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Safety culture and nuclear safety management. Analysis of the relationships of its variables through a bibliographic review and AHP.

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Objective: Based on previous literature reviews, this study examines the evidence about the key elements of the safety culture constructs applied in nuclear reactor operating organizations. Background: Safety culture (SC) is an organizational concept born in the nuclear industry to the behavioural elements in the safety management of nuclear facilities. This concept has been continuously revisited by academics and practitioners and has even been widely adopted by the conventional industry. Methods: systematic bibliographic review to identify key concepts of safety culture. Analytical hierarchy process (AHP) is applied to rank these concepts through an online questionnaire delivered to experts; Results: six articles were found, and four key concepts of safety culture were identified. These concepts were ranked in the following order after expert AHP online questionnaire results analysis: top management leadership, communication management, safety climate, and hazard and risk analysis; Conclusions: Based on this research the leadership actions are the most important nuclear safety management action to achieve the nuclear safety goals of the nuclear reactor operation.

Keywords: nuclear, safety, management, reactors, AHP.

1. Introduction

Safety culture (SC) is an organizational concept born in the nuclear industry to the behavioural elements in the safety management of nuclear facilities. Proposed by the International Nuclear Safety Advisory Group (INSAG) in INSAG (1986) and improved in INSAG (1991) this concept has been continuously revisited by academics and practitioners and has even been widely adopted by the conventional industry.

According to Acuña, Giménez, and Sánchez (2022), in the context of the nuclear industry the organizational factor comprises: direct observation management mechanisms, such as those related to the safety management system (SMS) processes, and indirect observation management mechanisms, such as those related to safety culture. Guldenmund (2010) emphasizes that another characteristic of SC is its intangibility and its quality of being diffuse, as it is based on adopted and shared assumptions among individuals in an organization, giving meaning to their perceptions and actions, as well as those of others.

Since its formulation in INSAG (1991), this construct has received many different approaches and contributions, moving away from the original approach. This original state defines: ‘‘Safety Culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance’’.

In this regard, Guldenmund (2010) also indicates that along the years "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 actually have, and often infused with normative overtones."

Based on the statements in previous paragraphs and from a practical standpoint, this paper seeks to identify the safety culture key components that are closely related to the safety management system processes and programs (which are directly observable mechanisms of management) of a nuclear power plant operation organization. This is postulated assuming that these key elements are considered to have greater significance and influence in the achievement of nuclear safety goals of this kind of organization.

2. Methodology

To aswer the following research question: What are the key elements of safety culture that are most relevant to achieving the safety goals of a nuclear reactor operating organization, mediated by its safety management system? A systematic literature review is conducted on literature reviews, state-of-the-art, and oversight papers regarding safety culture. The systematic literature review following the guidelines of José de Oliveira et al. (2019). SCOPUS and the, International Nuclear Information System (INIS) databases are used applying the following search strings in "title": "safety culture" AND "review," OR "state-of-the-art," OR "bibliometric," OR "oversight".

From the literature review, the key elements of safety culture are identified. The criterion for identifying the key elements is based on which ones were most commonly recognized as key in the literature and were also indicated in the IAEA's (2016) General Safety Requirements Part 2 standard, which pertains to the safety management of nuclear facilities.

Then, the AHP method of Saaty (1990) is used to rank the relative importance of the identified variables.

The input to the AHP methodology is obtained in two stages: First, through an online questionnaire based on Bryman and Bell (2011). In this questionnaire, experts' preferences between variables identified in the systematic review of the literature were investigated. The experts included researchers, nuclear reactor operators, and nuclear industry regulators.

Then, in the second stage, the preferences of the research team are surveyed in the comparison of all the criteria postulated and not repeated. In this way, the judgment of experts is obtained for the order of the variables and the judgment of the researchers to sensitize in future investigations to the relative importance between the postulated criteria.

Finally, the results are calculated, processed, and interpreted using the AHP methodology.

3. Results

3.1. Identification of safety culture key concepts (SCKC).

Applying the search criteria in SCOPUS and INIS databases, 134 results was founded in the first academic search engine and 359 results was founded. After removing duplicates, six documents were recovered.

Papers whose scope was specific to particular industries such as healthcare, aerospace, transportation, chemistry, and others were excluded. Additionally, case studies, documents focusing on specific regulatory frameworks of individual countries, technical papers, research studies, and guideline documents on assessing safety culture were also excluded. Only papers with a defined methodology for retrieving relevant works for analysis and content review were considered.

After applying all the aforementioned exclusion criteria, a total of six papers were obtained. The results of applying the search and exclusion criteria, can be observed in Fig. 1. Also that Figure shows their temporal distribution, and the temporal coverage of their literature reviews.

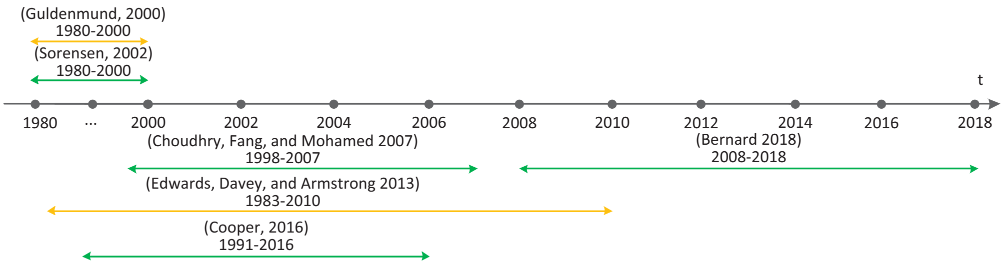

Fig. 1 Timeline of the retrieved papers and temporal coverage of its literature review.

After obtaining the documents, content analysis was carried out to identify key concepts in the SC. The content analysis implied recognizing the most relevant concepts regarding SC in each work. After identifying those elements in the content review, they were searched for in the "General Safety Requirements" (GS-R Part 2) of the IAEA (2016). Below, in Table 1, the breakdown of the results for the identified SC key concepts is presented, along with their presence or absence on the IAEA (2016).

Table 1 Breakdown of the SC key concepts and IAEA (2016) requirements coincidence.

#	Safety culture key concept/Paper	(Guldenmund 2000)	(Sorensen 2002)	(Choudhry, Fang, and Mohamed 2007)	(Edwards, Davey, and Armstrong 2013)	(Dominic Cooper 2016)	(Bernard 2018)	(1) TOTAL mentions	(2) IAEA (2016)	IAEA (2016) requirement	Coincidence between (1) and (2)
	Period coverage	1980-2000	1980-2000	1998-2007	1983-2010	1991-2006	2008-2018	-	-	-	-
1	*Safety management system*	-	-	√	-	√	√	*3*	√	*3, 5, 6, 7, 8, 13*	√
2	*Safety climate*	√	-	√	-	-	-	*2*	-	-	-
3	*Top leadership management*	-	-	-	-	√	√	*2*	√	*2*	√
4	Risk management	-	-	-	-	√	-	1	√	1, 5, 7, 12, 13	√
5	Communication	-	√	-	-	-	-	1	√	12	√
6	Management commitment	-	√	-	-	-	-	1	√	2	√
7	Safety training	-	√	-	-	-	-	1	√	3	√
8	Environmental control and management	-	√	-	-	-	-	1	-	-	-
9	Stable workforce	-	√	-	-	-	-	1	-	-	-
10	Positive safety promotion policy	-	√	-	-	-	-	1	√	2, 3	√
11	Behavioural practices	-	-	-	√	-	-	1	√	2, 3, 12 ,13	√
12	Norms	-	-	-	√	-	-	1	√	1, 9	√
13	Beliefs	-	-	-	√	-	-	1	-	-	-

14	Values	-	-	-	√	-	-	1	√	2, 8	√
15	Attitudes	-	-	-	√	-	-	1	√	2, 12	√
16	Assumptions	-	-	-	√	-	-	1	-	-	-
17	Expectations	-	-	-	√	-	-	1	√	1, 5, 8, 11	√
18	Safety performance	-	-	-	-	√	-	1	-	-	-
19	Learning	-	-	-	-	-	√	1	√	2, 12, 14	√
20	Human Performance	-	-	-	-	-	√	1	-	-	-

The results obtained and presented in Table 1 reveal a notable homogeneity in the focus of the identified SC key concepts, with a predominant emphasis on elements associated with operational management practices at the meso-organizational level. However, this homogeneity is not perfect or complete, as the work by D. Cooper (2016) specifically addressed individual operational aspects (at the micro-organizational or individual level).

Based on the results, the relevance of the SMS as a mediator of safety culture towards its more tangible expression is observed. Additionally, in alignment with the IAEA, the concepts most identified by the authors are SMS, safety climate, top leadership management, and risk management.

3.2. Concepts operationalization.

This section presents the operationalization of the SC key concepts identified in subsection 3.1.

Each concept is considered in the context of practical and pragmatic SC and safety management. For this each one was elaborated an operational definition. In the case of SMS, it took a particular operationalization considering two of the more distinctive process of this type of system: hazard and risk analysis and communication management. Acuña, Brollo, and Torres (2019) and, Domnic Cooper (2016). Communication management is a managerial practice of effective transmission of information within the organization, which influences and directs people's behavior. Newstrom (2011). On the other, hazard and risk analysis is a decision-making process characteristic of the nuclear industry, which is guided by regulations that are mostly risk-informed. For this reason, this typical process in the SMS of said industry gives specific input to the decisions and actions of senior management and, consequently, to its exercise of leadership on the safety status of the nuclear reactor organization. Next, the concepts are defined as variables by the research team of this paper:

Safety climate (V1): global perception of the safety aspects of the organization that can serve as a reference on which to develop one's own safe/unsafe behavior or on the judgment of others' patterns of safe/unsafe behavior. Top management leadership (V2): set of features and actions of the organization's senior management to achieve individual and organizational radiation and nuclear safety objectives. Hazard and risk analysis (V3): the process of identification and evaluation of the dangers of activity, the conditions that originate them, and their potential unwanted consequences. Communication management (V4): set of actions and processes (of design, planning, execution, measurement, and correction) to make known and knowing news pertinent to the nuclear safety of the organization.

3.2 AHP problem structure.

The AHP problem is structured by the objective of rank the impact on safety management of the SC elements identified in the previous section. For this purpose following Saaty (1990), three comparison criteria are defined for the four variables (SCKC identified in section 3.1). Thus, the structure of the problem is designed to compare for each criterion the relative importance between all the possible and non-repeated pairs of variables, the numerical analysis of the results is carried out by applying matrix algebra.

The mentioned criteria are: Criteria 1 (C1), general impact: Impact of the element on the general safety management results (achievement of organization safety goals). In this case, this criterion is used intended to determine which elements are the most important considering their overall impact on the organization safety goals and, considering the different elements' synergies. Criteria 2 (C2), individual contribution: impact of the individual (quantitative/qualitative) value of the element on the achievement of SMS safety objectives. Criteria 3 (C3), impact between elements: how much impact has one element on the other. This criterion is intended to determine which elements the most important are considering their mutual impact. In other words what element impact in the achievement of organization safety goals more than others?

The C1 criteria responds to evaluating the relevance of each concept in achieving the nuclear safety objectives of the facility. The C2 criteria allows evaluating the individual impact of the concept without considering that its manifestation in management interacts with the result of other concepts. The C3 allows evaluating the individual impact considering synergies or feedbacks of the performance of the other elements. In this way, C2 and C3 cover the possible dynamics that could occur in operational management and enable the expert who answers the questionnaire to evaluate relative importance.

With C1, C2, C3, and the concepts operationalized into variables the AHP problem and its structure is defined (see Fig. 2). Based on the structure of the problem, an online questionnaire was designed to collect the necessary data to perform the calculations required by the AHP methodology.

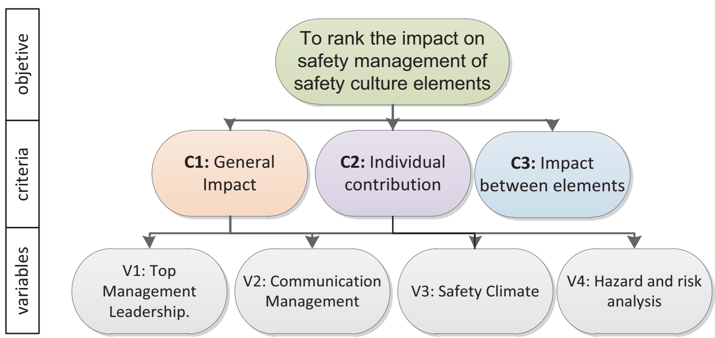

Fig. 2 AHP problem structure.

3.4 Questionnaire design

Based on the structure of the problem, a questionnaire was designed to collect the necessary data to perform the calculations required by the AHP methodology. Saaty (1990). The questionnaire. The questionnaire consisted in 18 questions structured in three sections (one for each criteria) of six questions each one. In each section, the expert was asked to indicate his preference between two of variables postulated covering the possible combinations of V1, V2, V3, and V4.

The definition of each variable was included in each question. To reveal the preference between the variables was used a Likert scale (0-9: 1 equal importance, 3 somewhat more important, 5 much more important, 7 very much more important, 9 absolutely more important and 2,4,6,8 like intermediate values). The definitions necessary to answer it are provided for each question.

The questionnaire was elaborated and was accessible via Google Forms (see https://forms.gle/5f4axLHAhGQWi9Qn7).

3.5 Results.

The questionnaire was send via mail and Research Gate to the mentioned experts.

Twenty questionnaires with responses were received. The distribution of responses according the type of experts was: academics (identified in

papers related to SC research): 60% of total responses, middle managers and nuclear reactor (PHWR and CANDU) operators: 20 % of total responses, regulators: 20 % of total responses.
The results were processed using matrix algebra following Saaty (1990) to obtain their normalized matrices, eigenvectors, and eigenvalues for each section of the questionnaire according to the AHP methodology. The results were evaluated individually by the consistency ratio (CR) and the consistency index (CI). Only the responses with a CR < 0.1 were accepted. With these results were calculated an arithmetic average of the accepted matrix responses considering 14 questionnaire responses (20% of the researchers questionnaire responses, 5 % of middle managers and nuclear reactor operators questionnaire responses and 5% of regulators questionnaire responses were rejected for not meeting the acceptance criteria of the CR). To improve this approach future research could consider geometric averages.
For the aggregated analysis of the matrixes for the calculation of the arithmetic averages, the acceptance criteria of CR was increased to 0.28 according the dispersion of the values and the considerations presented in Brufman (2015). These results are shown in Table 2, Table 3 and Table 4.

Table 1 Calculation of preferences for C1.

Variables	V1	V2	V3	V4	Normalized matrix				Eigenvector
V1	1	5	6	6	0.64	0.79	0.44	0.36	0.56
V2	1/5	1	6	5	0.13	0.15	0.46	0.32	0.27
V3	1/6	1/6	1	4	0.12	0.03	0.08	0.25	0.12
V4	1/6	1/5	1/4	1	0.11	0.03	0.02	0.06	0.06
TOTAL	1.55	6.48	12.70	15.56	-	-	-	-	-

Table 2 Calculation of preferences for C2.

Variables	V1	V2	V3	V4	Normalized matrix				Eigenvector
V1	1	6	6	6	0.64	0.93	0.49	0.31	0.59
V2	1/6	1	4	5	0.11	0.15	0.35	0.26	0.22
V3	1/6	2/9	1	4	0.10	0.03	0.08	0.20	0.10
V4	1/5	1/4	1/3	1	0.13	0.04	0.03	0.06	0.06
TOTAL	1.55	6.48	12.70	15.56	-	-	-	-	-

Table 3 Calculation of preferences for C3.

Variables	V1	V2	V3	V4	Normalized matrix				Eigenvector
V1	1	6	7	6	0.64	0.96	0.52	0.36	0.62
V2	1/6	1	6	5	0.10	0.15	0.46	0.29	0.25
V3	1/7	1/6	1	4	0.10	0.03	0.08	0.26	0.12
V4	1/6	2/9	1/4	1	0.11	0.03	0.02	0.06	0.06
TOTAL	1.49	7.61	13.69	15.33	-	-	-	-	-

The research team elaborated the pairwise comparison between criteria's (C1, C2 and C3). The results are shown in Table 4 and shown that C2 (Individual contribution) it is the most relevant criteria followed by C3 (Impact between elements) and C2 (General impact).

Table 4 Weighting of the criteria

Criteria	C1	C2	C3	Normalized matrix				Eigenvector	Research team priorization
C2	9	1	1	0.53	0.53	0.47	0.47	0.50	1°
C3	7	1	1	0.41	0.41	0.47	0.47	0.44	2°
C1	1	1/9	1/7	0.06	0.06	0.05	0.07	0.06	3°
TOTAL	17.00	2.11	2.14	-	-	-	-	-	-

According to the previous statements, the results obtained of the priorization are shown in Table 5.

Table 5 Results

Variables/Criteria	C1	C2	C3	Total	Priorization
Top management leadership	1.55	1.53	1.49	1.51	1°
Communication management	6.48	7.47	7.61	7.47	2°
Safety climate	12.7	11.99	13.69	12.78	3°
Hazard and risk analysis	15.56	13.11	15.33	14.23	4°
Weighting of the criteria	0.06	0.50	0.44	-	-

4. Conclusions

The results obtained (priority of leadership practices (variable V1 over the other variables) seem to be in accordance with the most recent recommendations or safety requirements and recommendations of international organizations. Both the International Atomic Energy Agency (IAEA) in IAEA (2016), the World Association of Nuclear Operators (WANO) in WANO (2016) and the Nuclear Energy Atomic (NEA) in OECD/NEA (2017) have promoted pragmatic leadership actions through practical tools such as SMS and training for plant personnel..

Moreover, the prioritization of leadership practices (variable V1) in the study's results also reflects the evolving understanding of the role of leadership in ensuring safety within the nuclear industry. Over the years, there has been a growing recognition that effective leadership plays a crucial role in creating a strong safety culture and fostering a proactive approach to risk management. Leaders who prioritize safety not only set the tone for the entire organization but also influence the attitudes and behaviors of their subordinates. The recommendations from international organizations, emphasizes the need for leaders to demonstrate a visible commitment to safety, actively engage with employees, and promote open communication channels. By incorporating leadership principles into their daily operations, nuclear facilities can enhance their ability to identify and address potential safety issues promptly. This integration of leadership practices into operational routines helps bridge the gap between theory and practice, ensuring that safety management concepts are effectively applied on the ground.

5. Research strengths and limitations

The strengths of this research lie in several aspects. Firstly, a defined methodology was employed, which included a systematic literature review and quantitative analysis using the AHP. This allowed for the collection and analysis of data in a structured and objective manner. Furthermore, a specific sample of nuclear reactor operating organizations was utilized, providing relevant and specific information about safety culture in this particular sector. This enhances the applicability of the findings to the nuclear industry as a whole. Lastly, this research addressed a highly important topic: safety culture in the nuclear industry. It contributes to the expansion of understanding and knowledge in this field, offering insights for the development of more effective safety practices and policies.

This study has limitations in terms of result generalization, quantitative analysis using the AHP, and questionnaire-based data collection.

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