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NUCLEAR SAFETY MANAGEMENT AFTER FUKUSHIMA ACCIDENT: A SYSTEMATIC AND CRITICAL REVIEW OF THE STATE OF THE ART

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Nuclear Safety Management after Fukushima accident. A systematic and critical review of the state of the art.

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Abstract. This study examines the available evidence about the state of the art of Safety Management in theory and practice applied in particular in the field of the nuclear reactors of the nuclear industry. (1) Background: During the last years, the operation of industrial facilities has advanced towards the integration of the various aspects of its management, mainly driven by the search and achievement of the highest operational performance in a competitive environment. The nuclear industry is no stranger to this movement, with the particular distinction of its main driver: safety in the operation of its facilities; (2) Methods: a systematic review to summarize and critically analyze state of the art on safety management, specialized in the management of nuclear power reactors and nuclear research reactors; (3) Results: out of 405 articles found, twenty-seven studies met the inclusion criteria for the synthesis and qualitative review, in particular, all these articles are about nuclear power reactors; (4) Conclusions: Based on the available evidence, the lack of frameworks and general models and integrators of the specific ones is the main deficiency of the area, where the conceptual, holistic or systematic models are of recent proposal and discussion.

Keywords: Nuclear, Safety, Management, Reactors

1 Introduction

Since its beginning, the nuclear industry has been a pioneer in developing and applying specific safety standards for the care of the worker, the environment, and society, integrating its own operating experience and accidents and that of the conventional industry. In these terms, this industry is considered from its technical performance as an ultra-safe macro-technical system (Amalberti, 2001).

In this sense, the academy has developed various theoretical approaches and models that explain the causes of the most relevant industrial accidents of the modern industrial era. These approaches have been integrated into the safety requirements and recommendations of the main relevant international and national organizations and mainly by the International Atomic Energy Agency (IAEA). These approaches were systematically integrating the lessons learned in the nuclear accidents that occurred (in Nuclear Power Reactors (NPP): Three Mile Island, 1979; Chernobyl, 1989; Fukushima, 2011. And in Research Reactors (RR) RA-2, 1983. By strengthening and expanding the scope of the domain of the factors that explain an accident and/or safety performance (Acuña et al., 2020).

In particular, this paper identifies and analyzes what specific academic contributions were made during the last decade to safety management in the operation of nuclear reactors, in light of the last nuclear accident that had consequences both on the assets of its operating entity, and in society as a whole (IAEA, 2015).

One of the lessons learned by the nuclear industry from the Fukushima Daiichi nuclear accident was the need to ensure the safety of its facilities with a more integrated approach to the factors that contribute to it (IAEA, 2014; Yang, 2014; IAEA 2015). Some of them being institutional, organizational, technology management and operation factors and human factors. These are included in the stream called Safety Management.

Safety Management (SM) is a relatively new and developing area of formal and multidisciplinary study (Pillay, 2015) that comprises a set of theories and practices on decision-making, resource management, execution of activities and tasks, and the results they achieve (positive or negative), about the safety performance of an industrial asset. These positive or negative results are directly related to the care and preservation of the organization's assets and those of society as a whole and the achievement and maintenance of a certain performance. Therefore, the care and preservation of these assets imply avoiding actions that have irreversible consequences (incidents and/or accidents). This is available from the design stages of the installation and the systems that operate and manage it.

2 Methodology.

2.1 Study Design, Search Strategy and Selection Process

Having considered conducting a systematic review, to carry out the study design, we follow the guidelines proposed by Oliveira et al. (2019). For this purpose, the SM of nuclear reactors was defined as a field study or objective of the survey.

To fulfill this objective, it was decided to use both academic search engines and specialized technical search engines. In this way, the search could be reached in documents published by non-academic publishers and/or presented in specialized conferences of the nuclear industry whose procedures are not academically indexed.

The academic search engines used were Science Direct and Scopus, and the INIS (International Nuclear Information System) of IAEA was used as a technical search engine. INIS "(…) hosts one of the world's largest collections of published information on the peaceful uses of nuclear science and technology. INIS is unique and valuable information resource, offering global coverage of nuclear literature". This search engine is widely used by academics and practitioners of the nuclear industry, so it was considered relevant.

These search engines were used for articles from peer-reviewed journals, presentations at congresses, and reports (technical documents), as the time window used the last ten full years, that is, from 2009 to 2019. This window and time filter allow us to survey the most recent publications before the Fukushima Daiichi nuclear accident that occurred in 2011 and how the lessons learned in this were incorporated into state of the art. Regarding the keywords used were: (safety management), (nuclear reactor), or (nuclear power plant). At the end of the keyword search, Zotero reference management software was used to select and record titles, abstracts, and full-text articles based on inclusion/exclusion decisions.

Studies were included if, for Scopus search:Contained the keywords "safety" and "management" and "nuclear" and ("reactor" or "plants") on Title+Abs+Keyboards. And for INIS search: Contained the keywords "nuclear and reactor" on All Words Filter.

Studies were excluded if they: were duplicates, referring to other facilities that are not reactors (e.g., accelerators, medical centers with radiation equipment, radioisotope plants, laboratories that operate radioactive sources). And if it was focused on SM applied on an only structure, system, component, or activity of the nuclear reactor (e.g., fuel, wastes, maintenance) without a vision about the totality of the installation.

2.2 Classification criteria

Considering the preceding paragraphs and the reading and analysis of the articles, five thematic areas were defined to classify the articles according to their contributions.

Criteria to classify the articles are:

- Frameworks and Theories for Safety Management: Articles whose content presents frameworks for addressing SM issues considering the particularities of NPP or makes theoretical statements about it.
- Safety Culture: Articles whose content presents applications or interpretations about Safety Culture as contributors to the understanding or measurement of SM.
- Management systems: Articles whose content presents proposals or cases of application of Safety Management Systems (SMS) at different organizational or institutional levels of an NPP.
- Applied Safety Management: Articles whose content presents case studies, development, or application of tools to implement or measure SM in Nuclear Power Plants.
- Safety Performance: Articles whose content presents different contributions to the application of tools for the measurement or understanding of safety performance.

3 General Results.

When applying the methodology described above, a total of 27 articles were recovered. The table below (Table 1) presents the qualitative synthesis of the articles recovered.

Table 1 Characteristics and summary of documents recovered.

#	Author (year of publication)	Title See Reference List	Country	Type of Document	Thematic Area Classification
1	Hildebrand M., et al. (2009)	[1	Norway	Conference Paper - Human Factors and Ergonomics Society Annual Meeting	Applied Safety Management
2	Kavoliunas M., et al. (2009)	[2	Canada	Professional Report – SAE International	Management Systems
3	Cullen R. (2009)	[3	UK	Conference Paper - Institution of Chemical Engineers Symposium Series	Safety Culture
4	Zhai Z. (2009)	[4]	China	Conference Paper - IEEE IEEM	Frameworks and Theories for Safety Management
5	Wahlström B., Rollenhagen C. (2010)	[5]	Sweden	Conference Paper - International Conference on Operational Safety Experience and Performance of NPPs and Fuel Cycle Facilities	Frameworks and Theories for Safety Management
6	Guldenmund F. (2010)	[6]	Netherlands	Journal Paper - Journal of Risk Analysis	Safety Culture
7	International Nuclear Safety Advisor Group (2010)	[7]	Austria	Professional Report – INSAG - IAEA	Frameworks and Theories for Safety Management
8	Paradies, M. (2011)	[8]	USA	Journal Paper - Process Safety Progress	Applied Safety Management
9	Himanen, R., et al. (2012)	[9]	Finland	Journal Paper - Journal of Risk Analysis	Applied Safety Management
10	Reiman, T., Rollenhagen, C. (2012)	[10]	Sweden	Conference Paper - World congress on Ergonomics - Designing a sustainable future	Frameworks and Theories for Safety Management
11	Shan Z. (2012)	[11]	China	Conference Paper - Probabilistic Safety Assessment and Management	Management Systems
12	Wu Y. et al. (2012)	[12]	China	Conference Paper - International Conference on Automatic Control and Artificial Intelligence	Frameworks and Theories for Safety Management
13	Latorre Navarro, et al. (2013)	[13]	Mexico	Journal Paper - Journal of Safety Research	Safety Culture
14	Wahlström B., Rollenhagen C. (2014)	[14]	Netherlands	Journal Paper - Safety Science	Frameworks and Theories for Safety Management
15	Akselsson R. (2015)	[15]	Sweden	Conference Paper - Conference on Safety and Reliability of Complex Engineering Systems	Management Systems
16	Kouabenan D, et al. (2015)	[16]	France	Journal Paper - Safety Science.	Safety Culture
17	Ruimin M., et al. (2015)	[17]	China	Journal Paper - Journal of Energy Policy	Management Systems
18	Ding C, et al. (2015)	[18]	Taiwan	Journal Paper - Safety Science	Applied Safety Management
19	Saqib N., Siddiqi M. (2016)	[19]	Pakistan	Journal Paper - Safety Science	Applied Safety Management

20	N. Dechy et al. (2016)	[20]	France	Conference Paper - International Conference on Human and Organizational Aspects of Assuring Nuclear Safety	Frameworks and Theories for Safety Management
21	Vieira Neto S., et al. (2017)	[21]	Brasil	Conference Paper - International Nuclear Atlantic Conference	Applied Safety Management
22	López de Castro, et al. (2017)	[22]	Spain	Journal Paper - Journal of Accident Analysis and Prevention	Safety Culture
23	International Nuclear Safety Advisor Group (2017)	[23]	Austria	Professional Report	Frameworks and Theories for Safety Management
24	Kim J., et al. (2018)	[24]	South Korea	Journal Paper - Annals of Nuclear Energy	Applied Safety Management
25	Martínez-Córcoles M., et al. (2018)	[25]	Spain	Journal Paper - Journal of Psychologist papers.	Applied Safety Management
26	Wahlström B. (2018)	[26]	Finland	Journal Paper - Safety Science	Frameworks and Theories for Safety Management
27	Sui Y. et al. (2018)	[27]	China	Journal Paper – Journal of Cleaner Production	Management Systems

3.1 Quantitative distribution of the articles.

The thematic distribution of the articles is detailed in Table 2. In this table, it can be seen that the dominant thematic areas are “Frameworks and Theories for Safety Management” with ten papers, followed by “Applied Safety Management” with seven documents, and finally with five papers “Safety Culture” and also 5 for “Management Systems”. Regarding the distribution of the types of documents retrieved, most are concentrated on papers published in Journals with 14 papers, followed by conference papers with ten papers and finally in Professional Reports with three documents.

The journals with the most publications are Safety Science (5 papers) and Journal of Risk Analysis (2 papers), the rest of the publications (7 papers) have each been made in other Journals (Journal of Risk Analysis, of Safety Research, of Energy Policy, of Accident Analysis and Prevention, of Nuclear Energy, of Psychologist papers, of Cleaner Production). This seems to confirm the multidisciplinary nature of SM.

Regarding the Conference Papers, they do not focus on any particular topic. These being presented at different conferences: of Human Factors and Ergonomics Society Annual Meeting, of Institution of Chemical Engineers Symposium Series, of IEEE IEEM, of International Conference on Operational Safety Experience and Performance of NPPs and Fuel Cycle Facilities, of World congress on Ergonomics - Designing a sustainable future, of Probabilistic Safety Assessment and Management, of International Conference on Automatic Control and Artificial Intelligence, of Conference on Safety and Reliability of Complex Engineering Systems, of International Conference on Human and Organizational Aspects of Assuring Nuclear Safety and of International Nuclear Atlantic Conference. The professional reports 2 correspond to INSAG and 1 to SAE International.

Table 2 Thematic Distribution and Tipology of Recovered Documents

Quantitative Distribution by Thematic Area		Quantitative Distribution by Type of Document		
Thematic Area	**Total Quantity (percentage)**	**Journal Papers (percentage)**	**Conference Papers (percentage)**	**Professional Reports (percentage)**
Frameworks and Theories for Safety Management	10 (37%)	6 (32%)	2 (40%)	2 (67%)
Applied Safety Management	7 (26%)	6 (32%)	1 (20%)	0 (0%)
Safety Culture	5 (19%)	5 (26%)	0 (0%)	0 (0%)
Management Systems	5 (19%)	2 (11%)	2 (40%)	1 (33%)
Total	**27 (100%)**	**19 (100%)**	**5 (100%)**	**3 (100%)**

The temporal distribution of the documents seems to be homogeneous, and there are contributions in all thematic areas. The authors with the largest number of papers carried out or in which they had participation as the main author are Wahlström B. with a total of 3 papers (2010, 2014 and 2018) and as the second author, also with three papers to Rollenhagen C. (2010, 2012 and 2014). Finally, with two documents, *INSAG* contributed in 2010, 2017. All contribute to the theoretical field (thematic area "Frameworks or Theories of Safety Management").

The years where most papers were found were in 2009, 2012, 2015, and 2018 with four papers. For 2009 Zhai Z.; Cullen R.; Kavoulinas et al.; Hildebrand M. et al. For 2012 the papers corresponding to Reiman T. & Rollenghagen C.; Himanen R. et al.; Shan Z. and Wu Y., et al., The 2015 papers are by Kouabenan D. et al.; Akselsson R.; Ruimin Mu et al. and Ding C., et al. Finally in 2018 the works found were by the following authors, Wahlström B; Sui Y. et al.; Kim J. et al. and de Martínez-Córcoles M., et al.

The largest amount of contributions come from China with five documents, followed by Sweden with three documents. There are two documents with affiliations in Austria, Finland, Spain, the Netherlands, and France. Finally, with 1 document, they make contributions: Norway, South Korea, Mexico, Taiwan, USA, Brazil, Canada, Pakistan, and the UK.

The number of publications in China is explained by the boom and development that nuclear energy has had in that country during the last twenty years.

3.2 Content Analysis.

This section presents a brief synthesis and discussion of the recovered documents, classified in the different thematic areas. It begins with the thematic area of "Frameworks and Theories for Safety Management," in which the documents present the greatest conceptual development. From this area, it would be expected that the other areas would come off. It will continue with the thematic area of "Applied Safety Management", followed by "Safety Culture" and it will end with "Management Systems".

The research discussion goes from the more general to the more specific contributions. Also, this development will be crossed with the contribution of the main theories of safety thinking that were detailed in section 1 of the introduction.

Frameworks and Theories for Safety Management.

Wahsltröm & Rollenhagen (2010) in their paper “Models, Methods and tools for Safety Management” indicates that there is no integrative model that can be used to understand or describe SM without falling into a trivial representation that is useless for plant managers or reactors heads, decision-makers or senior management of a reactor operating organization. Furthermore, these authors raise the need to develop a framework or a framework model that can integrate the contributions of all or methods that explain, analyze, or describe some relevant factor in safety. This need becomes stronger when the question is asked, “What is safe enough?” because these authors still have no answer.

These same authors in 2014, take up the analysis, in their previous work, and the paper “Safety Management as a multi-level control problem”. They propose to use a controlling metaphor to understand the problem of integrated and operational nuclear safety. This metaphor is useful for the design stages and their evaluation and should be adopted in the reactors' operation stage. This paper identifies the multiplicity of hierarchical levels involved in reactor safety. This multiplicity of levels and actors requires using a common language for a common understanding of the problem. For this, the metaphor of control is useful to define a conceptual framework for the identification, definition, and eventual integration of various models, also, for their input and output variables and state spaces. Finally, the authors propose to use the polycentric control design tools and the Man, Technology, Organization and Information model (MTOI) to integrate these conditioning factors of nuclear SM.

The paper "Systemic Thinking in support of SM in nuclear power plants" by Wahlström (2018), considers in the definition of the theoretical proposal of the works of Wahsltröm & Rollenhagen from 2010 and 2018. This authors defining a model of a Socio-technical system that can be used. The reality of an operational NPP presents dynamic interactions between the design of the operation and the practices of the operation. Each of them is feedback to the other two. For this reason, a system of systems models is required. This mode must consider the model plant states and perform an integration between hard and soft operating systems. This integration in Wahlström's words is only possible from the qualitative-quantitative systems of systems thinking “I see systemic thinking as a broad concept involving various kinds of models as well as the need for considering both entireties and details”.

The Technological view of the problem, and in particular in the design stage, deals with the plant architecture from the System Breakdown Structure (SBS). In the nuclear industry, SBS is known as structures, systems, and components (SSC). And tools and techniques of safety engineering are applied to it. These results guide SM during operation.

Related to the human-related view, the design of the prevention issues is aboard from the Hazards and Consequences analysis. This analysis identifies the natural, technical, or human sources and their relationship with the different plant states. Then again, Safety engineering encompasses actions for eliminating, isolating, controlling, and mitigating these identified risks applying mainly the concept of Defense in Depth (INSAG, 1996). In that to address the model of Failures, errors and deficiencies (risk analysis) from human errors and organizational deficiencies are still difficult. In this sense, it is convenient to consider the drivers and goals of the operating organization, the management systems involved, and the use of tools for decision support. Also, for other organizational issues, the methods of selection, education, training of personnel, the managers and leaders' behavior, and the involvement of the Stakeholders in the safety process are important. Considering this, the MTOI model seems the better way to accomplish it.

As a contribution to this vision, INSAG makes two clarifying contributions. The first, in 2011, the document "A Framework for an Integrated Risk-Informed Decision Making Process," details a methodology for the integration of operational risk from probabilistic (technology and human-related) and deterministic (technology-related) analysis. This methodology proposes a way of integrating the different approaches of the classical safety assessment. This is done by establishing requirements that focus attention on the reactor operating license holder and how to ensure that a decision made in one area does not conflict with other decisions. This proposal does not contemplate a multi-level vision in the decision-making characteristic of the operational face. Furthermore, it seems to have greater applicability to design tasks than to operational management tasks.

Meanwhile, INSAG in his document “Ensuring Robust National Nuclear Safety Systems - Institutional Strength in Depth” in 2017, he proposed a way to integrate this process and online safety analysis by merging the concept of defense in depth traditionally applied to the technological dimension of SM. This proposal considers the institutional dimension of risk and its impact at the operational level. This aspect is directly related to the lessons learned in the Fukushima accident. Likewise, with a pragmatic perspective, he presents the systemic vision proposed by Rasmussen (1997) as his main influence. In this pragmatic vision, the role of the regulatory entity and its deficiencies as an influencing factor in safety are included in the safety analysis. It also raises the need for a systemic vision of the SM problem that integrates human, organizational, and technical factors. The way to approach a Robust Nuclear Safety System as supra operational level is considering three levels. These levels are the level of the operator and holder of the operating license and its environment, the level of the regulatory body and the level of the stakeholders, and the exercise of their pressures.

Dechy et al. (2016) present a paper addressing modes of transfer of the lessons learned in industrial accidents to the nuclear industry. They were starting to wonder if all majors’ accidents have socio-technical roots (beyond technological differences). The authors identify common patterns and causes between both industries and propose two types of transfer the content issue: (a)“Knowledge of Accidents” and (b)“Culture of Accidents”. From them, and a bibliographic review identifies the so-called pathogenic organizational factors.

Finally, in this thematic area, the papers by Zhai et al. (2009) present the Event Analysis and Report System (for incidents or accidents) from 3 conceptual levels (root, nature, and surface). It states that an event is produced by socio-technical causes and a variety of factors (technical, human, and organizational) that must be integrated. This model takes some hypotheses from Reason (1997) since it proposes that: "While technical factors can be random, human and organizational factors do not appear randomly but interact with each other through a hierarchical structure of three levels: behavior (what), contextual (where) and conceptual (how)".

The authors propose using Failure Modes and Effects Analysis (FMEA) and Probabilistic Safety Analysis (PSA) to solve the qualitative dimensions of the problem. And for the quantitative analysis, proposes to use Bayesian Belief Net (BBF), and deterministic dynamic techniques. For them, it recognizes that the greatest source of inter-certainties comes from human and organizational factors. These should be analyzed in the framework of causal analyzes based on plant operational experience. This proposal seems to consider a complete image of a relevant event for the reactor's SM. But it is a tool for analyzing causes and not postulates proactive concepts that anticipate unwanted events.

Viera-Nieto et al. (2017), in their work Soft Systems Methodology as a Systemic Approach to Nuclear SM, explores the applicability of soft systems theory to SM issues. In their work, they emphasize that this methodology is useful for modeling complex socio-technical systems. Carry out a bibliographic review and establish the necessary analyzes in this method. The analyzes are that of roles (individuals), social (cultural), and political. To these analyzes is added the description of the vision of the problem of each stakeholder. Then activity models are made from identifying the clients, actors, transformation, "Weltanschauung", Owners, and Environmental constraints. Finally, highlights the experience of applying these systems in the Brazilian nuclear system.

In 2012, Wu et al. (2012) proposed the affecting factors of SM of nuclear power based on the Interpretive Structural Modeling (ISM) methodology. This tool is used for represented relationships with a multi-level hierarchical structure visually. The results is a very conceptual model with relations between safety factors that are more compatible with applying to design SM than operational SM. It is expected not to differentiate the stages of the life cycle of a reactor. The focus on safety should be consistent between stages. If the design stage were considered as the genesis of the modeling, it would be more applicable than considering the reactor's operational actions. Therefore, the work recommends refining and expanding the model using other tools such as Fuzzy AHP.

Applied Safety Management.

In this thematic area, papers were recovered with contributions in two directions. The first is about the measurement of safety performance (Hildebrandt et al. 2009), (Himanen et al. 2012), (Saquib et al. 2016), and (Martinez-Córcoles et al. 2018). The second concerning the development of tools to measure levels or degrees of SM (Ding et al. 2015), (Paradies, 2011) and (Kim et al. 2018).

As mentioned, several authors discuss the measurement of safety and performance. Saquib et al. (2016) reflect on the consistency of the use of various safety performance indicators. This consistency is questionable when these indicators are measured to calculate a single comprehensive and strategic indicator. Within the framework of this strategic safety indicator, the weighting of these different operational indicators has different impacts. That impact depends on the independence of the input data and how those data are independent of each other when they affect multiple indicators. To inhibit these unwanted effects, he proposes an objective equation.

Meanwhile, Martínez-Córcoles et al. (2018) state that the literature on safety behavior is scarce. Similarly, the definition of safety performance should be narrowed. To this end, it carries out a bibliographic review focused on measuring human factor safety in the nuclear industry context. He highlights his observation on safety compliance in terms of how prescriptive regulation appears to be in this industry. He attributes this to potential hazard by the understand of safety performance through relating risk, safety engagement, and safety compliance.

Hildebrandt et al. (2009) et al., discuss the need to modernize the Human Reliability Assessment (HRA) in the context of SM. For this purpose, the use and formation of communities of practice are proposed. From this, they propose a “living” HRA that takes as input the results of these communities of practice. Recognize the value of HRA as part of the Probabilistic Safety Analysis (PRA) of a nuclear power plant. It also identifies the need to develop methods that contemplate the cognitive dimensions of the operators.

Himanen et al. (2012) describe the regulatory requirements of the nuclear industry in Finland. This was done for four operational nuclear power plants. Describe how the PRA development process contributes to SM practices in the prevention of severe accidents. This is due to the need to define probabilistic safety criteria. This includes the frequency of core damage, a risk metric in nuclear safety. As the three levels for PRA was applied, the Finnish NPP operating institution gained mastery over these and other risk-informed applications.

Paradies (2011) qualitatively, compares the results of military nuclear reactors used for propulsion with reactors operated by civil organizations used to electricity generation. Given the exceptional safety record of the United States Navy reactor process, the author wonders how much this influences the military safety process. To answer this question, compare the philosophy of the US Navy with the process SM of the Chemical Process Center and its safety guidelines. In his analysis, the author identifies that there are many gaps between them. The gaps are identified in the difference in rigor posed by the military management model compared to the civilian one. That rigor seems to contribute to better safety results.

Ding (2015) develops a model to identify hidden factors and risk determinants in the nuclear power plant's operation. To do this, he analyzes the failure records of 342 pumps from a large nuclear power plant with a period of 28 years. To do this, use the Latent Growth Modeling (LGM) method. The author postulates hypotheses based on a bibliographic review and the characteristics of the expected failures of the different types of pumps. Using the mathematical model, he confirms four of his five hypotheses. Their contribution seems to be that identifying the factors contributing to risk in SM is always an unfinished task due to hidden factors.

Kim (2018), in his article "Development of a quantitative resilience model for nuclear power plants", is the first author to present the results of the application of the theoretical proposals of Hollnagel et al. (2006). This proposed model takes as input the lessons learned from Fukushima and the French electricity company's experience. To do this, resistance is defined based on the relationship of performance variables such as

Anticipation, Adaptation, Collective Functioning, and Robustness. To develop the quantitative model, 222 event reports from 2003 to 2016 are used. Finally, validate your model through statistical analysis, with data from 26 nuclear power plants. They argue that this model is complementary to classical nuclear safety analyzes results, both probabilistic and deterministic.Given the recent nature of this model, it is convenient to apply and validate it in other nuclear power plants in countries with cultures other than Korean.

Safety Culture.

In this thematic area, papers were recovered with contributions in 2 directions. The first concerning the discussion and utility of the concept of Safety Culture (Guldemund, 2010) and (Cullen, 2009). The second with the measurement of the safety climate as a proxy for the Culture of Safety of the organization (Latorre Navarro et al. 2013), (Kouabenan, et al. 2015), and (López de Castro et al. 2017).

Guldemun (2010), in his article "(Mis) understanding Safety Culture and Its Relationship to Safety Management," criticizes the treatment that academics and practitioners have given to the concept of Safety Culture (SC). His strongest statement is that "the culture concept is deprived of much of its depth and subtlety, and is morphed into a grab bag of behavioral and other visible characteristics, without reference to the meaning these characteristics might have and often infused with normative overtones."

In this sense, he performs a bibliographic review comparing SC's concept according to the components and layers that each author postulates. To link the SC to SM, he inspects how the SC assessment contributes to nuclear safety assessments,

The treatment of SC as the main basis for the study of nuclear safety is addressed by Cullen (2009). In his paper, he presents a practical way of internalizing the concept of the safety processes of a plant. When presenting the description of perception in the different processes, the differences in the vision of the participants in each one are shown. It concludes on the need to take actions to achieve a common understanding of SC's implications in all processes.

Another aspect of the academic application that was revealed about SC is its application to understand and measure the safety climate of the nuclear reactor's operating organization. In this sense, Latorre Navarro et al. (2013) present the development of a questionnaire and a standardized scale to be able to understand the nuclear safety climate in an NPP in Spain. He correlated these concepts with formal safety practices such as written procedures, and observable variables such as safety behavior and time pressure. Finally, he validates its results using factor analysis.

Koabenan et al. in 2015 argue that the safety climate is the key variable to explain the perceived risk and the involvement in safety on the part of the front-line managers of 2 French NPPs. To do this, it conducts questionnaires in the field to 63 managers. Their results are analyzed by SSPS software using Chronbach's Alpha test. The hypothesis is confirmed by its results. As a particular observation, they find that employees' safety behavior has almost no influence from managers. While the direct supervisors of the activities are influential in the perception of safety, in this sense, the paper by Castro et al. (2017) presents a similar work, carrying out a comparative study on the perception of daily safety by applying a Safety Culture Enactment Questionnaire to the staff of two Spanish NPPs. They use Confirmatory Factor Analysis to validate the consistency of the results and conclude that it is a valid tool for measuring safety culture.

Management Systems.

Papers with contributions in 2 directions were recovered in this thematic area. The first concern is conceptual discussions on applications of management systems Kavouliunas, et al. (2009) and Akselsson (2015). The second, with the implementation of management systems for safety in China Shan (2012), Ruimin, et al. (2015), Sui (2018).

For the discussion of the management systems' applications, Akselson (2015) recognizes that the requirements for these systems are relatively new and are in development. It also recognizes that there are no mature systems in the industry, particularly in NPPs. It still takes a lot of effort to have cadres of highly trained managers in the new vision of SM applied trough a management system.

On the other hand, it addresses the discussion about the indicators. It is necessary to propose indicators that can capture subtle and little obvious behaviors, deviations, or events that initiate accidents. Meanwhile, Kavouliunas (2009) establishes that nuclear SMS require developing a structured risk management process. The risks come not only from technological failures but from the interaction of technology with the man. This author recommends as imperative to develop objective decision-making mechanisms based on NPP data and risk. For this, developments must be made that integrate the probabilistic, deterministic, and quantifiable elements.

For experience in the implementation of management systems for safety in China, Ruimin (2015), in his paper "China's approach to nuclear safety - From the perspective of policy and institutional system," details the country's nuclear safety policy. This is reinforced because mechanisms that prioritize it are established from the political and institutional perspectives. Laws, institutions, ministries, and organizations aligned on a single priority. In this work, all the interventions of these elements are mapped during the life cycle of the numerous NPPs that are operational and under development.

Shan (2012) presents the experiences gained by the China General Nuclear Program Group based on the proposals of the National Regulatory Commission of the USA. To do this, they developed a Reactor Supervision Process. A system independent of the classic already implemented. This new system considers an implementation based on risk management and structured on three levels: the unit level, the site level, and the multi-site level.

Finally, Sui (2018) details the experience gained in implementing a SMS in an NPP in eastern China. This implementation was leveraged by the development of a computer system that made it possible to standardize data processing for decision-making.

4 Discussion and Future Research.

After the Fukushima Daichii accident, there is agreement on the risk factors and causes of nuclear accidents. These factors are technological, human, organizational, and institutional (which includes the regulatory). On the other hand, the models revealed in this paper for the thematic area of Frameworks and theories of SM still cover spaces that are too abstract and somewhat distant from those of technological safety engineering. No postulates are observed that relate physical variables of the plant and the "soft" variables of safety. In this sense, the concept of Safety Culture (a strong and useful concept) seems to become a free interpretation of each author that is diffuse or lax.

It is observed that these approaches require a complex process of internalization within each organization, and it would be advisable to review their scope and definition ontologically. On the other hand, as it is a discipline proclaimed as multidisciplinary, the application of tools from the theoretical field of SM to the practical field is wide but much unconnected in its results and many other times inconclusive. There is a research opportunity in addressing the question of what and how much is safe for the nuclear industry.

Regarding the recovered documents, 27 documents relevant to NPP were obtained, but none for nuclear research reactors. Although there was an accident in this type of reactor (RA-2, 1982) and there are currently more than 100 such reactors in operation, this object of study does not seem to arouse interest in the academy. Perhaps it is because both the risks, magnitudes, objectives, and interests are quite different for NPP and RR. Regarding the academic treatment revealed on SMS applied to the nuclear industry, there is no evidence of common features among them (framework, architecture, principles). In this sense, there is a theoretical gap in the consolidation of a specialized methodological framework that contemplates the treatment of the risk inherent in this industry.

As Wahlström (2010) stated, it is necessary to propose a framework that allows integrating all the models, meta-models, and concepts that were presented. For this, the proposal of Wahlström & Rollenhagen (2014) about assuming the metacentric of polycentric control and INSAG (2017) and Wahlström (2018) of implementing the systems system vision and the MTOI model seem to be the most appropriate to integrate them. Likewise, this proposal would allow a priori to be able to use as inputs the results of mature nuclear safety engineering tools in the nuclear industry and High Reliable Organizations.

5 Conclusions

SM was contextualized in the history of safety thinking and the causes of nuclear accidents and major industrial accidents.

The state of the art of SM for nuclear reactors was systematically surveyed. Science Direct, Scopus, and INIS were used to this end, and 27 academic articles and professional reports were retrieved. From this, the actual academic scope of nuclear SM has been identified. According to the methodology proposed by Olivera et al. (2019). Finally, the findings were critically discussed, and new lines of research were recommended.

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