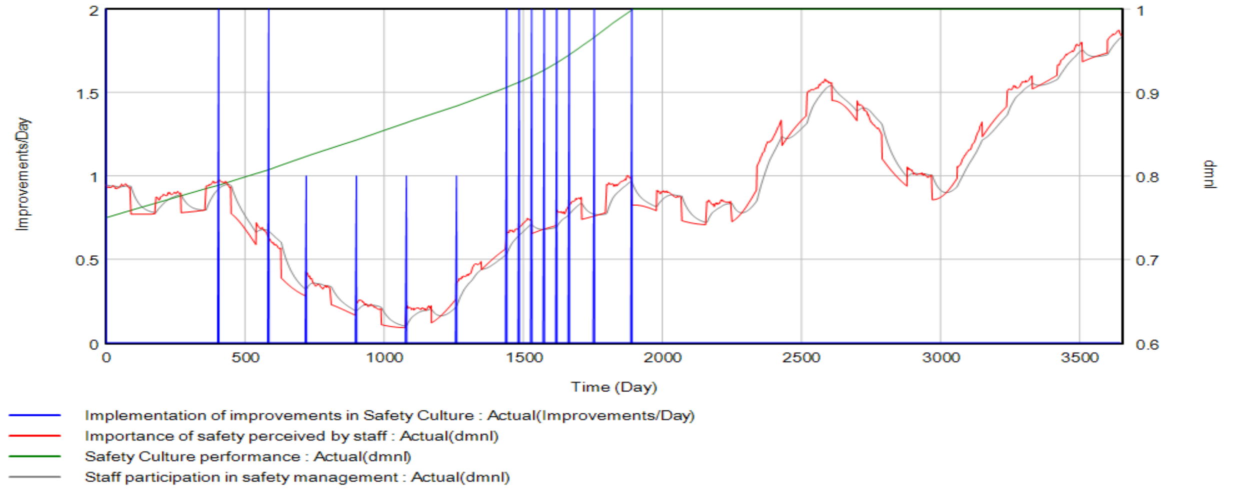
Figure 4 : Results regarding expected behavior 2



Source: authors' development

After 1,500 days of operation, safety culture improvements accelerate significantly as the implementation of improvement measures becomes more rigorous, bridging gaps between safety recommendations and performance. This milestone highlights the critical role of continuous improvement in strengthening safety practices, especially during later operational stages. Figure 5 next presents results on senior management commitment and influence.

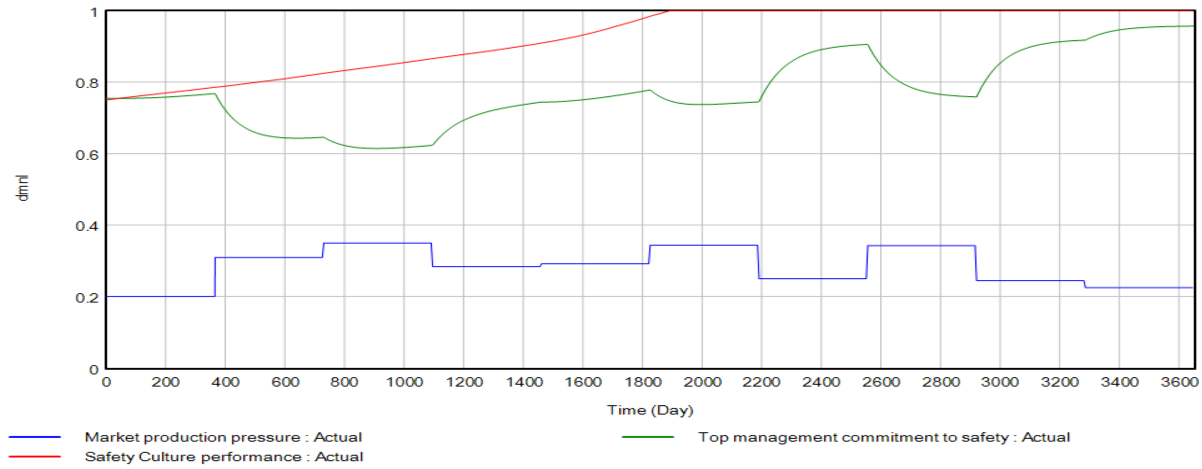
Figure 5 : Results regarding expected behavior 3



Source: authors' development

The results confirm the significant impact of senior management's active engagement and strong leadership on safety culture. Robust risk perception and unwavering commitment to safety have cultivated a stronger safety culture within the organization, underscoring the critical role of senior management in sustaining a positive safety environment throughout plant operations. Figure 6 presents findings on staff participation and adherence to safety.

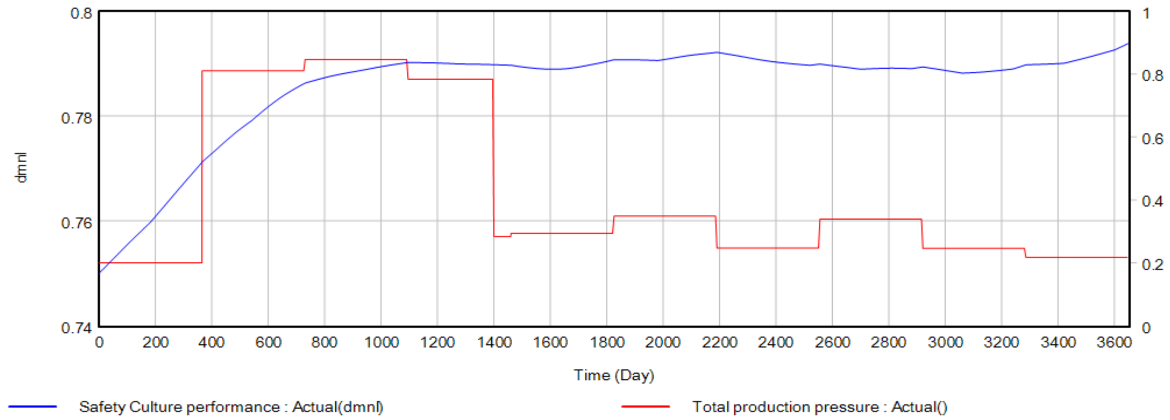
Figure 6 : Results regarding expected behavior 4



Source: authors' development

A stress test simulating three years of elevated production pressure revealed a measurable decline in safety culture performance, illustrating how prolonged high demands affect safety performance negatively (see Figure 7).

Figure 7 : Stress analysis to the model.



Source: authors' development

The analysis revealed notable shifts in the safety culture dynamics in response to the extreme load on production pressure. Specifically, there was a discernible decrease in safety culture performance. This finding aligns with the observations of [25] and [26], it identifies that sustained production pressures deprioritize safety focus, leading to gradual erosion in safety culture.

4. CONCLUSIONS

This study has advanced the understanding of nuclear safety culture by quantitatively modeling the interdependencies among various factors using system dynamics, addressing a significant gap in the literature. Previous studies primarily relied on qualitative assessments or static quantitative approaches that did not capture the dynamic interplay of factors influencing safety culture in nuclear power plants.

The introduction of a system dynamics model represents a significant contribution to nuclear safety research. By enabling the simulation of interactions over time, the model provides insights that are not apparent through static analysis. For example, our results demonstrate that leadership commitment plays a crucial role in initiating and sustaining improvements in safety culture. This finding aligns with the literature emphasizing leadership's role in shaping organizational culture and safety outcomes [29], [26]. However, our model uniquely illustrates how leadership influences other variables over time, thereby providing a roadmap for implementing and assessing changes.

The practical implications of our model are : by identifying leverage points where interventions could yield significant improvements, the model serves as a decision-support tool for nuclear power plant managers and policymakers. For instance, enhancing internal communication has been shown to directly affect staff's perception of safety's importance, leading to increased commitment and safer behaviors [15]. This improved safety culture is closely linked to enhanced operational performance, as demonstrated by previous research indicating that a strong safety culture reduces errors, mitigates risks, and supports efficient plant operation [11], [33].

Moreover, the model's ability to simulate various scenarios, including extreme conditions, enables organizations to prepare more effectively for potential crises. The stress test results underscore the resilience of a well-entrenched safety culture, even under increased production pressure. This finding should encourage the industry to maintain robust safety protocols, even when facing operational or market-driven pressures.

While the model provides valuable insights, several limitations need acknowledgment. The simplification necessary for modeling may overlook some nuances of organizational culture, such as subcultures within neither different departments nor the impact of external factors like regulatory changes [24], [14]. Future research could enhance the model's complexity to include these elements and examine their impact on safety culture more comprehensively.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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