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Identification and conceptual modeling for organizational factors affecting operational safety towards extending human reliability analysis methods

Tingting Cheng

The B. John Garrick Institute for the Risk Sciences, UCLA, Los Angeles, USA. E-mail:tingtingc@ucla.edu

Maryam Tabibzadeh

Department of Manufacturing Systems Engineering and Management, California State University, Northridge, Northridge, USA. Email: maryam.tabibzadeh@csun.edu

Hoda Jafary

The B. John Garrick Institute for the Risk Sciences, UCLA, Los Angeles, USA.

Harmandeep Gill

Department of Mechanical Engineering, California State University, Northridge, Northridge, USA

Davit Zaratsyan

Department of Manufacturing Systems Engineering and Management, California State University, Northridge, Northridge, USA

Ali Mosleh

The B. John Garrick Institute for the Risk Sciences, UCLA, Los Angeles, USA.

Organizational Factors (OFs) can affect the likelihood of accidents as well as the severity of their consequences by influencing the actions of individuals at work. Organizational issues are recognized contributors to accidents in several industries, primarily through their influence on the human behaviors of those who ultimately interact with technical systems. Current studies have developed models to quantify the impact of OFs on organizational performance and explore the organizational mechanisms that focus on the systemic and collective nature of organizational behavior. However, these methods lack focus on the explicit impact of OFs on operating crew behavior. In the field of Human Reliability Analysis (HRA), studies aim to assess operating crew errors through Performance Influencing Factors (PIFs), but they give limited consideration to the impact of OFs and rarely examine the underlying organizational mechanisms. To bridge this gap, this paper aims to: 1) develop a comprehensive list of OFs affecting operational safety through an exhaustive literature review and categorize them, 2) provide a model by incorporating these OFs through exploring their distribution in the dimensions of organizational characteristics and organizational structural units. Bayesian Belief Network (BBN) is suggested to be used for establishing the model due to its flexibility as a modeling vehicle for “soft” causal relations. The model is built upon three primary dimensions of organizational characteristics: behavioral, structural, and processes. This model is the first step toward incorporating an OF model into the HRA process, i.e., developing an extended HRA model for complex socio-technical systems with clear causal mechanisms among OFs and PIFs. The findings of this paper are expected to have broad applications for the risk assessment of socio-technical systems, with consideration given to organizational factors.

Keywords: organizational factors, risk modeling, human reliability analysis, organizational structure and processes

1. Introduction and brief literature review

Organizational issues are recognized contributors to accidents in several industries. In the nuclear field, discussions on organizational aspects as contributors to plant safety were intensified after the Three Mile Island (TMI) accident in 1979 and the Chernobyl accident in 1986. Organizational issues were also associated with the Fukushima accident in 2011, as highlighted by the

International Atomic Energy Agency (IAEA) report summarizing the results of an international expert meeting in 2013 (IAEA, 2013). The report states the importance of a systemic approach to safety that considers the human, organizational, and technological factors and the complexity of the interrelationships among them.

Organizational problems have long been viewed by the probabilistic risk assessment (PRA) community as important contributors to nuclear power plant (NPP) risks. The U.S. Nuclear Regulatory Committee (NRC) undertook research efforts to address OFs in the early 1990s, aiming at translating the qualitative results of social sciences research on OFs as inputs into PRAs (e.g., Wellock, 2021). Yet, despite advances in OF-related disciplines, the ambition to quantify OFs remains one of PRA's “grand challenges”.

The field of Human Reliability Analysis (HRA) shares milestones with OFs research following the TMI accident. HRA aim to identify, model, and quantify human errors and their contributors. Current HRA techniques incorporate OFs through Performance Influencing Factors (PIFs) (Cheng et al., 2024). For instance, procedures quality, training adequacy, and safety culture were included in several PIF sets and adopted in HRA methods, e.g., SPAR-H, CREAM, etc. However, these considerations of OFs lack a consistent and theoretically-based taxonomy, which infers that mechanisms behind OFs are underexplored (Pence & Mohaghegh, 2020).

Early OF theories contribute to proposing sets of OFs. The Model of Accident Causation using Hierarchical Influence Network (MACHINE) views accident causation as a process involving three levels: errors level, error-inducing factors level, and organizational factors level (Embrey, 1992). The Omega Factor approach (Mosleh & Golfeiz, 1999) represents an organization by a model not just a set of factors. An organization model is a descriptive and/or predictive representation of the way the organization affects the performance of its workers and work products. OFs were identified as a set of PIFs in HRA, however, the consideration of specific work processes of an organization is limited.

The Human Factors Analysis and Classification System (HFACS) is a qualitative framework for human errors analysis. It emphasizes OFs, such as safety culture, policies, and resource management, as critical units shaping conditions that influence human performance (Shappell, 2000). HFACS provides a comprehensive hierarchical classification system for identifying human and organizational factors and allows for the incorporation of quantitative methods, e.g., Bayesian Belief Network (BBN), to analyze the impact of organizational traits on human performance (Wang et al., 2024).

The Socio-Technical Risk Analysis (SoTeRiA) explicitly models the influence of safety culture, safety climate, and organizational practices on system risk (Mohaghegh et al., 2009a & 2009b). It links organizational-level factors to individual PIFs through causal pathways, enabling a dynamic and predictive representation of how organizational mechanisms impact safety-critical performances. However, organizational structure-related mechanisms were not explored.

The PHOENIX (Ekanem et al., 2016, 2024), as a representative advanced HRA method, incorporates OFs such as safety culture and team effectiveness by treating them as PIFs affecting human cognitive activities directly. However, under the OF-related PIFs, there is a lack of consideration of the nature behind those factors.

In summary, the following gaps remain: 1) Definitions of OFs in current HRAs are inconsistent and domain-specific, thus, exhaustive identification of OFs is needed from wider research fields. 2) Some HRA methods include OFs as PIFs, however, the mechanisms behind the OFs are examined inadequately. 3) Current OF modeling approaches develop organizational structural modality or causality between OFs to some extent. However, relationships between the OFs and organizational structural units, and the dimensions of organizational characteristics are not investigated.

Therefore, this study aims to present findings in two aspects: 1) the exhaustively identified OFs affecting operational safety in different industries through a comprehensive literature review, and 2) an initial model to incorporate these OFs towards extending HRA methods.

The outline of this paper is as follows. Section 2 presents our identified OF categories and examples of their attributes. Section 3 introduces the initial OF model. Discussion and conclusion are provided in Section 4.

2. Organizational factor categories and attributes

We conducted an exhaustive literature review to identify a comprehensive list of OFs that have affected the safety of operations in different high-risk industries, as a foundation to incorporate those factors into HRA more effectively and cohesively. We explored various safety-sensitive industries, encompassing oil and gas, aviation, transportation, nuclear power, chemical, construction, mining, and healthcare sectors. The OneSearch option provided by the California State University, Northridge's Library was utilized. OneSearch has subscriptions to several pertinent databases such as Scopus, Engineering Village, ProQuest, and PubMed.

The keywords "organizational factors" (contains an exact phrase in title) AND "safety" (contains in any field) were used, resulting in 341 search items. After refining the results to only include articles, conference proceedings, book chapters, and reports that were written in English, we found 321 search results. Further assessment was carried out based on two inclusion criteria: 1) the study addressed operational safety and 2) the abstract captured OFs affecting safety or there was an indication that some OFs, influencing safety of operations, were captured in the full text of the publication. Additionally, we viewed the references of those publications to find more possibly relevant sources.

A total of 278 references were found suitable. Each of the 278 references were reviewed and their identified OFs were captured. Among reviewed studies across different safety-sensitive industries, most of the captured OFs were in the context of nuclear power, healthcare, oil and gas, and aviation sectors (Tabibzadeh et al., 2024). After reviewing the 278 references, approximately 1,100 unique OFs were identified following some data cleaning.

In the next phase, those captured OFs were classified into 16 main categories based on the definitions provided for them by the reviewed studies and their similarity. A series of sub-categories were defined to capture different aspects of each OF category based on the factors captured from the literature review. Some sub-categories were broken down into sub-subcategories. We then developed a series of attributes for each sub-category and sub-subcategory in order to be able to evaluate and measure their status.

The 16 main categories of OFs developed based on the described literature review are as follows:

(1) Organizational strategy and goals
(2) Policies and procedures
(3) Organizational structure
(4) Organizational culture
(5) Leadership
(6) Communication processes
(7) Operational management
(8) Decision-making
(9) Risk and safety management
(10) Organizational change management
(11) Employee training and development
(12) Capability and competence
(13) Morale, Motivation, Attitude (MMA)
(14) Team dynamics
(15) Work environment and conditions
(16) External context and regulatory framework

As stated before, a series of sub-categories were developed to capture different aspects of each main category. For instance, for the "organizational strategy and goals" category, eight sub-categories were extracted from raw data. These eight sub-categories and brief descriptions for them are provided below:

- Goal Setting and Evaluation; the process and effectiveness of setting, reviewing, and achieving organizational goals.
- Goal Prioritization and Alignment; the clarity, ranking, and alignment of goals within the organization.
- Perception and Communication of Goals (e.g., safety, production, and performance); the extent to which goals are understood, communicated, and aligned with employee actions.
- Problem Identification and Resolution; the organization's ability to identify and resolve issues related to organizational goals effectively and efficiently.

- Organizational Commitment and Support to the Prioritized Goals; the organization's systemic integration of prioritized goals into policies and practices.
- Management Commitment and Support to the Prioritized Goals; the extent to which management commits to organizations' prioritized goals through engagement, communication, and actionable support.
- Safety Programs; systematic programs designed to promote and ensure workplace safety.
- Joint Regulation Mechanisms; collaborative mechanisms involving stakeholders to ensure compliance with safety standards.

As described before, a series of attributes were defined to evaluate the status of each OF sub-categories. The aim was to define each attribute to be relevant, identifiable, unique, and measurable. For instance, existence of documented goals prioritization (e.g., goal lists or planning documents), presence of a defined priority structure in goals, time allocated to high-priority goals (e.g., hours spent weekly), percentage of tasks or key performance indicators (KPIs) aligned with top-priority goals, and alignment of departmental goals with organizational goals (% consistency) are examples of attributes to evaluate the Goal Prioritization and Alignment sub-category.

3. Conceptual model of Organizational factors

3.1 Prerequisite foundation

To investigate the nature of OFs affecting operating crew performance, the Omega Factor model developed a conceptual framework, as shown in Fig. 1 (Mosleh & Golfeiz, 1999). The organization, represented at the bottom on the left, interacts with the plant systems at the top through the operating crew, which serves as the 'sharp end' performing operations or maintenance activities. The organizational structure is briefly modeled on the right, consisting of several levels, including factors influencing managers' behaviors, managers, supervisors, and personnel. The Product/Function/Objective represents the crew's output, which in turn affects the plant systems.

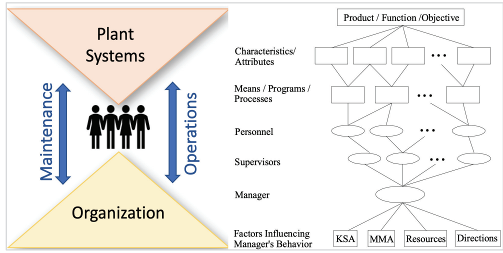

Fig. 1 Conceptual framework of Omega Factor model

Organizations function as systems of formal authority, regulated information flows, informal communication, work constellations, and ad hoc decision-making processes (Mintzberg, 1989). The primary functions of an organization broadly consist of: 1) Planning – defining objectives and determining appropriate means to achieve them; 2) Organizing – translating planned activities into a structured framework of tasks and authority; 3) Leading – managing daily interactions with individuals and groups; and 4) Controlling – ensuring that actual outcomes align with planned objectives through corrective actions where necessary.

In an organization, these functions are divided among different parts depending on the design of the organizational structure. Considering the variety of organizational structures, a general framework developed by Mintzberg, as shown in Fig. 2, is introduced. This framework is adaptable for analyzing various organizational structures, including divisional, hierarchical, and others (Lunenburg, 2021).

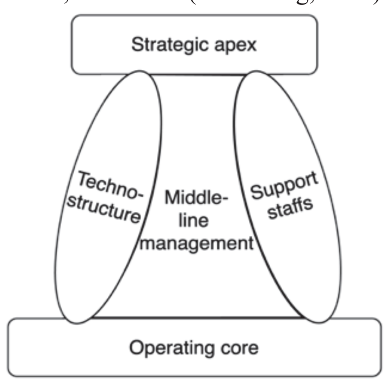

Fig. 2 Classic structural units in Mintzberg's model (Mintzberg, 1989)

An organization can be broadly divided into the following five units: 1) Strategic Apex, responsible for ensuring that the organization effectively serves its mission and meets the needs of those in power or control over it; 2) Middle-Line Management, tasked with directly supervising production processes and coordinating with other organizational parts; 3) Techno-Structure, which influences the work of others by designing workflows, planning operations, or training staff, without performing the tasks themselves; 4) Support Staff, providing assistance to the organization outside the core production or operational workflow; and 5) Operating Core, which interacts directly with technical systems to perform day-to-day operations.

Each unit may contain sub-units, depending on the organization's scale and structure, and all units interact with one another. This model can replace the bottom triangle representing the 'Organization' in Fig. 1.

3.2 Dimensions of organizational characteristics – Behavior, Structure, and Processes

For each unit in an organization, its functions are achieved by coordinating human behaviors, structures, and processes within that unit (Gibson et al., 2009). Consequently, three dimensions of organizational characteristics are considered to categorize the identified OFs.

The behavioral dimension refers to the characteristics involving the actions, patterns, and attitudes of individuals, groups, and the organization as a whole, such as individual attitudes, group dynamics, and organizational culture. Many characteristics, like MMA, culture and climate, and leadership, exist across all structural units, influencing their performance in different ways. These factors ultimately impact the safety performance of the operating core, which directly interacts with technical systems.

Referring to complex systems theory (Klein & Kozlowski, 2000), the concept of "Emergence" is adopted. Emergence describes how interactions between parts of a complex system produce new and unpredictable behaviors or properties not present in the individual components. Therefore, we adopt Emergent behavior to replace the behavioral dimension, where the included OFs are related to the actions and actionable patterns of individuals and groups that arise from interactions within the organization. Specifically, the OFs in this dimension encompass how people respond to organizational structures, policies, and both external and internal stimuli.

Likewise, Emergent Structure is adopted to replace the structural dimension, referring to organizational characteristics related to frameworks, patterns, or relationships that evolve over time and shape the organization. This includes both formal structures (e.g., policies) and informal patterns (e.g., workplace norms) that provide a foundation for system stability. The OFs in this dimension focus on relatively stable emergent patterns while acknowledging their dynamic nature over the long term.

The third dimension is Adaptive Processes, derived from complex systems theory (Klein & Kozlowski, 2000), replacing the processes dimension. It represents activities and dynamic mechanisms that evolve continuously to respond to changing conditions and organizational needs. The OFs in this dimension involve processes driven by feedback loops, learning, and decision-making, enabling the organization to adapt effectively.

Based on these three dimensions, the identified OFs are categorized as shown in Fig. 3. For example, Leadership can be classified under the behavioral dimension as it emerges from interpersonal influences and actions within individuals or groups. Similarly, Culture arises from shared values and norms through continuous social interactions. Structure Design reflects organizational architecture shaped by formal and informal influences. Policies and Procedures provide a framework for organizational functioning but are subject to reinterpretation and adaptation. Communication Practices represent dynamic processes facilitating collaboration and problem-solving, while Employee Training and Development reflects the ongoing process of building competencies over time. Note that the 16th OF - External context and regulatory framework is an external factor in terms of an organization, so, we exclude it in the following modeling process.

As mentioned above, organizational factors in different dimensions may exist in multiple structural units, either with the same or different characteristics. For example, group safety culture emerges from the shared perceptions of group members regarding safety practices, such as training. In this case, group and individual safety culture represent the same construct, even though they belong to different units (Mohaghegh & Mosleh, 2009). Conversely, team performance is a distinct example, as it results from the collective pattern of team members' performances. In other words, team performance is a complex function of individual performances and their interactions with one another.

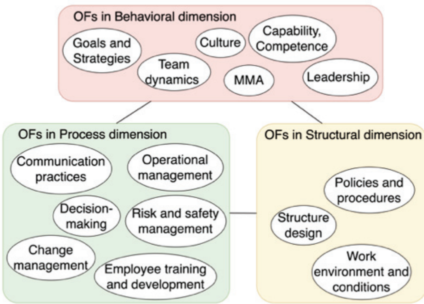

Fig. 3 OFs distributed in the three dimensions

Regarding this distinction, we refer to two qualitatively distinct types of emergences: Composition and Complication (Klein & Kozlowski, 2000). Composition describes phenomena that remain essentially the same as they emerge upward across levels, such as safety climate. In contrast, Complication describes phenomena within a common domain that become distinctively different as they emerge across levels, such as team performance.

Based on this distinction, a 'nested' OF model is developed where each unit includes three dimensions of organizational characteristics, as shown in Fig. 4. Some OFs may span multiple units, while others may be specific to a single unit. Furthermore, the nature of the same main OF across different units, which may consist of various subcategories, can also differ depending on the context.

3.3 Conceptual OF model

Considering the distribution of the main OFs in the organizational structural units and characteristics dimensions, respectively, we define the relations between OF and these two aspects as below. OF can be deemed as a two-tuple variable defined as OF_{xy}:

$$OF_{xy} = \{X, Y\}$$

$$(x=B, ST, P;\ y= A, M, T, SS, C, O)$$

where *X* and *Y* are multi-valued properties. *X={behavior (B), structure (ST), process (P)}; Y={ strategic apex (A), mid-line management (M), technologists (T), supporting staffs (SS), operating core (C), organization (O)}*. Note that the OFs are applicable for an entire organization, and its structural units. Thus, OF_{xO} represents the OFs in terms of the entire organization.

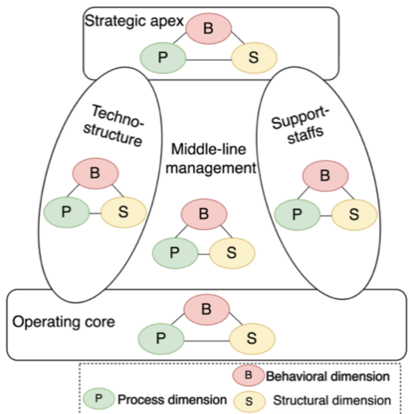

Fig. 4 Nested organizational factor model

OFs distribute into *B*, *ST*, and *P*. *B={b_1: Goals and Strategies, b_2: Culture, b_3: Team Dynamics, b_4: MMA, b_5:Capability and Competence, b_6: Leadership}*, *ST={st_1: Structure Design, st_2: Policies and Procedures, st_3: Work Environment and Conditions}*, and *P={p_1: Communication Practices, p_2: Decision-making Practices, p_3: Operational Management, D_4: Risk and Safety Management, P_5: Change Management, p_6: Employee Training and Development}*.

As some examples of OF_{XY}, OF_{b6A} represents the OF - Leadership of strategic apex; OF_{st3M} represents the OF - Work Environment and Conditions of middle-line management; and OF_{p1O} represents the OF – Communication Practices of the entire organization. For different cases, analysts can determine whether they want to analyze the groups or the entire organization. The same OF in different units may have unique nature, thus, each OF_{XY} can be modeled through the identified sub-factors and attributes, referring to specific theories, such as leadership theory (Northouse, 1995) and work process modeling (Curtis et a., 1992).

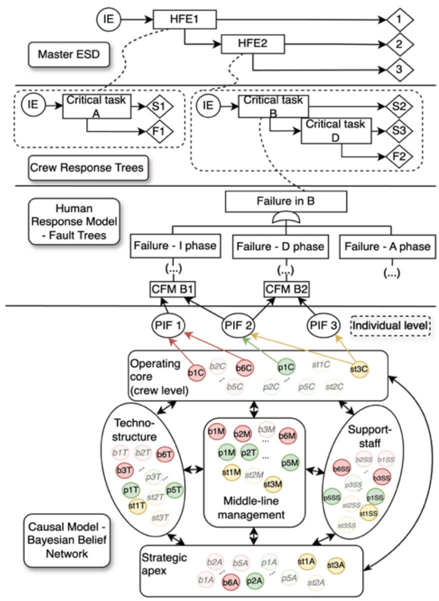

Fig. 5 Conceptual OF model connecting with Phoenix HRA framework

The nested OF model is unfolded and presented at the bottom of the Fig.5. The colored lines mean their influences on the HRA model (i.e., Phoenix). Each unit of the organizational structure incorporates the identified OFs, however, analysts can determine which OFs are applicable to different units in specific cases. In the example shown in Fig. 5, the nodes in solid colors represent the OFs selected for a specific unit, while the nodes in semi-transparent colors indicate OFs that are not selected for that unit.

5. Concluding remarks

To enhance HRA methods by modeling the impact of OFs on human errors, we have explicitly identified OFs from various fields and propose a conceptual OF model. A total of 15 main OFs, their subcategories and attributes have been identified. Using Mintzberg's '5-units' organizational structure and the three dimensions of organizational characteristics, a conceptual OF model has been proposed. Additionally, we have defined OFs as a two-tuple variable, considering their distribution across structural units and characteristic dimensions. The conceptual OF model has then been integrated with an HRA model.

For future work, we aim to further develop an OF model by analyzing the relationships between the identified main OFs, subcategories, and their attributes across structural units. Specifically, the mechanisms underlying organizational functioning will be clarified by examining workflows, information flows, and authority flows, as well as the interactions between structural units. The OFs will be allocated to corresponded units. When modeling OFs, the efficiency-thoroughness trade-off should be carefully considered (Hollnagel, 2009). Furthermore, theories such as High Reliability Organization (HRO) and Normal Accident Theory, which focus on high-risk industries, as discussed by Czarniawska (1992), would be beneficial in making OF modeling more aligned with the real-world organizational functioning.

This work is expected to support analysts in modeling diverse organizations while also providing a quantifiable approach for assessing the impact of OFs on human performance, ensuring compatibility with advanced HRA models.

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