

Analysis of the Potential for Resilience of Integrated Oil & Gas Operations in Brazil

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Abstract: Resilience is presented in literature as the capacity of a system to disarm, adapt and recover from unexpected events. Despite the increase of interest of industries and academia in the subject, there are a lack of models that describes the elements that condition and determines resilient performance. This article presents a knowledge model that characterizes intangibles which determine resilient responses and is a central piece in a data science strategy supporting monitoring and analysis of potential for resilience in high-risk industries. Through an interdisciplinary approach, this model was established using an integrative review of the literature and the contribution of experts from several areas. The potential for resilience is represented by a set of leading indicators that allows continuous monitoring of both static characteristics of complex operations and dynamic resource mobilization in the face of unexpected events. Knowledge engineering and data science techniques are applied to treat data from various sources. The established approach addresses several elements that are not traditionally explored in safety management systems, including those related to knowledge that determine resilient responses, as well as factors related to human, structural and relational capital that condition resilient performance. Results of the application of the model are presented, including how the analytical model supports the definition of knowledge management and safety investment strategies in oil and gas companies in Brazil. The approach supports the prioritization of actions and investments to promote safety and enable strategies to learn from accidents and positive conditions that make operations safer despite unpredictability in daily operational routine.

Keywords: Resilience Engineering; Human factors; Knowledge Management; Safety Management

1. Introduction

Complexity and instability are characteristic of socio-technical systems where responses to unexpected events, as well as the decision on the investments needed to promote safety, are critical challenges to operational safety management (Bergström et al., 2015; Hollnagel, 2014; McManus, 2008; Patriarca et al., 2017; Patriarca & Bergström, 2017).

Widespread approaches to operational safety applied to organizations are based on lagging indicators, implementation of detailed and rigid procedures and justification of accidents as behavioral deviations. The complexity of socio-technical systems determined by social, environmental and accelerated technological development makes these approaches not the most appropriate nowadays (Dekker, 2006; Lay et al., 2015). In this context, scientific and practical assumptions based on Resilience Engineering (RE) and Human Factors (HF) are alternatives for the design and evaluation of complex systems (Dekker et al., 2008; Hollnagel et al., 2006; Hollnagel, 2010, 2014; Nemeth & Hollnagel, 2014; Patriarca et al., 2018; Woods, 2009).

In industries such as oil and gas (O&G), where occasional accidents are critical for potential human, environmental, and economic damage, RE is being studied as an alternative approach to traditional safety management strategies. RE considers the analysis of HF (i.e., the interactive relationship amongst humans, works, and artifacts) from design to the operation of the system, considering not only the absence of negative aspects, but also the presence of positive ones (Hollnagel, 2014; Nemeth & Hollnagel, 2014).

The literature presents prominent works focusing on the analysis of potential for resilience (Nemeth; Hollnagel, 2014). However, most of them do not provide a roadmap for analyzing HF and their relationship to the potential for resilience in complex sociotechnical systems. Thus, the challenges that motivate this research are to identify (i) how to qualify HF and knowledge resources that condition resilient responses and (ii) how to establish leading indicators (Hollnagel, 2010; Patriarca et al., 2017) that allow continuous monitoring of these factors, promote learning and better target investments in operational safety management.

This work presents an alternative model that transcends monitoring approaches based on lagging indicators to evaluate factors that condition resilient performance, combining knowledge management, HF, RE and operational safety management.

2. Potential for resilience analysis

In several industries, accidents and incidents, beyond unintended or individual phenomena, result from social and organizational factors (Hovden et al., 2018). In complex operations, there is no way to predict everything that can happen. In the perspective of safety management, Hollnagel (2010) defines resilience as "the intrinsic ability of a system or organization to adjust its functioning before, during or after changes and disturbances, so that it can sustain the necessary operations under expected and unexpected conditions". According to Park et al. (2012), resilience is not a static property of the system but an emerging property resulting from a process of detection, anticipation, learning and adaptation to risk. This view significantly implies the adaptive management of complex systems and this stems from the importance of defining and evaluating resilience of operations in complex systems. Thus, it is critical to identify ways to qualify HF's that determine resilient responses and to analyse their condition of improving safety. Also, it is critical to establish methods to measure resilience and promote continuous learning to improve the potential for resilience of organizations (Stephenson, 2010). It is also critical to consider how knowledge could be managed to improve potential for resilience (Fraga; Varvakis; Sell, 2018; Sell et al., 2021).

There are models that deal with the measurement of resilience in organizations (Bahmra, Dani and Burnard; 2011, Lengnick-Hall et. al.; 2011, Stephenson; 2010, Alonso and Bressan; 2015), however, in these studies, knowledge is not considered as a critical organizational resource. Knowledge used by employees in their daily adaptations is often not recognized or documented (Rasmussen & Svedung, 2000), making it difficult to improve resilience (Rankin et al., 2014).

The Framework for Analysis of Resilient Responses (Sell et al.; 2021) gives the basis of this work. Its objective is to support comprehensive analyses by shedding light on several HF from the perspectives of the individual, work and organization, as proposed by Edwards (1988) and Hawkins (2017), but exploring knowledge as a key factor amongst other HF usual in Oil & Gas integrated operations. Resilience is a topic of interest to different areas, but internal and external factors make it particularly interesting for the O&G industry¹. At operational level, complexity and risk inherent in oil production and external factors, like fluctuation cycles in the price of raw materials and derivatives and social pressures in favor of replacing fossil fuels with renewable ones, raise concerns about organizational resilience (Bento et al., 2021).

Based on this framework, we analyzed models of indicators that could allow the monitoring of resilience potential in continuous flow.

2.1 Indicators adherent to Resilience Engineering

Indicators are a useful tool for inferring changes that can reflect on the safety of organizations. Performance indicators are most applied to traditional safety management, especially so-called *lagging indicators*, as they are objective, and quantifiable. They, however, measure results, things and events that have already occurred (e.g. incidents and accidents) and raise questions, because the retrospective bias may not indicate the real safety of the organization (Dekker, 2004; Grecco et al., 2014).

¹ Brazil is the largest oil producer in South America and the eighth largest in the world. The sector represents about 10% of Brazil's GDP and the country is in a leading position for the exploration and production of offshore oil in pre-salt province. International Energy Agency (IEA) estimates that in 2040, Brazil will produce about 50% of the world's offshore oil (International Trade Administration, 2021).

Grecco et al. (2014) advocate for indicators that could confirm long-term effects and not only immediate changes in dynamic environments. They suggest leading indicators focused on HF, good working practices and determinants of resilience in the anticipation of vulnerabilities. The big challenge is to identify measurable organizational factors that influence resilience and safety. For this, the elements of safety culture proposed by Reason (1997), Wreathall (1999; 2006) and Grecco et al. (2014) are a good starting point.

Reason (1997) addresses principles for understanding the causes of accidents, detailing elements that underpin later work (e.g., Wreathall, 1999; 2006):

1. **Management Commitment:** senior management infuses in the organization a sense of significance and value of human performance, both in words and actions.
2. **Learning culture:** learning should be obtained not only by the occasion of incidents and accidents, but also by regular activities.
3. **Flexibility:** organization's ability to adapt to new or complex problems in a way that maximizes its ability to solve problems without disrupting overall functionality.
4. **Awareness:** what is happening in relation to the quality of human performance and the current state of the system's defenses.
5. **Just culture:** supports the reporting of problems in the organization without being condescending to culpable behaviors.
6. **Readiness:** organizational technical competence necessary to achieve safety objectives.

Grecco et al. (2014) proposed a fuzzy logic-based model to assess safety culture using indicators capable of predicting changes in an organization's safety performance. In the work, Grecco et al. (2014) proposed a set of assertions that describe how a fictitious company referencing safety culture would address the typology of Reason (1990, 1997). Their model is indicated for managers to monitor and evaluate safety culture in organizational processes. It can be applied in any safety-critical organization², such as civil aviation and mining, with adjustments to indicators and metrics according to their characteristics (Grecco et al., 2014).

3. Methodology and research strategy

The indicators and analytical tools presented in this article were developed as elements of the framework described in Sell et al. (2021) applying *Design Science Research* (DSR) method (Peffer et al., 2006). Needs and objectives of the solution were identified applying organizational context modeling techniques proposed by CommonKADS (Schreiber et al., 1999). Seven companies in the O&G sector, including contractors and chartered workers, participated sharing information about their performance, statements from managers and data on safety management.

Regarding the development of the model of representation and analysis of HF, an exploratory literature review was developed, through which it was possible to identify studies in different industries (e.g., IOGP³, ERA⁴, ARGONNE⁵ and IAEA⁶). The first version of the model was established based on these studies and then evaluated by O&G professionals and specialists in areas such as sociology, social work, RE and knowledge management. As a result, it was designed a new version of the model.

The indicators guided collection, treatment and analysis of data obtained from the companies participating in the study. In the next section, we detail how the model was structured.

4. Resilient Performance Analysis Model

The framework proposed by Sell et al. (2021) is composed by:

- a knowledge model describing HF that condition the potential for resilience;

² Safety-critical organizations are those that operate in areas that involve significant risks to the safety of the environment or society. Safety is a prerequisite for its very existence. Uncertainties, complexity and contradictory requirements are inherent to safety-critical organizations (S. W. A. Dekker & Woods, 2010; Oedewald & Reiman, 2007; Reiman et al., 2015; Weick & Sutcliffe, 1999).

³ <https://www.iogp.org/>

⁴ <https://www.era.europa.eu/>

⁵ <https://www.anl.gov/>

⁶ <https://www.iaea.org/>

- information systems to handle and analyse different data sources;
- knowledge systems to support the prioritization of actions to improve the potential for resilience.

The framework’s knowledge model is composed by 136 factors, organized into first-order constructs (Individual, Work, and Organization). Figure 1 presents an overview of the factors, highlighting through the “Knowledge repertoire for adaptation” factor how they are described and associated with information sources to populate the model.

The framework knowledge model integrates the factors associated to the individual level (*i.e.*, workers’ competencies; psychological, physiological, and social conditions); to work (e.g. workload, internal conditions, procedures, and technologies); and to organizational aspects (e.g. policies related to people’s, knowledge management and safety management). Knowledge is explored through the perspectives of individuals (*i.e.*, the stock of workers’ knowledge and their repertory to deal with unforeseen events), work (*i.e.* knowledge required for work and information dissemination for safe work), as well as in the organizational perspective (*e.g.* policies for people management, organizational learning and knowledge management). The main factors are broken down into up to four levels of associated factors to provide an operational description to support their observation in the work environment.

In the next sections, we describe how we established leading indicators to support the evaluation of factors represented in the knowledge model.

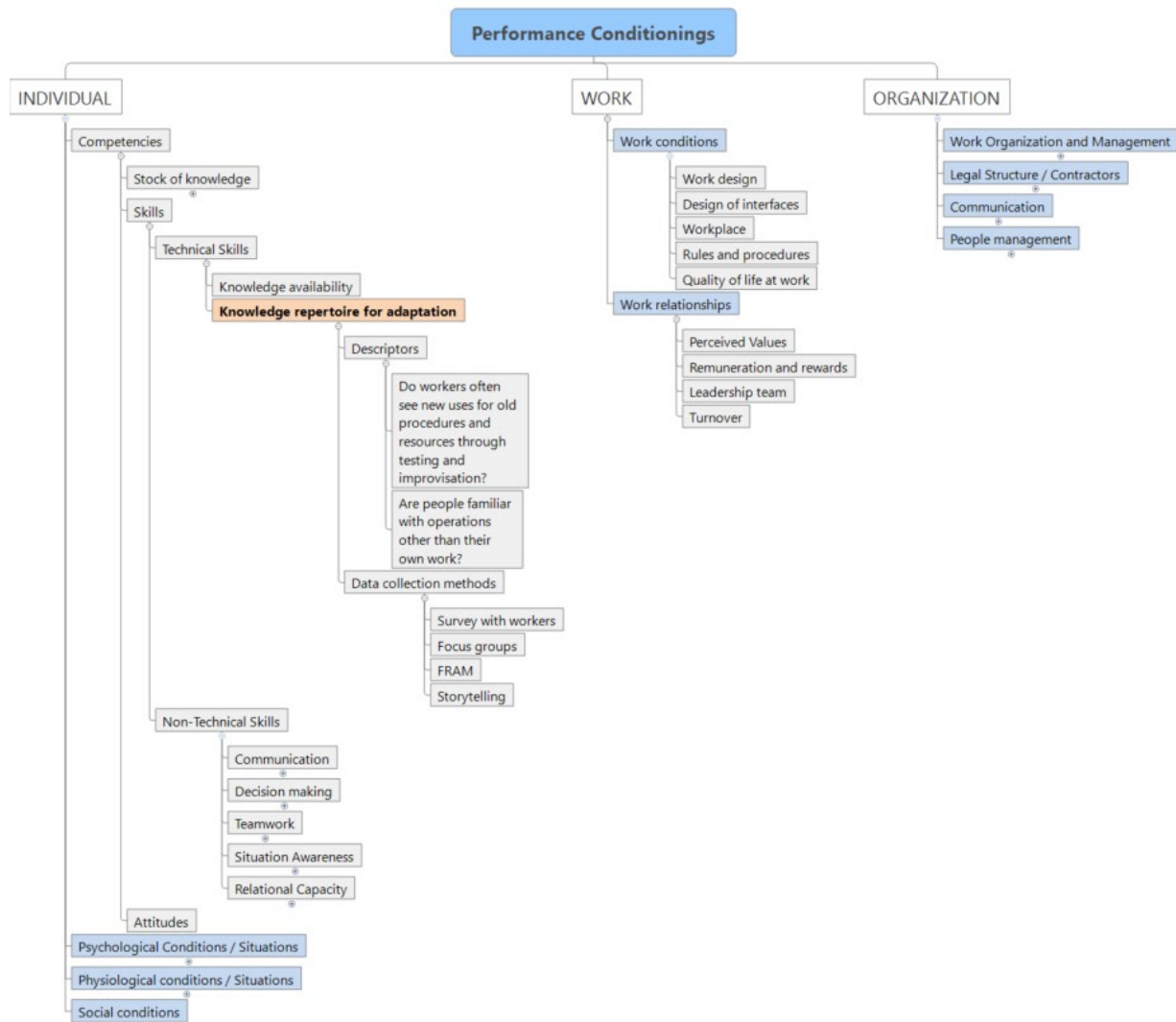


Figure 1: Overview of framework factors

Source: from authors

4.1 Strategy for structuring leading indicators

Our proposal for leading indicators were structured based on the Reason (1997) six attributes of safety culture and in the conceptual model of the framework described in Sell et. al. (2021). The indicator model was structured based on the following steps: (i) selection of a structure of indicators; (ii) adherence analysis of the indicators to factors that condition resilient performance; and (iii) review of the structure of indicators with the support of experts. Such steps are described in the following sections.

4.1.1 Selection of indicators

Grecco et al. (2014) suggest that the selection of indicators considers what needs to be monitored and not the ways in which monitoring can be done. Otherwise, the selection can be biased considering only what is possible or convenient to measure, not meeting the purposes of monitoring. In this sense, in the present work, we designed the instruments referencing models of safety culture indicators adherent to the principles of RE that were already applied in complex sociotechnical systems.

The model of Grecco et al. (2014) was selected as the basis for the present work due to its adherence to factors of our framework (Sell et. al., 2021). That model consists of 43 leading indicators grouped into 6 safety culture attributes, as described in the Table 1, aimed to assess the safety culture using safety performance indicators.

Table 1: Leading indicators grouped by safety culture attributes

Attributes	Leading indicators
Management Commitment	1.1 Human resources 1.2 Material resources 1.3 Commitment to safety 1.4 Safety policies 1.5 Procedure management 1.6 Training programs 1.7 Selection of competencies
Organizational learning	2.1 Dissemination of information 2.2 Information flow 2.3 Work management 2.4 Current working practices 2.5 Local adaptations 2.6 Content of the documentation 2.7 Documentation availability 2.8 Accident analysis 2.9 Investigation of incidents and accidents
Organizational flexibility	3.1 Ability to control the unexpected 3.2 Ability for flexibility 3.3 Professional recognition 3.4 Limits for safe work 3.5 Reports of adaptations 3.6 Incorporation of adaptations
Situational awareness	4.1 Problem communication 4.2 Information security 4.3 Communication mechanisms 4.4 Teamwork 4.5 Workload 4.6 Interpersonal relationships 4.7 People's tasks and skills 4.8 Awareness of limits 4.9 Preventive maintenance 4.10 Proactive actions
Just culture	5.1 Reports of deviations/concerns 5.2 Understanding errors 5.3 Perception of errors 5.4 Non-punitive actions 5.5 Peer reviews
Emergency preparedness	6.1 Emergency preparedness plan 6.2 Risk identification 6.3 Safety equipment 6.4 Alarm system

Attributes	Leading indicators
	6.5 Proactive procedures 6.6 On-site emergency training

Source: adapted from Grecco et al. (2014)

Grecco et al. (2014) suggest the attribution of an assertion for each attribute to guide the responses of the target audience and quantify the responses through metrics. To quantify the answers, a 5-point Likert scale was adopted, with "Strongly disagree" equivalent to one point and "Strongly agree" equivalent to five points. Table 2 presents an example of a metric attributed to the "Organizational Learning" attribute.

Table 2: Safety culture metrics

Attribute	Indicator	Metric
2 Organizational Learning	2.11 Success as a source of learn	Factors that ensure the success and safety of daily work are observed as a source of learning.

Source: adapted from Grecco et al. (2014)

4.1.2 Adherence analysis of indicators to the factors of the model

To achieve the main objective of this study, we evaluated the degree of adherence of the selected leading indicators to the factors that condition resilient performance. Beforehand it was known that complete adherence would not be achieved, as the factors are related to constructs that go beyond the safety culture, including, for example, leadership, communication and non-technical skills.

Table 3 presents an extract from the adherence analysis, where indicators 3.5 and 4.3 of the model by Grecco et al. (2014) were confronted with the 'Communication' factor, part of the Individual dimension of the framework.

Table 3: Example of adherence analysis between the indicators and the framework

Framework for Analysis of Resilient Performance (Sell et al., 2021)		Leading indicators (Grecco et al., 2014)	
Dimension > Factor > Associated Factors	Description	Indicator	Metric
Individual > Non-Technical > Skills	Workers: 1. voluntarily share information; 2. keeps others informed about progress and changes in work; 3. give appropriate feedback on time; 4. have adequate capacity to communicate with clarity and objectivity; 5. devote adequate time and attention to new information and confirm their understanding.	3.5 Report of adaptations 4.3 Communication mechanisms	3.5 Local adaptations of tasks are communicated by people. 4.3 To what extent communication mechanisms are available.

Source: from authors

When comparing the 43 safety culture indicators to the content of the framework, adherence was identified with 6 of its 10 factors, as described in Table 4. Workshops were then held with experts to review the mapping between the framework factors and the indicators proposed by Grecco et al. (2014), as well as to prospect indicators for the factors not contemplated in the mapping, as described in the next section.

Table 4: Result of the analysis of adherence of the indicators with the framework

INDIVIDUAL		WORK		ORGANIZATION	
Factors	Indicators	Factors	Indicators	Factors	Indicators
Competence / Repertoire	20	Working conditions	24	Management and organization of work	18
Physiological conditions	-	Working relationships	3	Formal legal structure	-

INDIVIDUAL		WORK		ORGANIZATION	
Factors	Indicators	Factors	Indicators	Factors	Indicators
Social conditions	-			Communication	3
Psychological conditions	-			People management	4

Source: from authors.

4.1.3 Review of indicators by experts

The last step of the method was to review the indicators by academic and professional experts working in O&G companies. The experts evaluated the content, relevance, and plausibility of the indicators.

At the end of this stage, the structure of indicators was reviewed based on the observations. A new version of the model was obtained, consisting of 48 indicators according to the reality of the O&G sector, where it is intended to expand the studies by the periodic application of surveys.

4.1.4 Application of knowledge systems

In order to analyze the structure and level of contribution of the indicators to operational safety management, a survey was structured and applied with teams from O&G companies. The questions were formulated to address the level of agreement of the teams with statements on the level of development of each leading indicators' metrics associated with their work environment.

A knowledge system was established to enable the analysis of the factors that condition resilient performance through the proposed leading indicators. The calculation method was adapted from the critical infrastructure resilience index, RMI (Petit et al., 2013). The final index of the second-order construct Resilience Performance Conditionings is based on the aggregation of equally weighted first-order constructs or attributes of resilient organizations (*i.e.*, Senior Management Commitment, Organizational learning, Organizational flexibility, Situational awareness, Just culture and Emergency preparedness).

Indicators are presented through a set of dashboards, which contain summaries of the qualitative analyses carried out for each factor. Figure 2 depicts the first screen of the knowledge system. An estimated score for each of the model first and second-order constructs is presented (data illustrated were anonymized and manipulated to respect the confidentiality of the information collected in the study). Users can drill down to obtain more detailed information and access specific dashboards with highlights associated with each factor.

The data collected through the survey and by other means were (*e.g.*, interviews, observation, document analysis) synthesized around the factors of the model. Through the analysis of the data, working groups were formed by the themes *Leadership*, *Just Culture*, *Operational Safety Events* and *Self Care*. The aim of these working groups is to deep the data analysis around each theme as well as develop action plans. In this sense, the model's indicators helped to guide the interventions in the companies, as well as to enable the future analysis of the results and impacts of the action plans developed, favouring learning and strengthening the potential for resilience.

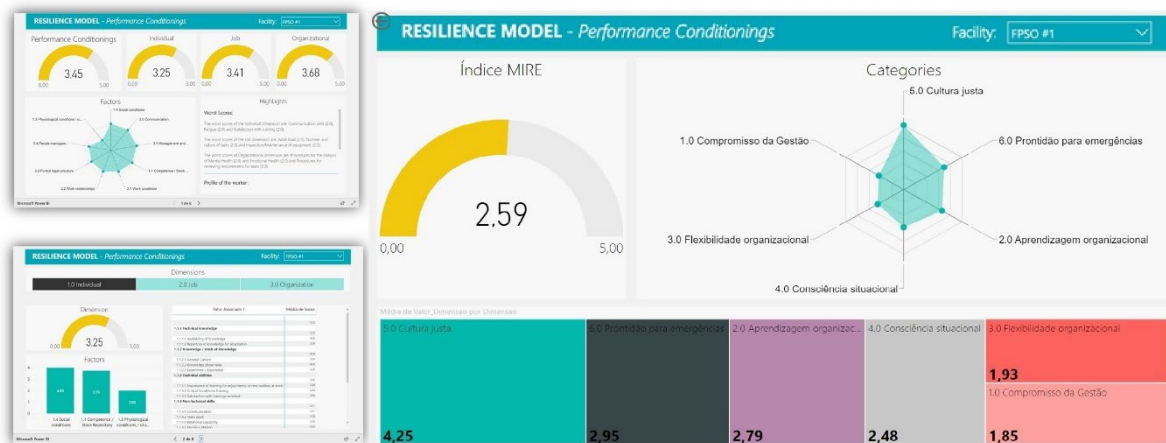


Figure 2: Partial illustration of the knowledge system

Source: from authors

5. Discussions and conclusions

In this paper, we presented a model that guides continuous analysis of the elements that condition resilient performance and described its application in the analysis of companies that operate in the O&G sector in Brazil. The model applies leading indicators to enable a holistic view of the conditions related to safety culture found in high-risk companies and to support an interdisciplinary analysis of the issues to be addressed to strengthen safety.

The analysis model offers a proactive tool which provides a basis for action without waiting for events, addressing strengths and weaknesses of safety culture attributes and HF that condition resilient performance. Through a systemic approach, exploring a wide range of factors that condition resilient performance, knowledge systems reveal the latent factors that contribute to the occurrence of safety events and the status of safety culture attributes. Several aspects related to knowledge are explored among the factors presented in the knowledge model. The indicators guide knowledge management interventions to address individual gaps or risks regarding knowledge determinant for critical tasks, as well as the analysis of policies and strategies for the enhancement of organizational learning and safety.

This study in the O&G industry in South America showed that the model offers interesting perspectives for resilience improvement. In fact, the leading indicators allowed the identification of potential issues in the Just Culture category, regarding items such as the distinction between acceptable and unavoidable errors, errors such as learning sources and fair treatment of subordinates. These issues are among those that are inherent to a punitive culture still very present in this industry and its implications can be correlated with other findings associated to communication and learning. These findings should be investigated more deeply in other companies in O&G industry.

The proposed analysis model may also be used to compare resilience potential with a given ideal pattern, but do not indicate potential improvements in safety management strategy. However, as described in related studies, this weakness could be addressed by a mobilization of experts to set up new measures and targets to be pursued.

The approach adopted to propose the indicators combining the steps developed by Grecco et al. (2014) with conceptual model, as outlined in the framework described in Sell et al. (2021), proved to be viable and adherent to the needs of the companies involved in the study. The framework is supporting the analysis of the effectiveness of investments in safety and reveal the potential risks not prioritized by current plans, contributing to the promotion of organizational learning. Considering that the model was applied in 7 organizations, it should be applied in more organizations to analyze its replicability in other contexts.

Future studies should further explore: a) the identification of additional information sources and data gathering strategies; b) the improvement of knowledge systems to automate the framework application; c) the continuous application of the framework to estimate how interventions affects resilience potential.

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