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A framework to assess Safety Performance Measurement Systems for construction projects based on the Resilience Engineering perspective

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A Framework to assess Safety Performance Measurement Systems for construction projects based on the Resilience Engineering Perspective

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ABSTRACT

PEÑALOZA, G. A. **A Framework to assess Safety Performance Measurement Systems for construction projects based on the Resilience Engineering Perspective**. 2020. Thesis (Doctor in Civil Engineering) - Postgraduate Program in Civil Engineering: Construction and Infrastructure (PPGCI), UFRGS, Porto Alegre.

Safety performance measurement systems (SPMSs) are key elements of safety management, contributing for creating cycles of continuous improvement. In the construction industry, the measurement of safety performance is often assessed by using indicators that are primarily based on regulations and standards, such as reportable accidents, lost time injuries and number of safety inspections, among others. However, the literature points out that these indicators provide limited support in decision-making and learning processes. There limitations are clearly explained by Resilience Engineering (RE) perspective, the theoretical perspective adopted in this investigation. The systems-oriented approach supported by RE is consistent with the focus of improving SPMSs, rather than individual metrics, and can potentially contribute to enhance the resilient performance of construction projects. Therefore, the aim of this research work is to devise a framework to assess SPMSs for construction projects based on the Resilience Engineering Perspective. The framework entails five guidelines for assessing SPMSs, and the use of two assessment tools: (i) the Technical, Organizational and Environmental (TOE) framework, for identifying sources of complexity; and (ii) the Resilience Assessment Grid (RAG), for analysing the four abilities of resilient systems. Four case studies in construction projects were carried out, one in Brazil, two in Chile and one in Norway. The methodological approach adopted in this investigation was design science research. The research process was divided into five main steps: (i) find a practical problem with potential for a theoretical contribution, (ii) obtain an understanding of the problem, (iii) develop a solution, (iv) test the solution and evaluate its utility, and (v) assess the theoretical contribution of the solution. The four case studies contributed to the development of the solution, by identifying improvement opportunities for each construction project, which provide evidences of the utility of the solution. Regarding the practical contribution of the solution, the operationalisation of each RE guideline during the assessment of SPMSs provided categories of analysis with different attributes which can be useful in the definition of strategies by which the SPMS contributes to resilience. Moreover, the use of TOE and RAG contributed for the understanding of sources of complexity and resilience on each construction project. The main theoretical contribution of the solution is the refinement of RE guidelines for SPMSs assessment, using as a point of depart recommendations of leading RE authors of the safety management field.

Keywords: Safety performance measurement systems, Resilience engineering, Project complexity

RESUMO

PEÑALOZA, G. A. **Uma estrutura para avaliar sistemas de medição de desempenho de segurança para projetos de construção com base na perspectiva da engenharia de resiliência**. 2020. Tese (Doutorado em Engenharia Civil) – Programa de Pós-Graduação em engenharia civil: construção e infraestrutura (PPGCI), UFRGS, Porto Alegre.

Os sistemas de medição de desempenho de segurança (SPMSs) são elementos essenciais da gestão da segurança, contribuindo para a criação de ciclos de melhoria contínua. Na indústria da construção, a medição do desempenho de segurança é frequentemente avaliada por meio de indicadores que se baseiam principalmente em regulamentos e normas, como relatos de acidentes, acidentes com afastamento e número de inspeções de segurança, entre outros. No entanto, a literatura aponta que esses indicadores fornecem suporte limitado nos processos de tomada de decisão e aprendizagem. Suas limitações são claramente explicadas pela perspectiva da Engenharia de Resiliência (ER), perspectiva teórica adotada nesta investigação. A abordagem orientada aos sistemas da RE é consistente com o foco de melhoria de SPMSs, ao invés de métricas individuais, e pode potencialmente contribuir para melhorar o desempenho resiliente de projetos de construção. Portanto, o objetivo deste trabalho de pesquisa é propor uma estrutura para avaliar SPMSs para projetos de construção com base na Perspectiva de Engenharia de Resiliência. A estrutura envolve cinco diretrizes para avaliar SPMSs e o uso de duas ferramentas de avaliação: (i) a estrutura Técnica, Organizacional e Ambiental (TOE), para identificar fontes de complexidade; e (ii) o Resilience Assessment Grid (RAG), para analisar as quatro habilidades dos sistemas resilientes. Foram realizados quatro estudos de caso em projetos de construção, um no Brasil, dois no Chile e um na Noruega. A abordagem metodológica adotada nesta investigação foi a *design science*. O processo de pesquisa foi dividido em cinco etapas principais: (i) encontrar um problema prático com potencial para uma contribuição teórica, (ii) obter uma compreensão do problema, (iii) desenvolver uma solução, (iv) testar a solução e avaliar sua utilidade e (v) avaliar a contribuição teórica da solução. Os quatro estudos de caso contribuíram para o desenvolvimento da solução, identificando oportunidades de melhoria para cada obra, que fornecem evidências da utilidade da solução. No que se refere à contribuição prática da solução, a operacionalização de cada diretriz de ER durante a avaliação do SPMSs forneceu categorias de análise com diferentes atributos que podem ser úteis na definição de estratégias pelas quais o SPMS contribui para a resiliência. Além disso, o uso de TOE e RAG contribuiu para o entendimento das fontes de complexidade e resiliência em cada projeto de construção. A principal contribuição teórica da solução é o refinamento das diretrizes de ER para avaliação de SPMSs, usando como ponto de partida as recomendações dos principais autores de ER no campo do gerenciamento de segurança.

Palavras-chave: Sistemas de medição de desempenho de segurança, Engenharia de resiliência, Complexidade do projeto

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1. INTRODUCTION

1.1 CONTEXT

Socio-technical systems can be defined as interconnected networks of people and technology that functions to achieve specific goals (Perrow, 1999). Those systems have become more complex in different fields of engineering in recent years. Several factors have contributed to this, such as: (i) the increasing use of new information and communication technologies which have made work processes more tightly-coupled and therefore more dependent on each other; (ii) growing customer demands to quality and reliability; (iii) market conditions and financial pressures (Rasmussen, 1997; El Maraghy et al., 2014). The adaptation to these and other sources of complexity has changed every day work, the contents of work processes, and the management systems in traditional workplaces (Hovden et al., 2010). New human roles have emerged, and the relationships between people and artifacts have been transformed (Dekker et al., 2011).

In fact, the need for an increased understanding of the factors that underlie and promote safety within socio-technical systems has significantly grown as a result of the accelerating complexity of contemporary work environments (Kleiner et al., 2015). Janackovic et al. (2017) argued that safety management in complex socio-technical systems must take into account the interrelations and dynamics between different elements and stakeholders in order to define and achieve safety objectives.

In the construction sector, Qazi et al. (2016) state that the increasing complexity of construction projects is due to the growth in the portfolio of projects, the competitive and dynamic environment, and the challenging characteristics of each unique project. According with Bakhshi et al. (2016) and Harvey et al. (2016) the complexity of projects has gained attention in recent years due to management needs for setting up organisational structures which are compatible with complicated contracting and with the increased legal controls, as well as for developing a resilient workforce. However, the traditional approaches to safety management in construction still remain sharply institutionalized through policies, plans and procedures that are difficult to adapt to the natural and inevitable changes in the work environment (Trinh et al., 2018).

A new way of thinking in safety management for complex socio-technical systems has then emerged, namely Resilience Engineering (RE) perspective. RE is concerned with the observation, analysis, design and development of theories and tools to manage the adaptive ability of organizations in order to function effectively and safely (Nemeth and Herrera, 2015). It means that an organization is resilient if it can function as required under both expected and unexpected conditions.

RE requires the implementation of innovative concepts and tools to enhance safety performance in environments that have variability and uncertainty (Dekker, 2019). It may be consistent with the nature of construction projects, described as temporary installations in which the changing working environment may lead to the emergence of unknown risks that are difficult to monitor and understand (Ringen, et. al., 1995; Carter and Smith, 2006).

1.2 RESEARCH PROBLEM

Most of the traditional approaches usually adopted for monitoring the safety performance in construction projects rely on post-accident data which do not reveal sufficient information to identify and control risks (Ahmad and Gibb, 2004). Very often, construction companies are limited to generate safety indicators required by regulations, such as accidents and lost time injury rates, to monitor and track organizational safety performance (Janicak, 2010). The use of those metrics results into reactive measurement systems that contain only lagging indicators, which are defined as direct metrics of harm and other safety related losses (Hopkins, 2009). Then, the goal of reactive Safety Performance Measurement Systems (SPMSs) is to keep the number of undesired outcomes as low as possible (Hollnagel, 2014).

Although these failure-focused indicators can be useful for benchmarking with other organizations or within a portfolio of projects at a corporate level, there is a growing acceptance in literature that such indicators are less useful in helping organizations to drive continuous improvement (Agnew, 2013) and are of little use for operational levels – e.g. to support to decision-making and to achieve learning (Köper et al., 2018).

By contrast, the use of leading indicators has been strongly recommended in literature, as measures that describe the level of effectiveness of the safety process (Hinze et al., 2013). These metrics result into proactive measurement systems, intended to identify safety problems and corrective actions before the occurrence of undesired outcomes (Hopkins, 2009). Moreover, the increased attention to the implementation of safety management systems, such as OHSAS 18001 (BSI, 2007), have contributed to the need for using leading indicators. However, how to use and assess the leading indicators in a continuous improvement cycle is a limitation pointed by several authors (Haight et al., 2014; Podgórski, 2015; Haas and Yorio, 2016).

A SPMS is a core element of any safety management system which encompasses a cycle of continuous improvement. Therefore, SPMSs are not limited to the design or selection of indicators, but includes the definition of protocols for data collection, processing and analysis, the formulation of strategies for disseminating indicators, and the revision of the SPMS on a regular basis (Janicak, 2010). In turn, the systems approach to safety measurement should not only control and learn from past accidents, but must also assist the management of risks throughout the project lifecycle (Kjellen, 2009).

The RE perspective is a new paradigm for the management of safety that focuses on coping with complexity to achieve success (Dekker, 2019). Therefore, a SPMS based on RE may contribute to the existing approaches for safety measurement, by helping to understand and monitor the changing nature of the sources of complexity that affect construction safety. From the RE viewpoint, SPMSs must contribute to the four abilities of resilient systems namely: respond (knowing what to do), monitor (knowing what to look for), learn (knowing what has happened) and anticipate (knowing what to expect) (Hollnagel, 2017). The validity of these four potentials has been widely recognised for promoting proactive strategies for the management of daily operations (Praetorius and Hollnagel, 2014).

However, there is a lack of studies in the literature on how to integrate the RE perspective in SPMSS, both in construction and in other domains. Saurin et al. (2016) is the only study that proposed criteria for SPMSs in construction industry based on RE principles. In healthcare, Raben et al. (2017) adopted RE to design safety indicators by modelling the work-as-done of a blood sampling unit. Although that study provided new insights in terms of what counts as safety indicators – by describing them as "*those functions or conditions necessary to obtain success*", it did not produce prescriptions on how to manage resilience within a systems approach.

1.3 RESEARCH QUESTIONS

Based on the contextualization and the research problem presented in the previous sections, the main question to be answered by this research study was proposed:

How to assess Safety Performance Measurement Systems (SPMSs) for construction projects based on the Resilience Engineering (RE) perspective?

In order to answer the main question, the following sub-question were proposed:

(a) To what extent previous research on SPMSs have adopted the RE perspective?

(b) How can a SPMS monitor the factors that affect complexity and resilience in construction projects?

1.4 OBJECTIVES

An assumption of this thesis is that SPMSs can contribute to the resilient performance of construction projects. It may imply that project participants must learn and adapt not just from incidents and accidents data, but also from the variability of construction work, in order to improve and facilitate the activities that are necessary for acceptable outcomes. Thus, the main objective of this work is:

To propose a framework to assess SPMSs for construction projects based on the RE perspective.

The specific objectives are:

(a) To propose RE guidelines for SPMSs assessment and to investigate the extent to which previous research on SPMSs have adopted the RE perspective, through a systematic literature review

(b) To propose steps to support the monitoring of complexity and resilience in construction projects

1.5 BOUNDARIES

A major boundary of the thesis is the focus given to the construction industry context, more specifically to construction projects. However, this type of limitation is envisaged when conducting case studies and Design Science Research. The data analysed is context-dependent, but the generated knowledge is expected to trigger reflections and actions for other contexts.

1.6 STRUCTURE OF THE THESIS

The thesis is divided into six chapters. The first chapter presents the context and research problem that outlined this investigation. In addition, the research questions and objectives were explained and the boundaries within the scope of this work was established. The second chapter present an overview of the research method, by encompassing the research strategy adopted in this investigation and by describing the research process in detail. The third, fourth and fifth chapters involved the development of a paper. Each paper aimed at address a specific research question and objective, as illustrated in Figure 1. The sixth chapter contains an appraisal of the research objectives and the suggestions for future research.

	Chapter 3 – *Paper I*	Chapter 4 – *Paper II*	Chapter 5 – *Paper III*
Research question	To what extent previous research on SPMSs have adopted the RE perspective?	How can a SPMS monitor the factors that affect complexity and resilience in construction projects?	How to assess SPMSs for construction projects based on the RE perspective?
Objective	To propose RE guidelines for SPMSs assessment and to investigate the extent to which previous research on SPMSs have adopted the RE perspective, through a systematic literature review	To propose steps to support the monitoring of complexity and resilience in construction projects	To propose a framework to assess SPMSs for construction projects based on the RE perspective

Figure 1 – Links between papers, research questions and objectives

2. OVERVIEW OF THE RESEARCH METHOD

2.1 Research strategy

Design Science Research (DSR) was the methodological approach adopted in this investigation. This approach aims to produce knowledge that can be used in an instrumental way to design and implement actions, process or systems to archive desired outcomes in practice (van Aken et al., 2016). March and Smith (1995), van Aken (2004), and Holmstrom et al. (2009) argues that the DSR provide support disciplines concerned with problem-solving, such as management, engineering and information systems. In those disciplines it is not sufficient to describe and understand a problem, but it is also necessary to develop and test solutions. In this sense, knowledge is developed in a direct way of action by engaging with real-life problems or opportunities (van Aken et al., 2016).

Every DSR research has an explanatory and design component. On one hand, the problem type, its causes and contexts are analysed, and, on the other hand, a design concept for addressing the problem is developed in cycles of testing and redesign (van Aken, 2004). Unlike other well-known strategies such as action research, which aims for case-specific improvements, the DSR seek to develop generic knowledge to support organizational improvement actions that can be transferred to various contexts within a specified application domain (Holmstrom et al. 2009; van Aken et al., 2016).

2.2 Research design

Figure 2 provides an overview of the research process carried out of this investigation. It is divided into three stages, namely stage A, B and C. Each stage contains steps of a DSR process, based on Kasanen et al. (1993) and Lukka (2003): (i) to find a problem of practical relevance; (ii) to obtain an understanding of the research topic; (iii) to collect data; (iv) to develop and implement a solution that has the potential for theoretical and practical contributions; (v) to test the solution and assess its practical contributions; (vi) to examine the theoretical connections and contribution of the solution. A common trend in DSR is that the research process is not linear, thus, involving interactions among the sequences of steps emerge (Vaishnavi and Kuechler, 2007).

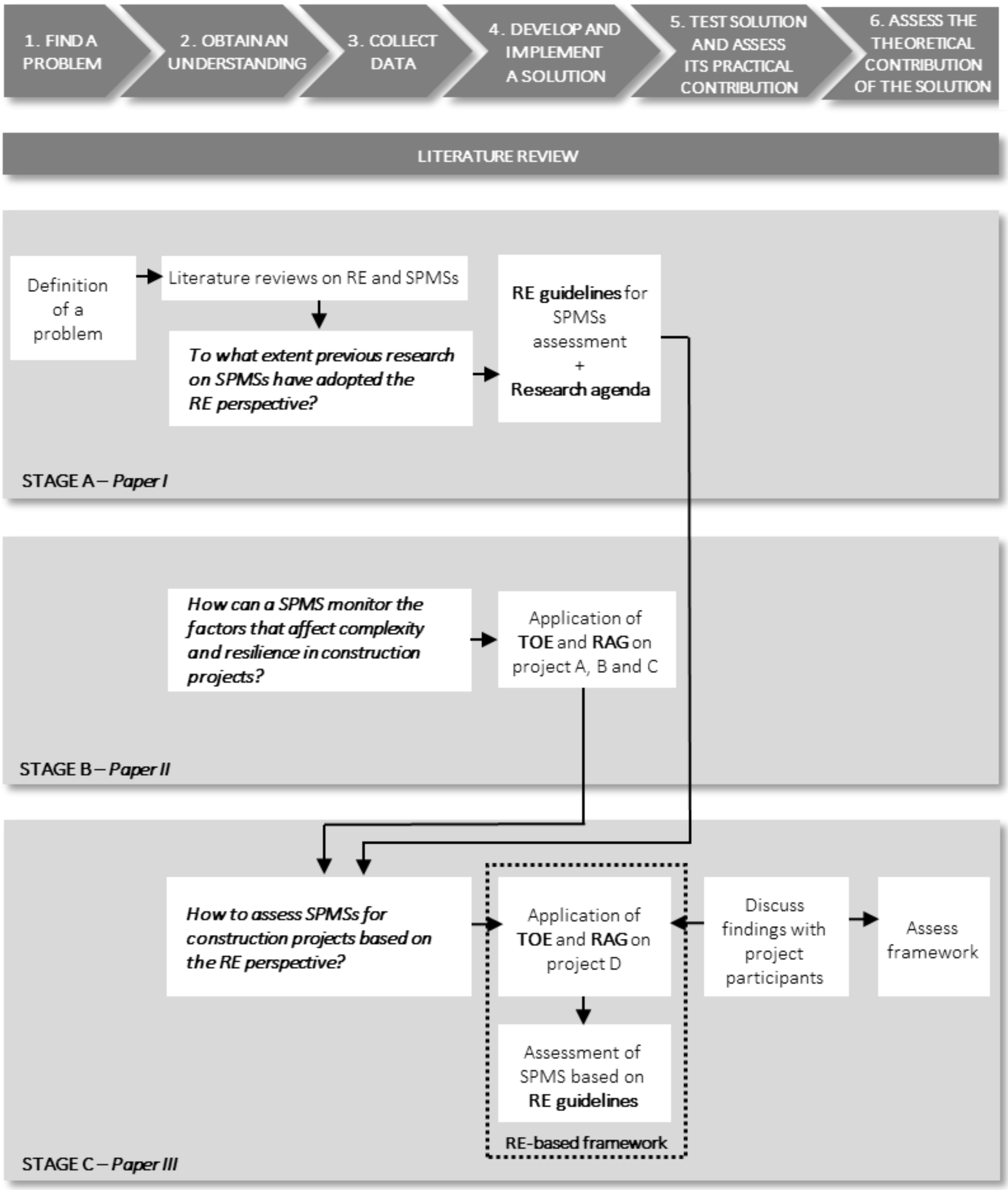

Figure 2 – Overall research process

Stage A involved the four initial steps: find a problem, obtain an understanding, collect data and develop a solution. The research process of *Paper I* consisted of five stages (Figure 3):

(i) definition of a problem with practical relevance and potential for theoretical contribution. From a theoretical point of view, the literature does not provide guidance on how to use the RE perspective for assessing SPMSs. From a practical point of view, there is evidence that most of safety indicators used in construction are primarily based on regulations and standards, which are usually of little use for supporting decision-making and learning – e.g. to maintain a balance between safety requirements and production pressures while coping with the variability of everyday work;

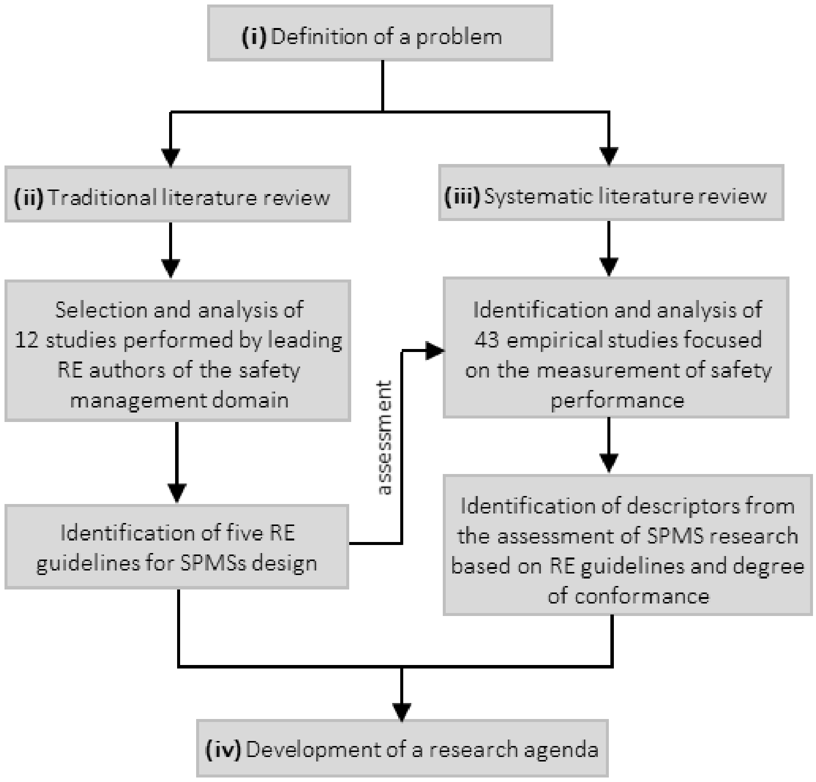

Figure 3 – Research process of *Paper I*

(ii) development of a traditional literature review based mostly on twelve studies delivered by leading RE authors of the safety management field. The aim of this step was to devise a set of RE guidelines for SPMSs assessment, being concerned with the whole cycle of defining, collecting, and learning from metrics:

(a) SPMSs should support the monitoring of everyday variability;

(b) SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities;

(c) SPMSs should facilitate learning from what goes well, in addition to what goes wrong;

(d) SPMSs should offer insights into the management of trade-offs between safety and other business dimensions; and

(e) SPMSs should evolve due to the changing nature of complex socio-technical systems;

(iii) development of a systematic literature review in which forty-three empirical studies, focused on the measurement of safety performance, were selected from different industry sectors. These studies were assessed through the lens of the five RE guidelines in order to explore the real extent to which the guidelines were adopted in SPMS research. Based on this assessment, fifteen descriptors emerged and, for each of these, a degree of conformance to the RE guidelines was established; and

(iv) development of a research agenda based on the gaps in knowledge identified in the literature reviews.

Stage B involved the second, third and four steps of the DSR process: obtain an understanding, collect data and develop a solution. The purpose of this stage was to explore the contribution of SPMSs as a means for monitoring and understanding the sources of complexity and resilience in construction. It was based on the assumption that both complexity and resilience are fundamental characteristics of the functioning of construction projects, and therefore they influence and are influenced by safety management. The research process consisted of six stages (Figure 4):

(i) selection of relevant cases, in order to explore and compare different contexts through a cross-case analysis. Three empirical studies were carried out in construction projects, one in Brazil (project A) and two in Chile (project B and C).

(ii) obtain an overview of the existing SPMS of each project. At this stage, semi structured interviews with the project and safety managers of each project were carried out. In addition, safety related documents were analysed and direct observations were performed over weekly visits to each construction site;

(iii) application of the Technical, Organizational and Environmental (TOE) framework (Bosch-Rekveldt et al., 2011) by means of semi-structured interviews in order to identify the sources of complexity as contributing factors that influence safety performance. The TOE questionnaire was applied to the project manager of each construction project;

(iv) assessment of the four resilience potentials by using the Resilience Assessment Grid (RAG) (Hollnagel, 2011). The original RAG was adapted to the construction project context by addressing 17 functions related to safety management and performance measurement. These functions accounted for the identification, operationalization, dissemination, and learning from the metrics. The RAG questionnaire was applied to the project manager and safety engineer of each construction project, in addition to the safety technician of one of the projects;

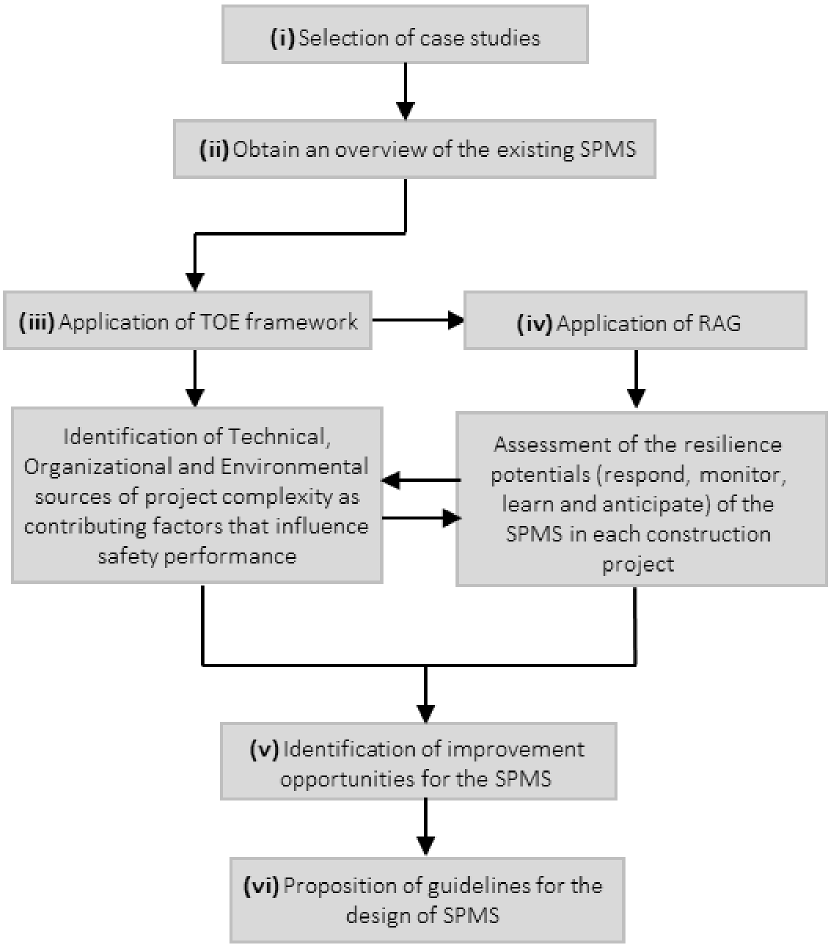

Figure 4 – Research process of *Paper II*

(v) identification of improvement opportunities for the existing SPMS based on the insights obtained from TOE and RAG. The use of the tools suggested opportunities of three types: those related to changes in other safety management sub-systems, design of new metrics, and revision of existing metrics; and

(vi) development of guidelines for SPMS design based on TOE and RAG application. This last step also involved the development of a conceptual model in which the relationship between the constructs encompasses by the guidelines were illustrated.

Stage C consisted of the proposition, application and evaluation of the framework for SPMSs assessment based on the RE perspective. The framework integrates the findings from *Stage A* and *Stage B* (Figure 5). This integration consists of using the five RE guidelines for assessing SPMSs as a link between RAG and TOE, which jointly provide a description of a construction project complexity.

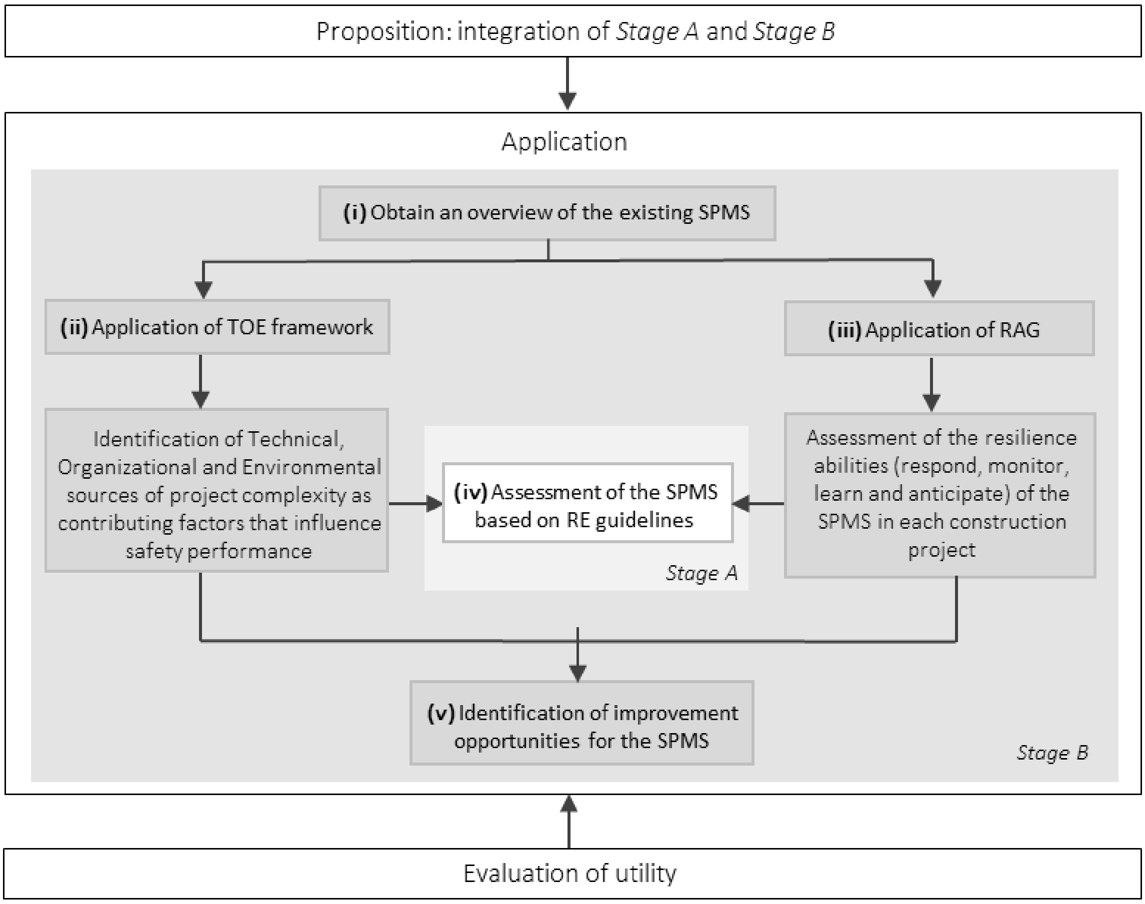

Figure 5 – Research process of *Paper III*

The application of the framework consisted of five stages:

(i) obtain an overview of the existing SPMS of the project consisted of semi-structured interviews with the project manager, site manager, and safety coordinator. Also, safety related documents were analysed and participant observations were performed over weekly visits to the construction site;

(ii) application of the TOE framework in order to understand how project complexity influences safety performance;

(iii) assessment of the four resilience abilities by using RAG.

(iv) assessment of the existing SPMS based on RE guidelines by using the data collected from the previous stages; and

(v) identification of improvement opportunities, based on the findings obtained from all stages. These opportunities were divided into three categories as suggested in *Stage B*.

TOE and RAG questionnaires were individually applied to a group of ten project participants: the project manager, the site manager, the safety coordinator, the foreman, and six front-line workers. The approach used in *Stage C* differs from *Stage B*, in which only the perspectives of production and safety managers were considered. In addition, participant observations and document analysis have supported TOE and RAG findings. Then, based on a case study in Norway (project D), the utility of the framework was assessed. The integration of findings from *Stage A* and *B* was supported by interviews, observations, and analysis of documents. Results pointed out exemplar approaches for applying RE ideas to SPMSs as well as they shed light on how complexity may either hinder or support a SPMS. Based on this, a conceptual model was devised in order to illustrate the relationships between the five RE guidelines for SPMSs assessment and the key contextual characteristics of the studied construction project (complexity attributes).

A RESILIENCE ENGINEERING PERSPECTIVE OF SAFETY PERFORMANCE MEASUREMENT SYSTEMS: A SYSTEMATIC LITERATURE REVIEW

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A resilience engineering perspective of safety performance measurement systems: A systematic literature review

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ABSTRACT

Although safety performance measurement systems (SPMSs) are key elements of safety management, previous research is usually limited to the proposal or assessment of indicators, without adopting a systems perspective. Furthermore, what counts as a well-designed SPMS is contingent to the adopted theoretical perspective, which is normally implicit. In this study, Resilience Engineering (RE) has been used for assessing SPMSs, providing an explicit and systems-oriented perspective. Previous research on SPMSs was analysed in a systematic literature review, with the aim of identifying whether RE offers a new perspective on SPMSs, and understand how RE has been put into practice in SPMSs. For each paper, there was an evaluation of how it accounted for five RE guidelines concerned with the design and implementation of SPMSs. The uptake of the guidelines was low on average, indicating that RE does not largely overlap with traditional assumptions of SPMS literature. However, there were several studies moderately or strongly aligned with those guidelines, suggesting that RE has been implicitly adopted to some extent. Descriptors were devised to convey approaches for the operationalization of the guidelines, providing a reference for the design of SPMSs informed by RE. A research agenda is also proposed.

1. Introduction

Performance measurement is a core element of managerial systems whatever the business dimension. It provides feedback from past and current performance, enables predictions to be made (Woods et al., 2015), and plays a role in satisfying the human psychological need for feeling in control (Dekker, 2014).

This study is concerned with safety performance measurement, addressed from a systems-oriented perspective. Instead of being limited to individual metrics, this investigation is concerned with Safety Performance Measurement Systems (SPMSs). A SPMS encompasses the design and selection of indicators; protocols for data collection, processing, and analysis; strategies for disseminating metrics; and a review process with the aim of regularly updating the system (Janicak, 2010). This systems-oriented perspective is relevant, as most studies are limited to the selection or implementation of a set of isolated metrics, which provide little insight on the nature of contributing factors to safety and may not be cost-effective (Øien et al., 2010).

SPMSs are either explicitly or implicitly based on a theoretical perspective on what is safety and how it can be obtained, which has implications for defining what counts as a relevant indicator and how they should be collected and analysed (Reiman and Pietikäinen, 2012). A common assumption adopted in the development and implementation of SMPSs is that safety can be described, and therefore measured, in terms of a particular state or condition related to freedom from unacceptable harm or risk (AHRQ, 2016). SPMSs that subscribe to this view rely mostly on lagging indicators, which monitor losses in terms of injuries and fatalities (Kjellén, 2009), being considered as reactive systems. This type of SPMS is widely used, as data collection and analysis are relatively simple, metrics are easy to understand by both managers and workers, and these can be used for comparisons with other companies or national data (Sgourou et al., 2010). However,

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reactive SPMSs have several drawbacks: (i) little predictive value, especially for accidents that arise from multiple contributing factors unlikely to reoccur in the same way; (ii) as there are relatively few serious accidents, lagging indicators make it difficult to distinguish trends from random variations; and (iii) their accuracy may be hindered by underreporting of undesired outcomes (Øien et al., 2011; Sinelnikov et al., 2015).

By contrast, other SPMSs give priority to leading indicators, which focus on the conditions or events that indicate the likelihood of outcomes (Kjellén, 2009), being considered as proactive. These SPMSs are concerned, for instance, with monitoring the status of the resources available for safe performance (Hallowell et al., 2013). However, previous research has indicated that leading indicators tend to be more context-dependent than lagging indicators (e.g. accident rates), which makes it difficult to identify general proactive indicators that have strong predictive power (Lingard et al., 2017). Overall, it has been accepted that SPMSs should comprise a mix of reactive and proactive indicators (Herrera and Tinmannsvik, 2012) but these should not demand too much resources for implementation (Hale, 2009).

In this study, the lens of Resilience Engineering (RE) has been used to support the identification of strengths and weaknesses of SPMSs. RE is concerned with the observation, analysis, design and development of theories and tools to manage the adaptive ability of organizations in order to function effectively and safely (Nemeth and Herrera, 2015). In turn, resilience is "the expression of how people, alone or together, cope with everyday situations – large and small – by adjusting their performance to the conditions" (Hollnagel, 2017, p. 14). It means that an organization is resilient if it can function as required under both expected and unexpected conditions. Performance adjustment implies in coping with the gap between work-as-done (WAD), which corresponds to what actually occurs in the workplace, and work-as-imagined (WAI), which corresponds to what people expect to occur (Hollnagel, 2014).

From the RE viewpoint, resilient systems have been defined as those that display four abilities at the system level, namely the abilities of monitoring, anticipating, responding, and learning (Hollnagel, 2017). This conveys a continuous improvement cycle, as learning must lead to the overall improvement of the other three abilities. Thus, it is reasonable to assume that RE is consistent with the aforementioned systems-oriented perspective of performance measurement systems. Besides, RE acknowledges the need for both proactive (e.g. anticipating) and reactive (e.g. responding) safety management (Hollnagel, 2014), thus providing a framework for assessing SPMSs. In spite of this, the literature does not provide guidance on how to use the RE perspective for assessing SPMSs.

Thus, it is possible that previous empirical research studies on SPMSs have partly or intuitively adopted the RE perspective. An investigation of the extent to which this occurs is necessary for two reasons: (i) it might help to clarify the extent to which RE premises, when applied to SPMSs, are new – this is relevant as there is still debate on whether RE offers an original perspective of safety management (Martinetti et al., 2019; Harvey et al., 2019); and (ii) it can shed light on how RE has been put into practice in the realm of SPMSs, even if unintentionally – this has a pragmatic value for offering ideas to practitioners interested in designing SPMSs based on RE. Against this background, the following research question was formulated for this research study: To what extent previous research on SPMSs have adopted the RE perspective?

This research question is addressed through a systematic literature review on SPMSs, which is relevant considering that performance measurement is one of the most common safety management research topics (Zhou et al., 2015). To our knowledge, this is the first literature review on SPMSs (either or not using the RE perspective), considering a systems-oriented perspective. In fact, there have been reviews on that topic focused on some industries, but limited to the definition of specific safety performance metrics. For example, reviews on leading indicators used for controlling major hazards have been carried out in maritime (Jalonen and Salmi, 2009), chemical (Bellamy and Sol, 2012) and process industries (Reiman and Pietikäinen, 2010; Swuste et al., 2016).

2. Research design

2.1. Research stages

This research work was divided into two main stages. The first stage was a traditional literature review focused on seminal authors, with the aim of defining a set of guidelines for the design of SPMSs aligned with RE. Those guidelines were used as a reference for analysing relevant research studies identified in the systematic literature review. This initial stage was based on nine book chapters (Hollnagel and Woods, 2006; Nemeth et al., 2008; Dekker et al. 2008; Hollnagel, 2009; Woods and Branlat, 2011; Hollnagel, 2014; Saurin et al., 2016; Hollnagel, 2017; Dekker, 2019) and three papers (Herrera and Hovden, 2008; Lay et al., 2015; Woods et al., 2015). These studies have been mostly developed by leading RE authors, whose ideas have been known to widely influence other researchers.

Those 12 publications were subjected to a thematic analysis (Braun and Clarke, 2006), by examining the design guidelines proposed by different research studies. In fact, these guidelines were fairly consensual, even though designated by different terms, such as "learn from experience" (Dekker et al., 2008; Lay et al., 2015), "learn from normal work" (Nemeth et al., 2008; Saurin et al., 2016) or "learn from everyday work" (Hollnagel, 2017). As a result, five RE guidelines relevant to SPMSs were devised (see Section 3.1).

The second stage of this investigation was the systematic literature review, which followed the steps suggested by Moher (2010): identification of papers; analysis; selection; and inclusion (Fig. 1). In the identification step, eight databases were considered: Web of Science, Scopus, Science Direct, American Society of Civil Engineers (ASCE), Taylor & Francis Online, Emerald Full Text and Google Scholar. These databases were queried between the 7th and 9th of June 2019 and the

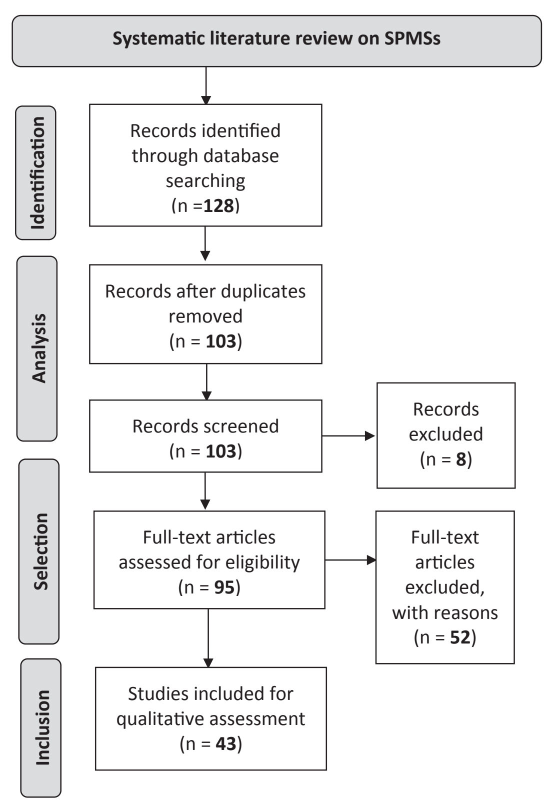

Fig. 1. Steps of the systematic literature review.

results for each of them were downloaded in single batches on the same day. The search criteria encompassed the terms *"safety performance"* AND *"measurement system"* OR *"safety indicators"* OR *"safety measures"* OR *"safety metrics"* OR *"assessment"* OR *"evaluation"* in the title, abstract, and keywords. At the end of this step, 128 papers were exported to a reference manager, and, after the removal of 25 duplicates, 103 papers were identified. In the analysis step, eight papers were excluded according to two criteria: papers written in other languages than English (2 records); and full content access denied (6 records). Concerning the selection step, the title and abstract of the 95 remaining papers were analysed according to one inclusion criteria, namely the use of an empirical approach that accounted for at least one of the following: (i) the proposition of frameworks, guidelines or indicators; and (ii) the practical implementation of indicators into an organization routine. No constraints were set on the nature of the research method, which could involve experimental analysis, case studies, or simulations, among others. Then, 52 papers were excluded because these were essentially theoretical, without support from empirical data or did not provide enough details of the empirical study. As a result, 43 papers were selected and included in the database.

2.2. Data analysis

The 43 papers were analysed according to three categories of information: (i) bibliometric information; (ii) extent to which SPMSs rather than only metrics were described; and (iii) alignment with the five RE guidelines. Regarding (iii) it is worth noting that the guidelines were not, with a few exceptions, explicitly mentioned in the papers. The analytical framework was therefore imposed on the studies as a heuristic device (see Table 1).

Thus, the papers were fully read and excerpts of text related to the guidelines were identified and coded into descriptors. These descriptors correspond to examples of approaches for the operationalization of the guidelines. Initially, specific descriptors were developed for each paper. Then, after several rounds of revisiting these specific descriptors, they were grouped into more comprehensive descriptors, generic enough to be applicable to several studies.

For instance, specific descriptors for the guideline "the SPMS should support the monitoring of everyday variability" were originally coded, for some papers, as *"the study proposed indicators based on standardized observation checklists for monitoring unsafe behaviours and conditions"* or *"indicators were selected according to the components of certified safety management system"*. Next, these were grouped into a more generalizable descriptor, such as *"a set of safety requirements (*e.g. *physical protections) are defined upfront as a basis for monitoring through indicators"*. Each study was associated to only one generic descriptor for each RE guideline.

Fifteen descriptors emerged from data analysis and, for each of these, a degree of conformance to the RE guidelines was established, as follows: strong alignment (score 2.0), moderate (1.0), weak (0.5), and no alignment (0.0). The aim of this scale is to facilitate discussion about the extent to which the guidelines were adopted in different studies. Also, the guidelines and the studies were ranked based on their average scores. Procedures described in this section were carried out primarily by the first two authors of this paper, who initially analysed half of the selected papers and developed their own Tables with descriptors. After that, a cross-check analysis was carried out to compare both codifications and obtain a consensus.

3. Results

3.1. Resilience engineering guidelines for SPMSs

Table 2 presents the five guidelines and the studies from which they emerged. All studies provided insights into two or more guidelines.

Guideline 1 prescribes that SPMSs should support the monitoring of everyday variability. It emerged from studies acknowledging that, in complex socio-technical systems, performance variability is an inevitable part of everyday work (Hollnagel and Woods, 2006) and often necessary for the production of required outputs (Lay et al., 2015). Therefore, the same variability sources usually play out both in accidents and everyday work. As the latter is much more frequent than the former, it offers more opportunities to understand the nature of variability (Dekker et al., 2008; Hollnagel, 2017; Dekker, 2019).

In turn, guideline 2 states that SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities. This guideline also arises from the complexity of the systems monitored by SPMSs. Control in complex systems relies as much (or more) on feedback as on feedforward mechanisms (Hollnagel and Woods, 2006). Furthermore, complex systems are continuously evolving, and therefore the system status may never be exactly the same again (Nemeth et al., 2008). Therefore, it is important to shorten the time lag between data gathering, data analysis, and feedback, which is a basis for action-taking (Saurin et al., 2016). For the purpose of real-time feedback, a mix of direct and indirect sources of information tend to be useful. A simple everyday example of this mix can be observed when driving a car: each driver can control speed and other performance parameters by visualizing the cockpit dashboard (direct access to information), while at the same time listening to news in the radio about traffic conditions (indirect access to information). Real-time feedback can also benefit from two other approaches: (i) a diverse group of analysts in terms of knowledge and skills, which can quickly identify

Table 1
Framework of data analysis.

	Categories of data analysis	Exemplar information searched in the selected papers
General categories	Bibliometric information	– Journal, year of publication, country where the empirical study was carried out, and industrial sector
	SPMS perspective	– Main activities of the SPMS accounted for by the study: design or select indicators; collect and analyse data; report and provide feedback; act on findings (Kaplan and Norton, 1996; Neely et al., 2005).
RE guidelines	(1) SPMSs should support the monitoring of everyday variability	– Indicators that provide information of work-as-done
	(2) SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities.	– Reporting mechanisms or indicators that provide real-time feedback. – Decentralization of data collection and dissemination
	(3) SPMSs should facilitate learning from what goes well, in addition to what goes wrong	– Indicators of desired outcomes (e.g. safe behaviours) and undesired outcomes (e.g. near misses, accidents). – Organizational routines for sharing and discussing information from these indicators
	(4) SPMSs should offer insights into the management of trade-offs between safety and other business dimensions	– Organizational routines or indicators that support decision-making for coping with trade-offs (e.g. number of times that the stop work authority is exercised) between safety and other business dimensions
	(5) SPMSs should evolve due to the changing nature of complex socio-technical systems	– Changes or improvements made in SPMS with the aim to keep them up-to-date in a dynamic environment

Table 2
RE guidelines for SPMSs.

Guidelines/sources	[a]	[b]	[c]	[d]	[e]	[f]	[g]	[h]	[i]	[j]	[k]	[l]
(1) SPMSs should support the monitoring of everyday variability	x	x		x	x		x		x	x	x	x
(2) SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities	x		x						x	x		x
(3) SPMSs should facilitate learning from what goes well, in addition to what goes wrong	x	x	x	x	x		x		x		x	x
(4) SPMSs should offer insights into the management of trade-offs between safety and other business dimensions	x			x	x	x	x	x		x	x	x
(5) SPMSs should evolve due to the changing nature of complex socio-technical systems	x	x		x				x		x	x	x

[a] Hollnagel et al. (2006); [b] Herrera and Hovden (2008); [c] Nemeth et al. (2008); [d] Dekker et al. (2008); [e] Hollnagel (2009); [f] Woods and Branlat (2011); [g] Hollnagel (2014); [h] Woods (2015) [i] Lay et al. (2015); [j] Saurin et al. (2016); [k] Hollnagel (2017); [l] Dekker (2019).

early warnings of deteriorating performance (Lay et al., 2015); and (ii) information technology, such as the use of wearables that monitor environmental, physiological and cognitive performance in real-time, triggering sensory warnings to workers (Dekker, 2019).

Guideline 3 conveys that SPMSs should facilitate learning from what goes well, in addition to what goes wrong (e.g. accidents). Hollnagel (2014) uses the term "what goes well" to refer to any situation in which there is presence of safety. In line with Hollnagel, an operational definition of what is covered by an assessment of what goes well is proposed, as follows:

(i) The assessment of latent conditions, such as unsafe conditions or unsafe behaviours, considering how people or systems keep those conditions under control. If this assessment is limited to pinpointing latent conditions as deviations from prescription, it is interpreted as the traditional focus on what goes wrong;
(ii) The assessment of safety management activities, such as safety inspections, risk assessments, and training, considering how these activities were carried out (e.g. whether training was limited to rule-following or included the development of adaptive skills). This assessment may be restricted to the counting of positive actions (e.g. number of safety inspections carried out), but this may be less important in comparison to how it is carried out; and
(iii) Instantiations of problem-solving with desired outcomes.

Near misses have been excluded from the definition of what goes well as these imply a release of energy (Cambraia et al., 2010), thus posing an imminent danger. Therefore, the adopted dividing lines between what goes well and what goes wrong are: (i) the existence of energy release; (ii) a focus on how energy release was prevented, instead of only counting deviations from work-as-imagined; and (iii) if counting is used, it should be focused on positive actions rather than negative – i.e. the larger-is-best type of metric.

As for guideline 4, it states that SPMSs should offer insights into the identification and management of trade-offs between safety and other business dimensions. Given the multiplicity of participants in complex systems and their potentially conflicting goals, trade-offs such as those between safety and efficiency tend to be ubiquitous (Woods and Branlat, 2011; Dekker, 2019). In practice, these trade-offs usually pend in favour of acute goals, such as efficiency, cost reduction, and fast delivery, instead of chronic goals (e.g. safety) (Woods, 2015). Hollnagel (2009) conveys this same idea as a generic trade-off between efficiency and thoroughness. Efficiency pressures push the system to the use of less and less resources, while concerns with thoroughness mean that the system should take the time to plan and understand how to produce the required outputs (Dekker, 2019).

Lastly, guideline 5 is concerned with the evolution of SPMSs. It means that, in order not to become stale, SPMSs should evolve due to the changing nature of complex socio-technical systems (Dekker, 2019). For instance, if a SPMS points out that the "margin of manoeuvre" of an operation is getting narrower, a greater frequency of monitoring the size of this margin is necessary (Woods, 2015). Guideline 5 can also be interpreted as a consequence of the law of requisite variety, which indicates that the variety of the controller (e.g. SPMS) needs to match the variety of the controlled process (e.g. production processes monitored by a SPMS) (Ashby, 1991).

It is worth noting that these five RE guidelines are complementary, and, to some extent overlapping to other guidelines for SPMSs. For example, Peñaloza et al. (2020) compiled a set of general guidelines for SPMSs in several industrial domains – e.g. identify and prioritize critical processes to be covered by the SPMS. However, the five proposed guidelines have an explicit rationale based on RE, which justifies why these are relevant and under which circumstances this relevance grows – i.e. when complexity increases.

Furthermore, the proposed guidelines are logically associated with the four abilities of resilient systems proposed by Hollnagel (2017):

(i) Respond (knowing what to do): this is related to guideline 4, as the management of trade-offs implies making-decisions and responding to them. It is also related to guideline 5, as the SPMS adaptation to a changing environment may be framed as an adaptive response;
(ii) Monitor (knowing what to look for): this is clearly connected to guidelines 1 and 2, which are directly concerned with monitoring;
(iii) Learn (being able to acquire the right lessons from the right experience): this is directly connected to guideline 3.
(iv) Anticipate (knowing what to expect): this ability may be a result of the effective deployment of all guidelines, as this may result in the production of information for anticipating threats and opportunities in the short and long-term.

3.2. Bibliometric information

The 43 papers were published in 20 different journals, which suggest that a broad audience is interested in the topic of safety performance measurement. *Safety Science* had the largest number of papers (37%), followed by the *Journal of Construction Engineering and Management* (7%). Other well-known journals in the safety science field had low participation, such as *Accident Analysis and Prevention*, *Journal of Safety Research*, *Reliability Engineering and System Safety,* and *Process Safety and Environmental Protection* – each one of these accounted for 4.6% of the total.

The empirical studies reported in the papers were carried out in 19 countries, with a higher frequency of the United States (11 papers), Norway (5) and Australia (3) followed by Italy, Hong Kong, Poland, Slovenia, Spain and UK (2 each). In total, 82% of the studies were published in the last six years (from 2013 to 2019). Several industrial sectors were addressed, as shown in Fig. 2.

3.3. SPMS perspective: systems or indicators?

Fig. 3 shows the frequency in which the selected papers took into account the main activities involved in performance measurement systems (Kaplan and Norton, 1996; Neely et al., 2005), namely: design and/or select indicators; collect and analyse data; report and provide feedback; and act on findings. Fig. 3 was based on a thorough analysis

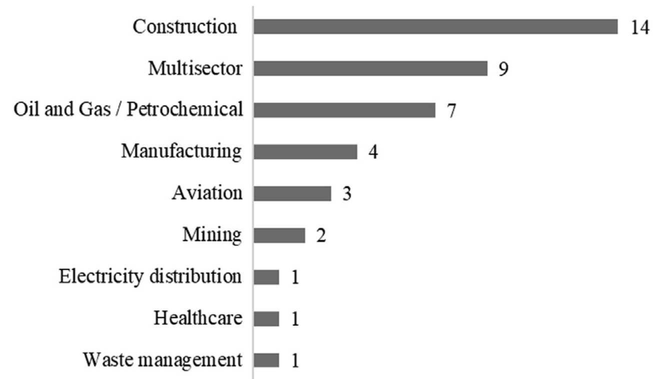

Fig. 2. Distribution of papers per sector.

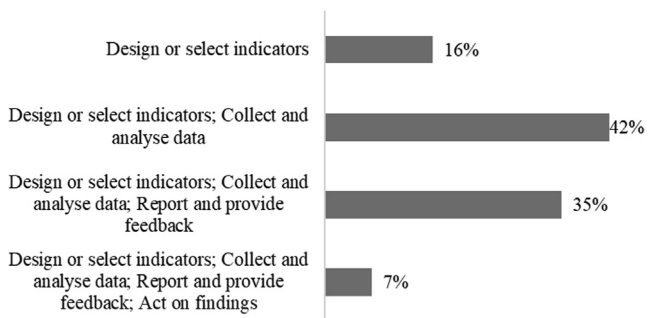

Fig. 3. Percentage of SPMS activities accounted for by the selected studies.

of how each paper addressed those activities (see Appendix A). The focus on indicators instead of systems is made evident by the fact that the most frequent activities were the design or selection of indicators, and data collection and analysis (42%). Furthermore, in most studies there were long time lags (up to one year) between data collection, analysis, and feedback.

Only three studies (7%) have explored all activities involved in SPMSs (Cameron and Duff, 2007; Li et al., 2015; Awolusi and Marks, 2016). For example, Awolusi and Marks (2016) defined real-time indicators in close collaboration with project participants. Those responsible for data collection received training for the identification of behaviours and conditions to be monitored. Immediate feedback was provided to construction workers so as they could adjust their performance. The implementation of corrective actions involved training on the avoidance of awkward postures during ground-level work.

3.4. Assessment of the RE guidelines

3.4.1. SPMSs should support the monitoring of everyday variability

Fig. 4 presents the descriptors obtained for guideline 1 (mean = 0.70). The study by Raben et al. (2018) was the only connected to descriptor A. It provided a sound example of applying guideline 1, as it was based on a deep understanding of WAD as a whole, instead of disconnected fragments. In that investigation, the variability of everyday work of the blood sampling process was modelled through the Functional Resonance Analysis Method (FRAM). The proposed model was used to identify key inter-related functions that contribute to desired outcomes. Then, a set of candidate leading indicators were identified for those functions, such as "to identify patient with special needs", "to walk to blood sampling room when called".

As for descriptor B, it refers to studies concerned with the monitoring of everyday variability based on a set of safety requirements defined upfront as a reference for WAI. As the main drawback, the approach adopted by these studies implies in monitoring fragments of WAD as if these were independent from each other. Furthermore, safety

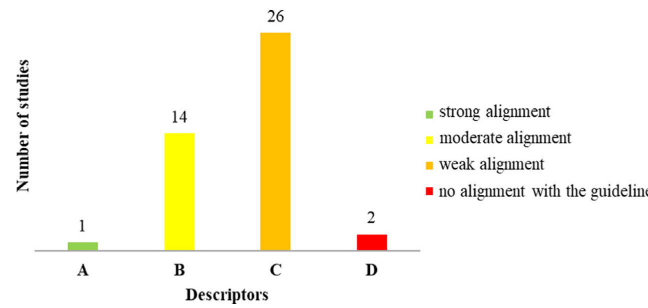

Fig. 4. Descriptors of guideline 1 and their frequency. Notes: A: Context-specific indicators were identified from a formal analysis and modelling of work-as-done; B: A set of safety requirements are defined upfront as a basis for monitoring through indicators. However, requirements are presented in a generic way (e.g. "use of personal protective equipment; safe behaviours"), thus also defining WAI in a generic way; C: A set of safety requirements (e.g. physical protections, management activities) are defined upfront as a basis for monitoring through indicators - e.g. "percentage of completed corrective actions in relation to safety audits". The variability of everyday work is assessed against a strict definition of WAI; D: No alignment with the guideline.

requirements are defined in a generic way. Although this makes it difficult to define what counts as a gap between WAI and WAD (e.g. there may be more demanding competences for the person collecting and analysing data), it provides flexibility and possibly a wide scope for monitoring everyday variability – this ambiguity is the main reason for considering descriptor B moderately aligned with guideline 1. For example, Laitinen et al. (2013) proposed a list of observable items as indicators of the behaviour of workers and conditions in manufacturing workplaces, such as "worker uses the necessary personal protective equipment, and does not take obvious risks", and "workstation, tools and equipment are ergonomically designed".

Descriptor C corresponds to relatively detailed specifications of WAI, which set a clear reference for the monitoring of everyday variability. Studies associated with descriptor 3 follow the traditional approach for safety inspections and audits, which is concerned with deviations from regulations, procedures and other manifestations of WAI. Although this facilitates the monitoring of the gap between WAI and WAD, there is an additional drawback in relation to studies associated with descriptor B: monitoring tends to ignore variability types that are not clearly related to WAI, as this is narrowly defined. Due to this drawback, studies related to descriptor C were coded as weakly aligned with guideline 1.

Some studies can be used to illustrate descriptor C. Podgórski (2015) in multiple sectors, Haas and Yorio (2016), in mining, and Ghahramani and Salminen (2019), in manufacturing, proposed metrics based on the safety management system components set by the standard OHSAS 18001. The number of corrective actions completed, number of risk assessments, and number of safety training hours are examples of indicators suggested in those studies. It is worth noting that none of the three studies is concerned with the direct monitoring of the variability of production activities in which hazards play out. Rather, there is an emphasis on monitoring whether safety management activities were conducted as frequently as imagined.

3.4.2. SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities

Fig. 5 presents the descriptors obtained for guideline 2, which had the lowest average score (0.40), as a consequence of 30 out of 43 studies not aligned with it. This suggests that, even when useful information is produced by SPMSs, it might not be timely communicated to those who need that information most. This can be a consequence of an overreliance on centralized and bureaucratic safety management systems.

Descriptor A, the most aligned with guideline 2, derived from three

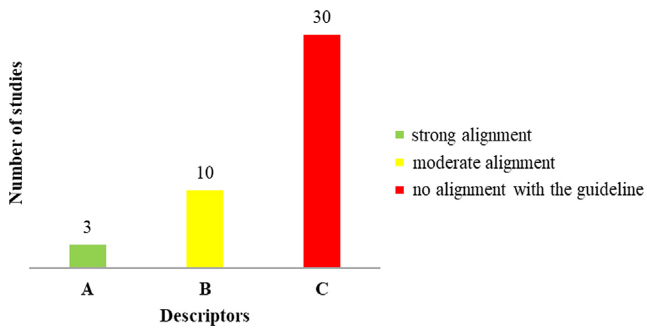

Fig. 5. Descriptors of guideline 2 and their frequency. Notes: A: Indicators results are available in real-time to workers (e.g. observations of workers behaviours, immediately followed by feedback from the observer to those being observed); B: Although indicators are gathered in real-time (e.g. observations), there is either a delay or no feedback is provided to workers. There can be feedback provided only to managers; C: No alignment with the guideline.

studies (Li et al., 2015; Awolusi and Marks, 2016; Tamim et al., 2017) that provided real-time feedback to workers during the whole work shift. The indicators used in those studies were framed as "signs" or "early warnings" of safety risks in specific processes, in the gas and oil, and construction industries. In all three studies the support of information technology was essential to provide real-time feedback. For example, Awolusi and Marks (2016) developed an automated monitoring tool to facilitate data collection and analysis of safety performance in a construction project. Activities were monitored through video cameras over a period of eight months. Observations were carried out by means of a checklist of safe and unsafe behaviours and conditions, from snapshots taken at one-hour intervals. The analysis and results were provided in real-time to workers, triggering appropriate interventions, such as adjustments in travel paths of heavy equipment to reduce proximity to workers. As a drawback, workers did not have direct access to information in order to self-organize, depending on external controllers.

Descriptor B was identified from 10 studies in which data were collected in real-time, but there was either a delay in data communication or no feedback was provided to workers. For example, Rajendran (2012) performed more than one thousand observations of construction activities in a construction project, over a period of 37 weeks. Each observation lasted 10 s and unsafe behaviours of workers were identified. However, feedback was not provided to workers during or after observations – only managers received information on the overall results of the observations.

3.4.3. SPMSs should facilitate learning from what goes well, in addition to what goes wrong

Fig. 6 presents the descriptors obtained for guideline 3, which had the highest average score (0.90). All studies were either coded as moderately or weakly aligned with this guideline. A common feature found in all papers is that these are concerned with the nature of the events that trigger learning (e.g. accidents), but do not discuss how and when organizational learning takes place. Also, no details are usually provided on the practical actions resulting from the use of indicators adopted to monitor these events. These were the main reasons why no study was coded as strongly aligned with guideline 3.

Descriptor A emerged from 29 studies that considered a mix of indicators addressing both what goes wrong and what goes well. However, this descriptor was considered to be moderately aligned with the guideline as the indicators based on what goes well were limited to safety management activities rather than production activities. For instance, Pawłowska (2015) investigated 60 companies in multiple sectors, concluding that the learning focus of safety indicators was determined by law provisions and certified safety management systems, for instance based on OHSAS 18001. As for what goes wrong,

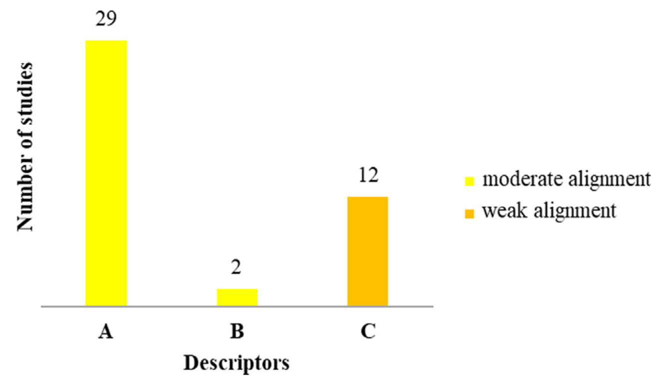

Fig. 6. Descriptors of guideline 3 and their frequency. Notes: A: There is a mix of indicators based on both what goes well and what goes wrong; B: The indicators only focus on what goes well – the implicit assumption is that learning results from understanding everyday work variability; C: The indicators only focus on what goes wrong – the implicit assumption is that learning results from understanding undesired outcomes.

companies had to present data required by regulations, such as the "cost of occupational accidents". As for what goes well, there were metrics related to activities required for the certification of safety management systems, such as the frequency of safety inspections (Pawłowska, 2015).

Descriptor B was identified from two studies in which indicators provided insight into the underlying reasons of desired outcomes. For instance, Raben et al. (2018) modelled WAD in a blood sampling process, and identified key functions for achieving desired outcomes – e.g. "to identify patients with special needs". Those authors suggested that the proposed model and those key functions could be used as a learning platform, for example, in training new staff. The other example of descriptor B is provided by Skogdalen et al. (2011), who analysed operators' adaptability to risk for preventing deep water blowouts. Some indicators were devised from learning how operators identified early warnings of hazards getting out of control, and responded to these – e.g. if operators realized that the mud weight was too low, they took corrective actions.

Studies aligned with descriptor C were limited to facilitate learning from what went wrong in terms of accidents or other types of losses, such as machine breakdowns. For instance, Seyr and Muskulus (2016) proposed indicators for marine operations focused on failures during the installation and operation of an offshore wind farm – e.g. "annual failure rates for turbine subsystems". Basso et al. (2004) combined incident investigations and analysis of major accidents of 50 companies from multiple sectors in order to define a threshold for "negative indicators" such as the "non-compliance with procedures about dangerous substances" and the "number of incidents due to wrong observance of procedures and instructions".

3.4.4. SPMSs should offer insight into the management of trade-offs between safety and other business dimensions

Fig. 7 presents the descriptors and results obtained for guideline 4 (mean = 0.70). Five studies proposed or applied tools that facilitated the management of trade-offs (descriptor A), having a strong alignment with guideline 4. One of these studies (Woods et al., 2015) proposed a framework for the analysis of whether the portfolio of indicators was balanced in terms of including indicators related to both efficiency and safety. Once a balanced portfolio is devised, it can facilitate the management of trade-offs between safety and efficiency. The study by Rubio-Romero et al. (2018) was the only one that proposed indicators to directly assess the trade-off between safety and efficiency. These indicators were focused on the waste management sector and involved, for instance, the ability of employees to prioritise safety over production. However, little details on how to operationalize or implement

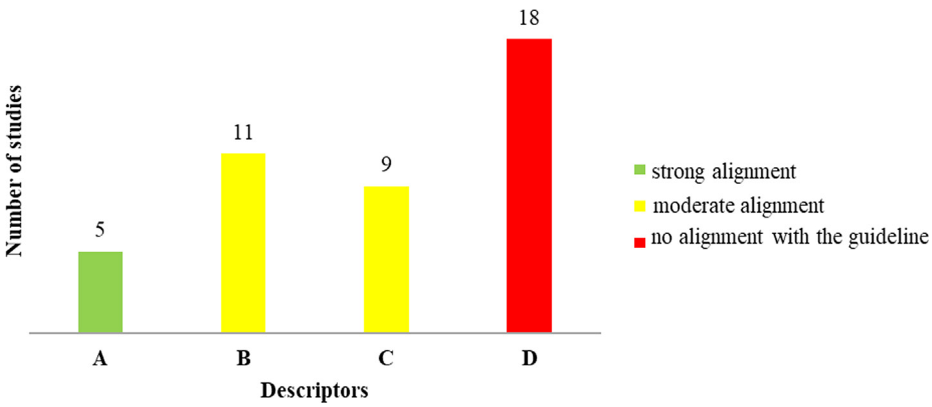

Fig. 7. Descriptors of guideline 4 and their frequency. Notes: A: Tools or frameworks have been proposed to manage trade-offs between safety and other business dimensions; B: The study provides quantitative evidence that safety performance contributes significantly to performance in other business dimensions, such as quality and productivity; C: Some of the proposed indicators indirectly monitor the trade-off between safety and other business dimensions – e.g. stop work authority, requests of priority or emergency, cost and time delays; D: No alignment with the guideline.

these indicators were provided.

Descriptor B encompasses 11 studies that, while not proposing indicators or tools to monitor the trade-off, offer empirical evidence on how it plays out. This indirect approach of guideline 4 justifies the moderate, rather than strong alignment with it. For example, in the construction sector, Poh et al. (2018) provided quantitative evidence that the percentage of tasks completed was a good predictor of safety performance. Findings suggested that, from the perspective of the construction project as a whole, there was no trade-off between achieving safety and the expected project timeline (Poh et al., 2018).

Descriptor C was obtained from studies that have proposed indicators that indirectly shed light on the trade-off between safety and other business dimensions. No specific examples of managing the trade-off were provided by those studies. For example, Salas and Hallowell (2016) proposed indicators for the oil and gas sector, which offered insights into the trade-off between safety and efficiency – e.g. the "number of times that the stop work authority is exercised in the year". A possible interpretation of this indicator is that the more the stop-work authority is applied, the more the trade-off is pending in favour of safety.

Also, for the oil and gas sector, Gerbec and Kontić (2017) proposed the joint analysis of a broad set of indicators, encompassing safety occurrences, lost revenues, lost clients, fines, and implications for regional economy, among others. Those authors illustrate the relationships between these indicators by reporting a case of spilling during methanol transhipment, which led to a major fire at the cargo terminal and had a strong business impact. An important message conveyed by that study is that both safety and financial losses usually go side-by-side.

3.4.5. SPMSs should evolve due to the changing nature of complex socio-technical systems

Fig. 8 presents the descriptors obtained for guideline 5 (mean = 0.70). As a drawback common to all studies, there was no longitudinal investigation describing how socio-technical systems evolved over a long time period, and how SPMSs coped with changes. Descriptor A corresponds to nine studies that presented conceptual frameworks or models for updating the SPMS or set of indicators. Considering all five guidelines, this was the descriptor with the largest number of strongly aligned studies. For example, the framework developed by Salas and Hallowell (2016) for oil and gas operations adopted a PDCA cycle for revising measures based on near-miss reporting and safety performance outcomes. Haas and Yorio (2016) also used PDCA to identify relevant indicators for different production activities, which change over time. Leveson (2015) developed the System-Theoretic Accident Model and Processes (STAMP), which detects when the underlying assumptions of a leading indicator are no longer true, and therefore new or revised indicators are necessary. Sultana et al. (2019) also applied STAMP for the development of safety indicators in the oil and gas sector.

Raben et al. (2018) identified indicators from the blood sampling process based on a model of WAD (descriptor B). In principle, this model could be updated on a regular basis, supporting the update of corresponding indicators. However, no guidance on how to operationalize this model was provided, which justifies the moderate alignment with guideline 5.

Descriptor C emerged from 24 papers, which pointed out the need for updating the SPMS, but do not provide any guidelines on how to do this – this justifies the weak alignment with guideline 5. For example, Skogdalen et al. (2011) refer to the need for monitoring organizational complexity that could lead to changes in safety management, including the SPMS (Janackovic et al., 2017). Hallowell et al. (2013) suggest that when an indicator does not lead to improvements, it should be removed from the SPMS. However, no further discussion on this type of assessment of indicators is provided.

4. Discussion

Fig. 9 summarizes the assessment of the guidelines. The level of alignment with RE was in general low, as indicated by the low average scores for the guidelines, ranging from 0.40 to 0.90 (in a scale from 0.0

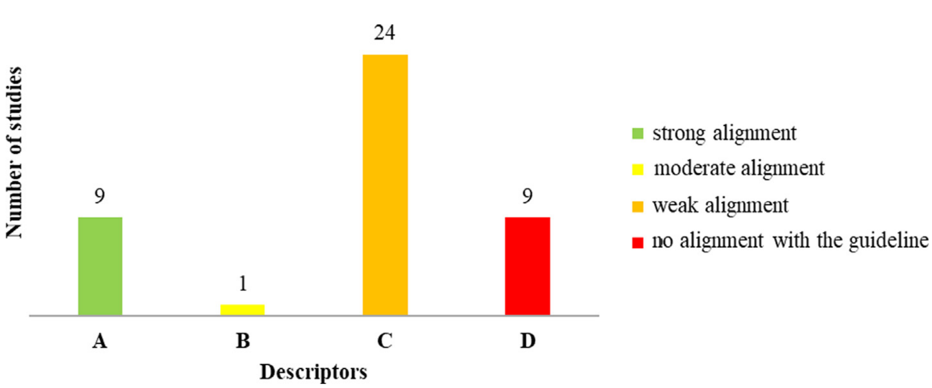

Fig. 8. Descriptors of guideline 5 and their frequency. Notes: A: The study proposes a conceptual framework for updating SPMSs or set of indicators; B: If a SPMS is based on a model of WAD, it could be updated on a regular basis and then set a basis for updating the SPMS. However, the study does not show how this could be done; C: The study acknowledges the need for updating SPMSs, but provides no clear guidelines to do this; D: No alignment with the guideline.

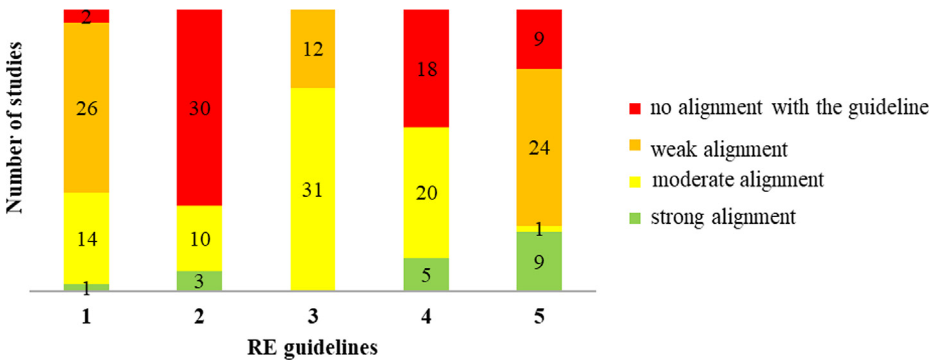

Fig. 9. . Uptake of the guidelines by the reviewed studies. Notes: 1: SPMSs should support the monitoring of everyday variability; 2: SPMSs should provide real-time feedback; 3: SPMSs should facilitate learning from what goes well, in addition to what goes wrong; 4: SPMSs should offer insights into the management of trade-offs between safety and other business dimensions; 5: SPMSs should evolve due to the changing nature of complex socio-technical systems.

to 2.0). On the one hand, low compliance with the guidelines points out that the RE perspective does not largely overlap with traditional assumptions of SPMS literature – i.e. it offers a new and under explored perspective. On the other hand, when considering studies individually, variability in the uptake of guidelines is observed.

The studies by Li et al. (2015) and Awolusi and Marks (2016) obtained the highest mean score (1.40), resulting from moderate alignments with guidelines 1, 3 and 4, and strong alignments with guidelines 2 and 5. Furthermore, these two studies were sound examples of implementing all SPMS activities. A possible interpretation for this finding is that a system-based perspective for performance measurement can contribute to the adoption of RE, and vice versa. This may occur because RE is systems-oriented, being concerned with the whole cycle of defining, collecting, and learning from metrics. It is also worth noting that these two studies were carried out in the construction industry, which has been rarely addressed in the RE literature, in comparison to other sectors, such as healthcare and aviation (Righi and Saurin, 2015).

In turn, the studies by Basso et al. (2004), in multiple sectors, and Coleman and Kerkering (2007) in underground coal mining, had the lowest mean score (0.20). Both of them had weak alignments with two guidelines and no alignment with the others. These studies are representative of traditional approaches as the analysis of injuries and lost work-day rates are emphasized.

Fig. 9 also shows that there were examples of moderate or strong alignment with all guidelines. This points out that RE has been implicitly used by many studies on SPMSs. Therefore, a full uptake may be facilitated by drawing upon existing strengths, as the guidelines are logically related to each other. Fig. 10 presents some important logical relationships between the guidelines, based on emerging insights from the reviewed papers. This figure highlights the central role played by guideline 1 "SPMSs should support monitoring of everyday variability". In fact, information produced from this type of monitoring supports all other guidelines. For instance, learning from what goes well and what goes wrong (guideline 3) requires information on how variability is playing out. A similar reasoning applies to relationships with the other guidelines. In turn, guideline 1 may benefit from others, such as in the case of the feedback loop between guidelines 1 and 3. Learning from what goes well and what goes wrong can result in changing the approach for monitoring everyday variability – e.g. learning can reveal that certain types of events or working situations are more worth monitoring than others, as they offer richer learning opportunities.

The wide implications of guideline 2 (feedback in real-time), which was the least adopted in the reviewed studies, are also shown in Fig. 10. In particular, real-time feedback is closely related to two other guidelines that may involve real-time decision-making on the spot in production settings. Firstly, the management of trade-offs between safety and other business dimensions (guideline 4) might benefit from accurate real-time feedback on performance. Of course, real-time feedback may be less relevant when trade-offs are addressed by higher hierarchical ranks, involving decision-making at strategic and tactical levels. Secondly, real-time feedback can help to identify short-term monitoring and learning priorities (i.e. influencing guidelines 1 and 3),

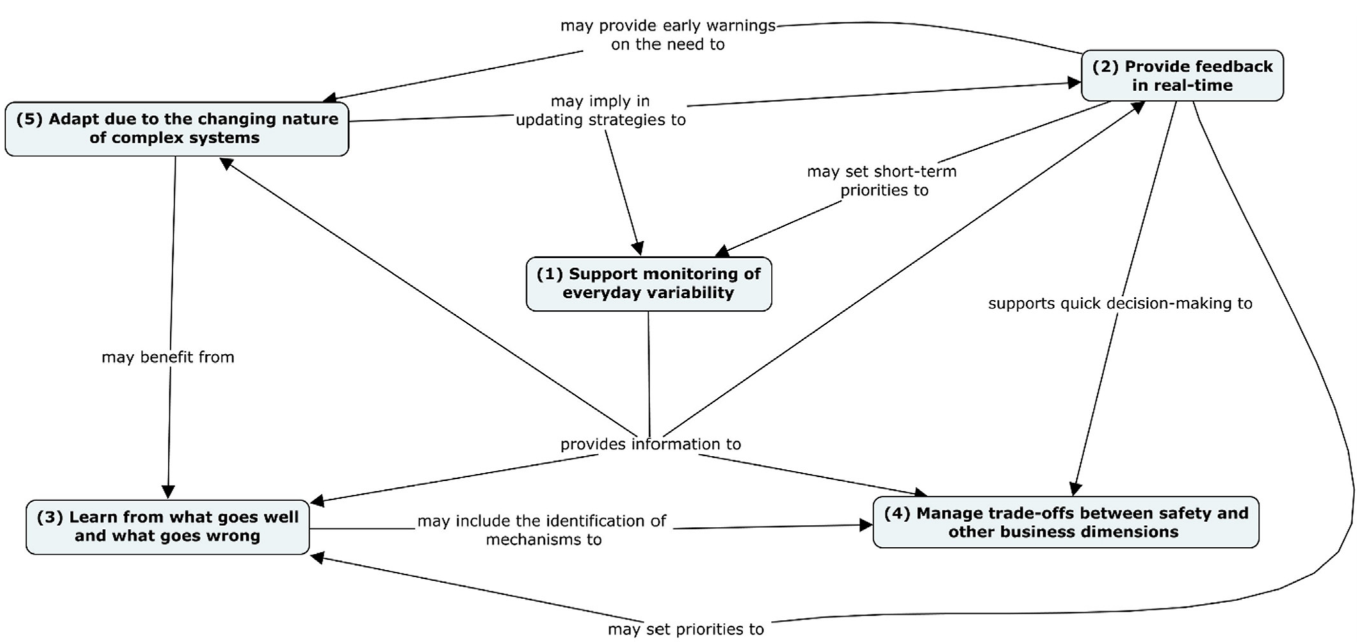

Fig. 10. . Relationships between RE guidelines for SPMSs.

guiding the reallocation of SPMSs resources - e.g. people in charge of collecting and analysing data may focus on priorities identified from real-time feedback.

As for guideline 5, "adapting due to the changing nature of complex systems", Fig. 10 suggests that it mostly depends on other guidelines. This make sense as this adaptation may be interpreted as a SPMS response to a changing environment: effective adaptation benefits from learning on what goes well and what goes wrong, and from monitoring everyday variability. Also, feedback in real-time may support SPMS short-term adaptive responses, such as the reallocation of resources.

5. Conclusions

5.1. Contributions of this study

This study has assessed to what extent previous research on SPMSs was aligned with the RE perspective. Forty-three research studies were analysed, considering five RE guidelines. Based on examples extracted from the literature, fifteen descriptors used for summarizing practical approaches emerged. Descriptors and corresponding studies strongly or moderately aligned with RE provide a reference for researchers and practitioners interested in designing SPMSs.

The number of studies associated with strong alignment with the guidelines was low, ranging from zero (SPMSs should facilitate learning from what goes well, in addition to what goes wrong) to nine (SPMSs should evolve due to the changing nature of complex socio-technical systems). This points out that: (i) RE perspective does not largely overlap with the assumptions of traditional SPMS literature; and (ii) RE is far from being mainstream in SPMSs research, despite offering a new perspective.

Some interactions between the five guidelines were identified, pointing out that these have synergistic relationships. Therefore, it might be possible to build upon strengths of SPMSs that are not RE oriented, if these partly account for the guidelines. In fact, the highest scoring studies identified in this review did not refer explicitly to RE, which suggests that there can be contextual factors that may naturally lead a SPMS to evolve towards that approach – e.g. opportunistic use of new technologies, and an organizational culture that values resilience.

5.2. Limitations

Some limitations of this study must be pointed out. First, there might be other RE guidelines or perspectives that are useful for SPMSs, such as the notion of "graceful extensibility" coined by Woods (2018). However, the set of five guidelines offered a robust account of RE, by being associated with the four abilities of resilient systems. Second, the real extent to which the guidelines were adopted may have been masked by the lack of implementation details in some papers – this is understandable as the papers were not intentionally concerned with the implementation of those guidelines. Third, the academic literature might not accurately represent the real diversity and approaches for SPMSs. Fourth, as usual in systematic literature reviews, the adopted inclusion and exclusion criteria may have missed useful studies. Fifth, while RE guidelines are theoretically sound, cause-effect links between their level of adoption and superior safety performance is elusive. This limitation must be put into perspective for two reasons: a SPMS is an element of a broader safety management system, and therefore the evaluation of its isolated impact on performance is difficult; and the same limitation applies to the non-RE oriented approaches for conceiving SPMSs.

5.3. Research agenda

The gaps in knowledge identified in the systematic literature review provided the basis for a research agenda. This agenda encompasses opportunities related to each individual guideline and for SPMSs as whole, as follows:

(i) SPMSs should support the monitoring of everyday variability: there is a need for developing SPMSs concerned with monitoring WAD as a whole, rather than as a set of fragmented elements, as commonly addressed by checklists. This could benefit from the use of descriptions of WAD (e.g. by using FRAM or similar purpose methods) as a basis for conceiving and operating SPMSs. There is also a need for a deeper understanding of variability in safety management activities. Only the outcomes of these activities (e.g. number of risk assessments carried out), rather than their processes, are usually monitored by SPMSs;

(ii) SPMSs should provide real-time feedback: innovative data analytics and big data technologies offer a wide range of possibilities for expanding the use of this guideline (Poh et al., 2018; Melo and Costa, 2019). The effectiveness of these technologies for the purpose of real-time feedback might benefit from: criteria for prioritizing activities in which real-time monitoring is cost-effective; the identification of different users of information and their requirements in terms of contents and format; and the provision of organizational resources (e.g. training, supervision) so as those receiving real-time feedback can take immediate corrective actions;

(iii) SPMSs should facilitate learning from what goes well, in addition to what goes wrong: an initial research opportunity related to this guideline refers to the development of taxonomies of successful events. The expanded definition of what goes well that has been proposed in this paper (see Section 2) may be a starting point for a comprehensive taxonomy. Furthermore, there is a research gap related to the identification of barriers to combine learning from success and failure in the same organization – e.g. are there trade-offs between both approaches? Learning from what goes wrong is entrenched in regulations and safety management education. Thus, another necessary research contribution refers to more empirical evidence on the effectiveness and value added by learning from what goes well;

(iv) SPMSs should offer insights into the management of trade-offs between safety and other business dimensions: further SPMSs studies should focus on the explicit monitoring of trade-offs, and also on the reinterpretation of existing metrics from this perspective. While there are established approaches of applying this guideline to production activities in which hazards play out (e.g. stop work authority), similar mechanisms could be devised for monitoring and managing these trade-offs in managerial activities that may create or amplify safety risks at the front-line - e.g. are there trade-offs between quality (or finance, or environment, etc.) management and safety?

(v) SPMSs should evolve due to the changing nature of complex socio-technical systems: further studies should explore longitudinal investigations of SPMSs, shedding light on whether and how these evolve over time. It is also worth investigating the bidirectional relationship between SPMSs and safety performance – i.e. while trends in performance may require updates in the SPMS, it is also possible that changes in the SPMS affect performance.

Moreover, further studies are necessary to assess the utility and applicability of the guidelines and descriptors in the design or evaluation of SPMSs, considering different sectors, with distinct complexity characteristics. This may shed light on the extent to which context impacts on the relevance of each guideline. From a practical perspective, the guidelines and descriptors could be used for the identification of improvement opportunities in real SPMSs, possibly making contributions towards making safety management systems more resilient. This line of inquiry may also set a basis for the development of a taxonomy of maturity levels for SPSMs regarding RE.

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Appendix A. Selected studies in light of SPMS activities and methodological approaches.

Studies	SPMS stages			
	1. Design and/or select indicators	2. Collect and analyse data	3. Report and provide feedback	4. Act on findings
Hallowell et al. (2013)	literature review, expert panel, historical data	**ND**	**ND**	*R stop work authority program should be reiterated and stressed by the safety personnel. A lack of worker empowerment may be a symptom of poor safety culture
Raben et al. (2018)	Functional Resonance Analysis Method (FRAM)	questionnaire, observation checklist	by means of FRAM (visual representation of a process)	**ND**
Woods et al. (2015)	historical data	historical data, expert panel	over 3-years period, by means of the Q4-Balance framework	**ND**
Laitinen et al. (2013)	literature review	observation checklist, correlation analysis, regression analysis	over 3-years period, by means of graphical charts	**ND**
Awolusi and Marks (2016)	literature review	observation checklist, historical data, computer-based, correlation analysis	feedback was provided in real-time during data collection, by means of graphical charts	specific training for ground-level work
Janackovic et al. (2017)	literature review, expert panel, multicriteria decision-making	**ND**	**ND**	**ND**
Pawłowska (2015)	literature review	questionnaire, correlation analysis	**ND**	**ND**
Skogdalen et al. (2011)	literature review, historical data	computer-based	**ND**	**ND**
Poh et al. (2018)	historical data	computer-based, regression analysis	**ND**	**ND**
Rajendran (2012)	literature review, historical data	observation checklist, correlation analysis	over 1-year period, by means of graphical charts	*R to be effective, a minimum of 30 observations per week are needed
Haas and Yorio (2016)	literature review, historical data, expert panel	questionnaire	**ND**	**ND**
Li et al. (2015)	literature review, historical data	observation checklist, expert panel, computer-based	feedback was provided in real-time during data collection. Then, results were reported over 7-month period, by means of graphical charts	specific safety training for critical unsafe behaviours (e.g. being struck by rebar falling from the crane hook)
Gerbec (2013)	Resilience-based Early Warning Indicators (REWI)	historical data, questionnaire	**ND**	*R monitor process safety on a regular basis and develop procedures for safe operations compliant with work instructions
Cameron and Duff (2007)	literature review, questionnaire	historical data, questionnaire	over 6-month period, by means of graphical charts and reports	a greater dissemination of risk assessments in pre-start meetings improved subcontractor's safety performance after 3-months intervention
Lingard et al. (2017)	historical data	historical data, correlation analysis, regression analysis	over 5-year period, by means of graphical charts	*R management activities should be described as positive indicators (e.g. measures of actions taken to proactively manage workers' safety)
Salas and Hallowell (2016)	literature review, historical data	historical data, regression analysis	over 1-year period, by means of graphical charts	*R process workflow or model is needed for establish safety indicators
Gopang et al. (2017)	literature review	questionnaire, regression analysis	**ND**	*R need improvements in safety measures, e.g., protective clothing, waste disposal system
Köper et al. (2009)	Balanced Scorecard	historical data, questionnaire, regression analysis	by means of Balanced Scorecard (visual representation of strategy map)	*R human resources strategy should be aligned with business strategy
DeArmond et al. (2011)	literature review	questionnaire, historical data, correlation analysis	**ND**	**ND**
Podgórski (2015)	literature review, multicriteria decision-making	**ND**	**ND**	**ND**
Rubio-Romero et al. (2018)	literature review, expert panel	questionnaire	**ND**	*R provide mechanisms to employees to have access to sources of help (e.g. prevention services, special installations), so that they can deal with unexpected safety incidents
Tamim et al. (2017)	literature review, historical data	computer-based	feedback was provided in real-time during data collection	**ND**
Hinze et al. (2013)	historical data	historical data, correlation analysis	**ND**	**ND**
Shea et al. (2016)	literature review	questionnaire, correlation analysis	**ND**	**ND**
Øien et al. (2011)	Resilience-based Early Warning Indicators (REWI)	historical data	**ND**	**ND**

Sadeghi et al. (2015)	literature review	historical data	**ND**	***R** determine the thresholds of the hazards tolerated by humans that are not available in standard documents (e.g. transmission mechanical energy)
Gerbec and Kontić (2017)	Bayesian Belief Network	historical data	**ND**	**ND**
Di Gravio et al. (2015)	multicriteria decision-making	historical data	over 4-year period, by means of graphical charts	***R** promote a reporting culture and avoid missing information. The more the events database is accurate, the more the analysis will be flawless
Coleman and Kerkering (2007)	historical data	historical data	over 4-year period, by means of graphical charts	***R** improvements in underground mining technology by replacing hazardous techniques (e.g. the use of overshot muckers in small operations)
Sheehan et al. (2016)	literature review	questionnaire, correlation analysis, regression analysis	over 1-year period, by means of graphical charts	***R** develop a safety leadership training program for managers at all levels, especially for middle managers
López-Arquillos and Rubio-Romero (2015)	literature review, expert panel	historical data	**ND**	**ND**
Robson et al. (2017)	historical data	historical data, correlation analysis, regression analysis	over 3-year period, by means of graphical charts and tables	***R** decision-makers should not use audit scores as leading indicators in the absence of supporting empirical data
Sinelnikov et al. (2015)	literature review	questionnaire, correlation analysis	**ND**	**ND**
Guo and Yiu (2015)	literature review, questionnaire, System Dynamics	**ND**	**ND**	**ND**
Seyr and Muskulus (2016)	literature review, historical data	**ND**	**ND**	**ND**
Wong and Tse (2013)	literature review	observation checklist	over 1-year period, by means of graphical charts	***R** responsible for safety inspections should perform a set of sampling inspections of each item (e.g. 10). It should be documented for inspection training
Saurin et al. (2016)	literature review	historical data	**ND**	***R** safety reports should include key indicators from other performance areas (e.g. project time and cost as proxy measures of production pressures)
Leveson (2015)	System-Theoretical Accident Model and Processes (STAMP)	historical data	**ND**	***R** assumptions underlying engineering decisions (design rationale) should be documented (e.g. safety–critical changes) and used as leading indicators
Johnsen et al. (2013)	literature review, historical data, expert panel	**ND**	**ND**	**ND**
Sgourou et al. (2012)	historical data	questionnaire	monthly, by means of a conceptual model	**ND**
Basso et al. (2004)	historical data	historical data, correlation analysis	over 1-year period, by means of graphical charts	**ND**
Ghahramani and Salminen (2019)	literature review, historical data	historical data, regression analysis	**ND**	**ND**
Sultana et al. (2019)	System-Theoretical Accident Model and Processes (STAMP)	historical data	**ND**	***R** the plant should update indicators periodically and use threshold values as early warnings of critical items

Note: ***R** means that only recommendations for action-taking were presented. **ND** means that actual activity was not described.

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MONITORING COMPLEXITY AND RESILIENCE IN CONSTRUCTION PROJECTS: THE CONTRIBUTION OF SAFETY PERFORMANCE MEASUREMENT SYSTEMS

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Monitoring complexity and resilience in construction projects: The contribution of safety performance measurement systems

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ABSTRACT

Although complexity and resilience are key inter-related characteristics of construction projects, little is known on how to monitor these characteristics and their implications for safety management. This study investigates the contribution of Safety Performance Measurement Systems (SPMS) as a means for monitoring and understanding of sources of complexity and resilience in construction. It is based in three empirical studies carried out in construction projects, two in Chile and one in Brazil. Two main tools were applied in these studies: (i) the Technical, Organizational and Environmental (TOE) framework, focused on complexity; and (ii) the Resilience Assessment Grid (RAG), focused on resilience. Improvement opportunities were identified for existing SPMS. Also, a set of guidelines for the design of SPMS emerged from these studies as well as a model that explains the connections between the main constructs encompassed by the guidelines.

1. Introduction

The construction industry has been affected by growing sources of complexity, such as the increasing number of supply chain members, new technological alternatives involving off-site production, rising number of regulations, and innovative procurement approaches (Bakhshi et al., 2016). Thus, coping with complexity has been more and more a part of everyday work in construction project management, bringing threats and opportunities for safety management (Dekker et al., 2011). However, complexity is usually only regarded as a threat to project performance in general (Luo et al., 2016), which may be due to the consideration of just one or two complexity attributes - e.g. the study by Antoniadis et al. (2011), which addressed only organizational interaction as a complexity attribute. In fact, complex systems are defined by multiple attributes, such as diversity, variability, non-linearity, and tight-couplings (Perrow, 1984).

Furthermore, the focus on the downside of complexity neglects its possible contribution to resilience, which is defined as “the ability of a system to adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions” (Hollnagel et al., 2006). Resilience Engineering (RE) is the discipline concerned with the observation, analysis, and design of resilient socio-technical systems (Nemeth and Herrera, 2015). One of the core ideas of RE is that monitoring everyday variability, which is an attribute of complex systems, is useful for coping with complexity (Hollnagel, 2017).

Although resilience is probably ubiquitous in construction sites, given the complexity of these environments, so far there is little empirical evidence on the nature of this resilience and its influence on performance. This is in contrast with other sectors, such as healthcare and aviation, in which there is a growing number of descriptions of what resilience looks like (Braithwaite et al., 2016).

Safety performance measurement systems (SPMS) can play a role in understanding and monitoring both the changing nature of the sources of complexity that affect construction safety, as well as the resilient strategies for coping with complexity. However, SPMS in construction are usually based on lagging indicators (Janicak, 2009; Hinze et al., 2013), which are direct measures of harm (e.g. injury rates) and other safety related losses (Hopkins, 2009). Thus, SPMS tend to be reactive by focusing only on a small fraction of everyday performance, while neglecting the large number of situations in which the same variability sources that caused accidents were already present, but not as visible as

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in accidents (Hollnagel, 2012). A complementary approach implies the use of leading indicators, which focus on the monitoring of functions and events that allow for the identification of safety problems and remedial actions before the occurrence of undesired outcomes (Hopkins, 2009).

Therefore, this investigation was guided by the following research question: how can a SPMS monitor the factors that affect complexity and resilience in construction projects? An assumption of this study is that both complexity and resilience are fundamental characteristics of the functioning of construction projects, and therefore they influence and are influenced by safety management. Although resilience is interpreted by many authors as one of the attributes of complex systems (Cilliers, 1998; Siemieniuch and Sinclair, 2006), these constructs have been analysed separately in this investigation, by using specific tools for assessing each of them.

Regarding the sources of project complexity, the Technical, Environmental and Organizational (TOE) framework, proposed by Bosch-Rekveldt et al. (2011), can be used to identify the most salient sources of complexity and their influence on the safety performance. Previous applications of the TOE in construction have not explored its contribution to safety management, but rather to other aspects such as decision-making concerning the choice of construction technologies (Brady and Davies, 2014), innovation (Floricel et al., 2016), and portfolio management (Lukosevicius et al., 2017).

As for the monitoring of the contributing factors to resilience, the Resilience Assessment Grid (RAG), devised by Hollnagel (2011), can be used for assessing the four potentials of resilient systems: (i) respond (knowing what to do), (ii) monitor (knowing what to look for), (iii) learn (knowing what has happened), and (iv) anticipate (knowing what to expect). RAG has been used for monitoring these potentials in different sectors, such as nuclear power plants (ARPANSA, 2013), air traffic management (Ljungberg and Lundh, 2013), and healthcare (Hunte and Marsden, 2016). No application of RAG in the construction industry has been reported in the literature.

In order to answer the research question, three empirical studies were carried out in construction projects, two from Chile and one from Brazil. The application of both RAG and TOE framework in these projects gave rise to three new guidelines for the design of SPMS in construction as well as a model that links the constructs encompassed by the guidelines.

2. Literature review

2.1. Construction projects as complex socio-technical systems

According to Vidal et al. (2011), project complexity is "the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system". Therefore, complex projects need managerial approaches suitable to their nature (Williams, 1999), which implies supporting decision-making under uncertainty and adjusting the plans in face of variability (Giezen, 2012). Moreover, Floricel et al. (2016) suggest that the type and level of project complexity should be considered when defining the most suitable approach for controlling risks.

The attribute view is often used to define complexity in both the fields of management and social sciences: it assumes that complex systems in general share some interrelated attributes, such as a large number of elements, emergent properties, nonlinear dynamics and adaptive behaviour (Walker et al., 2010). This view has also been used in the construction management literature (Baccarini, 1996; Bertelsen, 2003; Dao et al., 2016).

Those attributes are usually divided into two main categories (ElMaraghy et al., 2014): (i) the ones that represent structural properties of the system, such as the number and diversity of parts; and (ii) those that represent functional characteristics of the system, such as resilience and dynamic interactions. Table 1 presents key attributes proposed by Cilliers (1998), and some examples from the construction industry.

2.2. Resilience engineering in construction

In construction, the concept of resilience has been usually investigated from the perspective of the built environment ability to cope with natural and human-induced disasters (Bosher et al., 2007). The organizational and systems-orientated resilience engineering perspective is relatively new in this sector, and not yet widespread neither in academia nor in practice. Wehbe et al. (2016) pointed out that construction teams with timely and tightly connected interactions have higher resilience to anticipate risks and better safety performance. Chen et al. (2017) concluded that the resilience of construction workers had a negative impact on psychological stress.

Saurin et al. (2008) re-interpreted some construction safety best practices in light of resilience engineering, concluding that safety planning, proactive performance metrics, accident investigations, and monitoring of production pressures may support resilience by increasing teams' awareness of hazards and creating opportunities for learning. Sapeciay et al. (2017) identified the lack of organizational support to resilience in construction projects, and also suggested that the industry would benefit from the use of resilience assessment tools. Overall, resilience engineering has been used both for the understanding of how resilience plays out in construction as well as to provide insights into interventions that otherwise could be reductionist and ineffective.

Table 1
Attributes of complexity and examples in construction.

Attributes	Examples
Large number of elements	Large number of workers, transportation equipment, construction materials, subcontractors, regulations, designers, clients
Diversity of elements	Subcontractors with different organizational cultures and levels of expertise, or skills; different client profiles in the same project; customization possibilities offered to clients; different contractual arrangements with designers and subcontractors
Dynamic interactions	Formal and informal exchange of information between stakeholders, regulatory agencies, and client; interactions between different flows of materials and components. These interactions are dynamic because they change over time.
Non-linear interactions	A small variation in the output of an operation (e.g. a design error) can cause large disruptions (e.g. demolition of built areas or need for rework)
Couplings	Some construction phases (e.g. earthworks, foundations, structure, masonry, roofing, etc.) must follow a rigid sequencing, making them tightly-coupled. This implies that there is little or no margin of maneuver for alternative sequencing. However, organizational arrangements in the construction supply chain tend to be loosely coupled (Dubois and Gadde, 2002).
Openness	Construction sites are subject to external variability such as changes in the weather, changing regulations, and macroeconomic situation of the country or region. There may also be interactions with other construction sites from the same or from other companies – e.g. the subcontractor reduces the size of its crew in a less important project, and transfers the workers to another project considered to be more important.
Gap between work as imagined and as done	Construction sites have rules to prescribe how work should be done (i.e. "work-as-imagined"). In practice, it may be impossible to follow those rules as they cannot anticipate all working situations (de Carvalho et al., 2018). As a consequence, people adjust their performance (i.e. "work-as-done"), in order to create or maintain desirable conditions, to compensate for limited resources, or to avoid undesirable consequences to individuals or to the organization (Hollnagel et al., 2015).

2.3. Safety performance measurement systems: requirements and design guidelines

Safety performance measurement provides information to support decision-making on preventive measures, anticipate threats and identify opportunities for improvement (ICAO, 2013). In order to be effective, SPMS should meet some requirements (Kjellén, 2000), such as: (i) *reliability*, as the extent to which repeated measurements provide the same results; (ii) *accuracy* of measurement methods to avoid systematic errors due to under-reporting or manipulation; (iii) *adequate coverage* of different factors that affect accident risks (e.g. technical, organizational and human); (iv) the information presented to decision-makers should be *relevant, easy to understand* and should be *available when it is needed*; (v) *timeliness* to detect and process data on changes as well as to implement corrective actions; (vi) the methods for data collection, analysis and distribution of information must promote *involvement of the interested parties and shared understanding;* and (v) *cost-effectiveness,* by not consuming too many resources for implementation and at the same time contributing to the reduction of undesirable events.

In several industrial domains, additional guidelines for designing and implementing SPMS have been proposed (Table 2). These guidelines seem to be strongly based on principles of performance measurement systems in general (Kaplan and Norton, 1996; Neely et al., 2000) by following the plan, do, check, and act cycle for continuous improvement.

Safety performance measurement systems should include both quantitative and qualitative data. However, a common problem in construction companies is that metrics are chosen simply because they are easy to collect or to compare with metrics from other similar companies, rather than based on their relevance to support decision-making on critical processes (Costa et al, 2004). This traditional approach limits the predictive value of the metrics adopted, and their utility to drive system improvements (Carder and Ragan, 2003).

Table 2
Guidelines for designing and implementing SPMS.

Guidelines	Sources
Designate responsibilities and accountabilities for controlling risk, collecting information and compiling reports	HSE, 2006; Hinze et al. (2012); ICAO, 2013
Establish multidisciplinary teams comprising all relevant disciplines to identify indicator need and use	OECD 2008; ICMM, 2012
Set safety goals/target and objectives of performance levels. Compare performance with goals/target	HSE, 2006; Hollnagel et al., 2008; Reiman and Pietikäinen (2010); ICMM, 2012; ICAO, 2013
Identify all business areas that are relevant for safety performance	HSE, 2006; OECD 2008; Hollnagel et al., 2008; Reiman and Pietikäinen (2010); ICMM, 2012; IChemE, 2015
Devise process models (i.e. how safety is brought about). Determine data needs and data gaps for setting up the SPMS	HSE, 2006; Hollnagel et al., 2008; Reiman and Pietikäinen (2010); ICMM, 2012; ICAO, 2013; IChemE, 2015
Identify and prioritize critical processes to be covered by the SPMS	HSE, 2006; OECD 2008; ICMM, 2012; ICAO, 2013; IChemE, 2015
Understand the nature of threats and opportunities. Identify alerts or signs of good or bad safety performance that will indicate a current or developing problem in a particular indicator or sector	Hollnagel et al., 2008; Reiman and Pietikäinen (2010); ICMM, 2012; Herrera (2012); ICAO, 2013
Identify critical measures and define specifications	Hollnagel et al., 2008; Reiman and Pietikäinen (2010); ICMM, 2012; Hinze et al. (2012); Hallowell et al. (2013); ICAO, 2013; IChemE, 2015; IOGP, 2016
Combine system-specific leading and lagging indicators	Reiman and Pietikäinen (2010); Hollnagel (2011); Herrera (2012); Hallowell et al. (2013)
Perform real-time monitoring	HSE, 2006; OECD 2008; Hollnagel et al., 2008; ICMM, 2012; Hinze et al. (2012); Hallowell et al. (2013); ICAO, 2013; IChemE, 2015; IOGP, 2016
Educate managers and directors regarding the roles and assumptions underlying the SPMS	ICAO, 2013; IChemE, 2015
Act on findings and decide corrective actions. Review measures and make improvements to meet goals	HSE, 2006; OECD 2008; Reiman and Pietikäinen (2010); ICMM, 2012; Hinze et al. (2012); Hallowell et al. (2013); ICAO, 2013; IOGP, 2016; IChemE, 2015
Report and provide feedback	HSE, 2006; Reiman and Pietikäinen (2010); ICMM, 2012; Hallowell et al. (2013); Hinze et al. (2012); ICAO, 2013

3. Research method

3.1. Research strategy

Design Science Research (DSR) was the methodological approach adopted in this investigation. DSR involves the development of an innovative artefact to solve a class of problems, and simultaneously provides a prescriptive scientific contribution (Holmström et al., 2009). This artefact should be interpreted as a generic design, i.e. a "design model to support well-trained and experienced designers to make their own context specific design" (van Aken et al., 2016).

In this study, the generic design that addresses the research question has two elements: (i) a new set of guidelines for the design of SPMS in construction; and (ii) a conceptual model that connects the main constructs encompassed by those guidelines. This design emerged from three case studies in which RAG and TOE were used to assess how the SPMS could monitor sources of complexity and resilience.

The unit of analysis in all case studies was the SPMS of individual construction projects. One of the case studies was carried out in Brazil (Project A) and two in Chile (Projects B and C). Both intra- and cross-case analysis were developed, so that different contexts could be explored and compared. The main selection criteria for choosing the construction projects was the willingness of the company to take part in the research study, and the fact that each company had a well-established SPMS, including some standard routines for safety data collection and analysis.

3.2. Research design

The research process was divided into six stages (see Fig. 1): (i) selection of relevant cases; (ii) obtaining an overview of the existing SPMS of each project; (iii) assessment of the complexity dimensions encompassed by the TOE framework; (iv) assessment of the four resilience potentials by using RAG; (v) identification of improvement opportunities for the existing SPMS based on the insights obtained from TOE and RAG; and (vi) development of guidelines for the design of SPMS and the associated model. Stages (i) to (iv) accounted for the explanatory phase of DSR, by producing data for understanding and describing SPMS, complexity, and resilience. Stages (v) and (vi) accounted for the prescriptive or design phase of DSR, in which a new theoretically and empirically based artefact was devised.

While the first case study (Project A) was carried out over a period of two months, it took around a month to carry out simultaneously the case studies in Projects B and C. The sequential nature of the case studies created an opportunity for refining the protocol for data collection from the case study in Project A in Brazil to the ones carried out in Chile.

3.3. Description of the projects

Table 3 presents a brief description of each project. The three projects were of different types and were in different construction phases during the case studies.

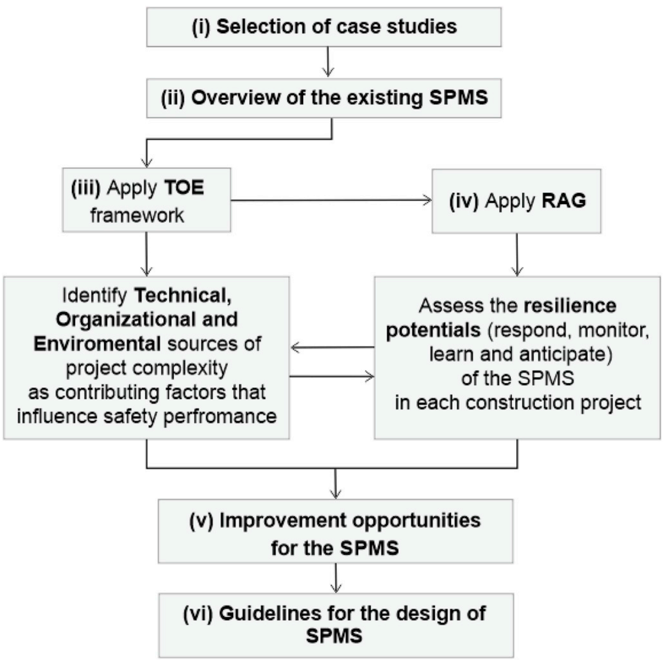

Fig. 1. Research design.

3.4. Data collection

Established good practices of case-based research were followed for data collection, such as the use of multiple sources of evidence, the use of quantitative and qualitative data as well as the validation of results with company representatives (Yin, 2013). Table 4 provides an overview of the sources of evidence used across the aforementioned research stages. Stage (vi) – development of the guidelines – does not appear in Table 4 as it was based on the analysis of data collected in the previous stages as well as on the literature review.

Table 3
Main characteristics of the studied construction projects.

Characterization criteria		Construction projects		
		A	B	C
Company size		Large size construction company that has been operating for 30 years in Southern Brazil	Large size construction company that has been operating for 50 years in several States in Chile	Medium size construction company that has been operating for more than 35 years in Santiago, Chile
Project	Type	Ten residential buildings with 3 floors each	Four warehouses for logistics operations, around 15-m high.	One mixed-use building (residential, offices and shops) with 12 floors and 4 underground basements
	Main construction technologies	Cast in place concrete structure. Interior/exterior masonry walls	Prefabricated steel roofs and walls, and precast concrete columns	Cast in place concrete structure, interior drywall and exterior masonry walls
	Area	17.000 m2	80.000 m2	22.000 m2
Construction phase being carried out during case study		Masonry, plumbing and electric services	Assembly of precast columns and roof, and urbanization	Foundations

Several safety related **documents** were analysed, including standardized operating procedures, description of performance indicators, checklists, safety and production schedules, and safety reports. In general, these documents specified how the safety management system was expected to work from a legal and technical point of view.

Direct observations were carried out over weekly visits to each construction site, focusing on understanding the main hazards and the corresponding preventive measures adopted by the company, as well as planning and administrative activities related to safety management. The researcher who conducted the observations has also had the opportunity of engaging in informal conversations with workers and managers to understand why and how certain activities occurred. Notes and insights from observations were recorded in a diary.

Two types of **semi-structured interviews** were conducted in each case study, the interviews for applying TOE, and the ones for applying RAG. The **TOE framework** consisted of 50 questions across the technological (15 questions), organizational (21 questions), and environmental (14 questions) dimensions – each question is associated with a potential source of complexity. The technical aspects account for interrelations between technical processes, use of new technology, client requirements, quality specifications, variety and dependencies of tasks, as well as technical risks. The organizational aspects address the interfaces between different design disciplines, the experience of the project stakeholders, expertise and skills availability, contract types, resources and organizational risks. The environmental dimension accounts for the interference with existing site, political and market influence, weather conditions and environmental risks, among others (Bosch-Rekveldt et al., 2011).

The TOE questionnaire was applied to the project manager of each construction project, as the person in that position was able to have a broad view of the project context. The interviews lasted on average 1 h, and were recorded and fully transcribed (Table 5). At the beginning of each interview, the researcher presented an overview of the questions contained in each section of the questionnaire. Then, the interviewees were asked to answer those questions that they regarded as relevant for safety management. As a result, a relatively small number of questions, from the 50 contained in the questionnaire, were discussed in detail.

RAG has an original script of 54 questions associated with the four resilience potentials (Hollnagel, 2011). These questions are not domain-specific, and Hollnagel recommends the adaptation of the script to each context. However, Hollnagel does not present a verifiable method for justifying the original questions, nor he prescribes how an adaptation should be carried out. Initially, a pilot application of the original questionnaire was carried out with the safety engineer of construction project A. Based on that, the RAG script was re-structured as follows, for the purpose of this research study:

(i) Fourteen original questions were left unchanged because the pilot application pointed out they were easy to understand and clearly relevant to construction;
(ii) The wording of six original questions was adapted either to avoid the use of technical language that could be unfamiliar to respondents (e.g. trade-offs) or to make them more objective. These adaptations sometimes involved splitting the original question, and therefore there were 9 adapted questions. The remaining original RAG questions were discarded either because they were perceived to be too abstract (e.g. does the organisation have a clearly formulated model of the future?) or overlapping with the others; and
(iii) Twenty-two new questions were included, based on previous studies of safety management best practices in construction, which were relevant for SPMS and could be logically connected to the four potentials of resilient systems. Although only one of these studies is explicitly connected to resilience engineering (Saurin et al., 2008), the others (Hinze et al., 2013; Hallowell and Gambatese; 2009; Choudhry et al., 2008) were considered to be

Table 4
Overview of the sources of evidence.

Sources of data		Duration			Research stages				
		A	B	C	(i)	(ii)	(iii)	(iv)	(v)
Document analysis						X		X	
Direct observations		4 h 45min	3 h 35min	2 h 50min		X			
Semi-structured interviews	Interview to apply the TOE framework	1 h 20min	1 h	1 h 10min				X	X
	Interview to test the original RAG questions and adapt them to construction projects	2 h	–	–			X		
	Interview to apply the final version of RAG	5 h 22min	3 h 40min	3 h 55min			X		X

Note: (i) cases selection; (ii) understanding of the existing SPMS; (iii) the four resilience potentials, (iv) sources of project complexity that influences safety performance; (iv) improvement opportunities for the SPMS.

Table 5
Profile of the of interviewees and duration of the TOE interviews.

Job	Service time in construction industry	On site work	Duration
Construction project A			
Project manager	14 years	full-time	1 h 20 min
Construction project B			
Project manager	9 years	full-time	1 h
Construction project C			
Project manager	12 years	full-time	1 h 15min

Table 6
–Profile of the of interviewees and duration of RAG interviews.

Job	Service time in construction industry	On site work	Duration
			RAG questionnaire
Construction project A			
Safety Engineer	5 years	part-time	1 h 55 min
Safety Technician	6 years	full-time	2 h 15 min
Project manager	14 years	full-time	1 h 45 min
Construction project B			
Safety Engineer	7 years	full-time	2 h 20 min
Project manager	15 years	full-time	1 h 50 min
Construction project C			
Safety Engineer	10 years	full-time	2 h 15 min
Project manager	12 years	full-time	2 h

also relevant. Resilience engineering does not necessarily imply in not using general safety best practices (Hollnagel, 2017).

The final version of RAG consisted of 45 questions (14 original + 9 adapted + 22 new) addressing 17 functions related to safety management and performance measurement. All of these questions, along with their sources (original RAG, adapted, new) are presented in Appendix A). These functions account for the identification, operationalization, dissemination, and learning from the metrics. When answering the set of questions related to each function, the interviewees were asked to assign scores that indicated how well they thought the function was carried out. As suggested by Hollnagel (2017), scores were assigned in a six-point Likert-type scale: 0 (missing), 1 (deficient), 2 (unacceptable), 3 (acceptable), 4 (satisfactory), 5 (excellent). While these descriptors supported the assignment of scores by individual respondents, they were not useful for the interpretation of non-integer average scores from several respondents. A radar chart was used for presenting the average scores from all interviewees of each project.

Table 6 presents the profile of the RAG interviewees and the duration of the interviews. At the beginning of all interviews, a brief introduction of the four potentials was provided by one of the researchers. The interviews were audio recorded and fully transcribed. The professionals interviewed were chosen for being strongly involved with both production and safety management. Thus, in construction project A, the RAG questionnaire was applied to the safety engineer, safety technician and project manager, while in construction projects B and C it was applied to the safety engineer and project manager.

3.5. Data analysis

Qualitative data from all sources were subjected to a content analysis (Pope et al., 2000) in which excerpts of text were identified from interviews' transcripts, documents and notes from observations. Relevant excerpts of text were those associated with four data analysis categories (Table 7), which in turn have a correspondence to the research stages previously presented in Fig. 1: (i) overview of the existing SPMS; (ii) the four resilience potentials, (iii) sources of project complexity that influence safety performance, and (iv) improvement opportunities for each SPMS. For each case study, the excerpts of text identified from data sources were coded according to the association to the data analysis categories e.g., data from RAG were tagged according to the four potentials.

4. Results

4.1. Overview of the existing SPMS

Both countries (Brazil and Chile), where the case studies were carried out, have comprehensive occupational safety regulations (ILO, 2018). In Brazil, the main regulation applicable to the construction industry is NR-18 (Work conditions and environment in the construction industry), which was launched in 1978. In Chile, the main regulation is NCh436 (Prevention of work accidents), which was established in 1951. Also, in both countries every construction project must have a safety and health program, which must be developed and implemented by the main contractor. However, only in Chile the client is responsible for contracting an insurance company that monitors safety performance at the workplace, including data collection related to accidents and lost time injury rates.

In Project A, the workforce was fully subcontracted and the performance of the subcontracting companies was assessed by the main contractor on a monthly basis, and there were financial incentives attached to safety performance. In construction projects B and C, around 30% of the workforce was subcontracted.

Regarding the safety management staff, the construction projects in Chile had a general safety manager for the company, three one safety coordinator in charge of two or three construction projects, one safety engineer and one safety technician full-time on site, as well as a representative of the insurance company. In the Brazilian project, there was only one general safety engineer who was in charge of several projects, and one full-time safety technician on site.

Table 7
Framework of data analysis.

Category of data analysis	Relevance from this research study	Examples of information sought in the sources of data
Overview of the existing SPMS	To understand the main characteristics of the SPMS of the three studied construction projects	Hierarchical levels of control, description of safety indicators, people in charge of data collection, time lag between processing and analysis, and means for dissemination of results
The four resilience potentials	To identify the current status of the resilience potentials in the construction project.	This assessment was based on a set of functions regarding the SPMS, such as: use of metrics for decision making, type of indicators, corrective actions, report and dissemination channels, learning style
Sources of project complexity that influence safety performance	To investigate which sources of project complexity had an impact on safety performance according to the existing types of hazards	Technical: project phases, construction methods, equipment/machines, software. Organizational: project teams, standards and procedures, behaviours, experience/skills. Environmental: stakeholders' perspectives, weather conditions and stability of exchange rates, raw material pricing
Improvement opportunities for the SPMS	To identify practical potential consequences of the joint analysis of the SPMS from the resilience and complexity perspectives	Possibilities for adding new elements (e.g. new metrics) to the SPMS or changing existing elements, so as it could offer a more precise account of how complexity and resilience influence each other

Another difference is that both construction projects in Chile were using, for the last five years, the Last Planner System of production control (Ballard, 2000). The Last Planner System deals with uncertainty and variability by involving subcontractors and lower level management in the planning and control process (Ballard, 2000). At the short-term planning level (it has usually a one-week planning horizon), this system increases planning reliability by only assigning to production those work packages that have all necessary resources available, and therefore can be carried out. In the medium-term planning level (it has usually a 6 to 12-week planning horizon), constraints are identified and removed, ensuring that the necessary information, materials and equipment are available (Ballard and Howell, 1998).

Project A had five safety management indicators, while Project B had four, and Project C had three. While the existing lagging indicators were the typical ones, such as accidents rate and lost time injury rate, some leading indicators had been developed for the specific context of each company, being mainly focused on legal requirements. Only in Project B the "number of reported near misses" was collected and used to prevent accidents. A near miss is as an instantaneous event, which involves the sudden release of energy, which has the potential to generate an accident (Cambraia et al., 2010). In that project, the safety technician identified near misses during routine safety inspections by observing and questioning workers. Then, the safety engineer used this information to improve job safety analysis, which in turn support workers training.

The aim of the NR-18 (Brasil, 2015) and NCh436 (Chile, 2000) indicators was to evaluate the compliance with these regulations. Both indicators were calculated from checklists, which contained respectively 245 and 158 requirements related to a variety of equipment, materials, machines, work permits, and site conditions. In project A, the index of documents compliance (e.g. maintenance records of machinery, training certifications to carry out certain tasks) was also based on a checklist and the "cost estimate of fines" index was based on a classification proposed by the Brazilian regulation NR-28 (inspection and penalties), which defines the potential fine for the non-compliance to requirements set by other regulations.

In Project A, the formal safety inspections were conducted on a weekly basis focusing on compliance with legal requirements while in Projects B and C were conducted once a month. Table 8 presents the main characteristics of the SPMS of the three construction projects.

4.2. Sources of project complexity that influence safety performance

4.2.1. Technical

Table 9 summarizes the sources of technical complexity that affect safety performance in the three construction projects. In Project A, the **large number and diversity of legal requirements and associated documentation** that must be monitored was pointed out by the interviewees as having a negative impact on safety performance. As a result, the safety technician reported that he spent most of his time dealing with paperwork that did not add much value from the perspective of workers' safety. Bureaucracy introduced by safety management (Dekker, 2014) may be interpreted as an addition of unnecessary complexity, since it creates a number of new interactions that waste resources that could be applied for effective safety management.

The **interdependence between construction phases and the non-linear interactions arising from these** was pointed out by the interviewee as another source of technical complexity that hindered safety performance. For instance, the masonry activities were dependent on the installation of electrical pipes (Fig. 2). According to observations carried out by the research team, several walls had to be reworked due to the difficulty of passing electrical pipes through the internal holes of bricks. There were blockages in those holes, caused by excess of mortar that had not been properly removed. Some rework had to be done, and the workstation for performing that task was improvised, creating fall hazards and contributing to poor quality.

In Project B, a reported source of technical complexity that influenced negatively safety performance was the **uncertainty in project scope due to changing client requirements**. For example, the construction site was intended to have two accesses from one main highway, but when the case study was carried out the accesses were still undefined by the client as the connection to the highway required a detailed road traffic scheme. Meanwhile, the access of heavy equipment and machines to the construction site occurred through a narrow secondary road, affecting the local traffic of vehicles and pedestrians.

In both Projects B and C, the **dynamic interactions between project participants** – in terms of formal and informal exchange of information and resource flows – was pointed out as a beneficial source of complexity for safety performance. In both projects the Last Planner System implied in daily and weekly collaborative planning meetings in which commitments were managed. This created opportunities for identifying hazards, such as possible interferences between parallel activities, and setting responsibilities to participants.

4.2.2. Organizational

Table 10 summarizes the two sources of organizational complexity that were identified. In Project A, the complexity associated with the **gap between construction methods as imagined and as done** hindered safety performance. For example, wall intersections were designed to be built by interweaving blocks (Fig. 3). However, workers completed each wall separately and then improvised mechanisms to hold the distance from one brick to another until the other wall was built.

By contrast, the **diversity of stakeholders' perspectives and skills** was pointed out as having a positive impact on safety performance in the three projects. The diversity of perspectives is useful when discussing

Table 8
Overview of the SPMS of the three projects.

Safety indicators	Frequency of collection	Type	Main responsible for data collection	Time lag for collection, analysis and processing of results	Dissemination of results
Construction project A					
01. Index of compliance with the NR-18 regulation	weekly	Leading	safety engineer	15 days	Indicators were usually disseminated in: (i) managerial monthly meetings that addressed all projects under way, involving the project manager, the safety engineer, the site manager of each project, quality and administrative departments; (ii) weekly safety dialogs involving the safety manager, safety technician and all operational workers; (iii) safety committee monthly meeting involving the safety engineer, safety technician, team supervisors and the safety subcontractor – this was responsible for the installation and maintenance of temporary protections. There was a lack of formal written reports summarizing the key topics and corrective actions. There was no control panel to visualize the indicators evolution
02. Cost estimate of fines for non-compliance to NR-18	monthly	Leading	safety engineer		
03. Index of documents compliance	weekly	Leading	safety engineer		
04. Accident rate	monthly	Lagging	safety engineer		
05. Lost time injury rate		Lagging	safety engineer		
Construction project B					
01. Index of compliance to NCh436	monthly	Leading	safety engineer/ safety technician	10 days	Indicators were disseminated in: (i) managerial monthly meetings for the specific project involving the project manager, the site manager, the safety coordinator and safety engineer and quality, administrative and supply departments. The discussions were supported by charts that presented the evolution of all indicators over time, and by a dashboard which only showed the evolution of accidents and lost time injury rates; (ii) safety committee meetings involving the safety representative from the client; the safety engineer, safety technician and the representative from the Regional Ministry of Health who audit the construction site once a month. After the meetings a report was handed off to the interested parties. The reports of near misses were also discussed in short-term planning meetings once a week, and in daily safety dialogs involving the safety engineer, team supervisor and operational workers
02. Number of reported near misses	daily	Leading	safety technician	1 day	
03. Accident rate	monthly	Lagging	safety engineer/ insurance body	15 days	
04. Lost time injury rate		Lagging	safety engineer/ insurance body	15 days	
Construction project C					
01. Index of compliance to NCh436	monthly	Leading	safety engineer	10–12 days	Similarly to project B, indicators were disseminated in managerial monthly meetings for the specific project and in safety committee meetings. The discussions were also supported by charts with the evolution of the indicators over time and by the dashboard of accidents and lost time injury rates evolution. Indicators results and the reports from the meetings were also disseminated through a cloud-based platform (Alma Suite) to all managerial levels of the project
02. Accident rate		Lagging	safety engineer/ insurance company		
03. Lost time injury rate		Lagging	safety engineer/ insurance company		

Table 9
Sources of technical complexity.

Project	Sources of technical complexity that influence safety performance	Associated hazards or benefits
A	**(-)** Large number and diversity of legal requirements and associated documentation to be controlled	High administrative workload for safety staff, making them to stay away from the front-line, and limiting the time available to plan and control safety
	(-) Interdependence between construction phases and the non-linear interactions arising from these	Undetected or late detection of interdependencies, causing rework that is carried out without proper safety planning and control
B	**(-)** Uncertainty in project scope due to changing client requirements	Undetected interferences affecting the local traffic of vehicles and pedestrians
C	**(+)** Dynamic interactions between project participants	Collaborative arrangements and straightforward communication between parties

Note: (+) positive and (-) negative influence on safety performance.

alternative construction techniques and having a wide range of skills is helpful when solutions for unplanned situations are needed, as stated by the project manager of construction A:

> "The tacit knowledge of workers empowers them to bring new ideas that they developed and tested in other construction sites"

Similarly, in Projects B and C, the diversity of stakeholders' perspectives and skills also supported the choice of proper construction methods during safety and production planning meetings. This occurred, for instance, with subcontractors that performed highly specialized activities, such as the design and construction of anti-seismic structures.

4.2.3. Environmental

The sources of environmental complexity are summarized in Table 11. In project A, the **uncertainty in weather conditions** was mentioned by the safety manager as a hindrance to safety performance. For example, the electrical system of the elevator was damaged by floods that also increased the risk of electrical shocks.

In project B, interviewees reported the **uncertainty of the political and economic situation of the external environment** of the country as Chile was going through presidential elections. This was perceived as a contributing factor to rising prices of some supplies, which could create financial pressures on other areas, such as safety.

A key source of environmental complexity in Project C, from the point of view of the interviewees, was **interactions with neighbours and municipality laws**. As the construction site was located in a densely populated urban area, it was necessary to implement strict controls for preventing hazards to the community. On the one hand, safety performance was benefited since awareness of health and safety issues needed to be higher. On the other hand, the project manager believed that this also could affect the safety performance negatively due to the productivity pressures resulting from work-hour restrictions and stricter safety controls.

4.2.4. Cross-case analysis of TOE framework results

In total, five sources of project complexity were identified in Project A, four in Project B and three in Project C. These may be interpreted as

Fig. 2. Interdependency between masonry and electrical pipes: (a) unblocking internal holes of bricks; (b) inadequate workstation; (c) wall after adaptations.

Table 10
Sources of organizational complexity.

Project	Sources of organizational complexity that influence safety performance	Associated hazards and benefits
A	**(-)** Gap between construction methods as imagined and as done	Improvisations that may lead to potential damages
B **C**	**(+)** Diversity of stakeholders' perspectives and skills	Variety of alternatives and solutions to construction techniques and methods

Note: (+) positive and (-) negative influence on safety performance.

important sources of complexity influencing safety, which could be identified from a relatively short data collection reflecting specific phases of the three construction projects. None of these sources can be eliminated by design, which implies that project management needs to cope with them, by developing the four resilience potentials. For instance, it is possible to cope with uncertainty from weather conditions by: designing proper drainage and pumping systems to reduce the effects of heavy rains (responding); being aware of weather forecasts for the short and long run (monitoring and anticipating); and redesigning responses based on their effectiveness in previous events of inclement weather (learning).

Only two sources were observed across the three projects and both of them had a positive influence on safety performance. One of these was the diversity of stakeholders' perspectives and skills (organizational complexity), which tends to exist in construction projects due to the variety of trades and design disciplines involved. However, the benefits from this diversity can be greater when there are systematic and formal mechanisms for production control, such as the Last Planner system (projects B and C), that can support the dynamic interactions between project participants and the sharing of clear goals between teams (technical complexity).

In turn, six sources had a negative influence on safety and, regardless of being identified in specific contexts and construction stages, they can be possibly generalized to most construction projects. For example, the large number and diversity of legal requirements (technical), the uncertainty in weather conditions (environmental), and the gap between construction methods as imagined and as done (organizational), are all part of everyday work in construction projects. However, the extent to which these sources of complexity will be drawbacks depends on context – e.g. the degree to which regulations are enforced and whether they are prescriptive or performance-based; the size of the construction site, effectiveness of drainage systems, and the nature of the building can make it more or less vulnerable to flooding; and the degree of standardization of production processes and workers training. These could

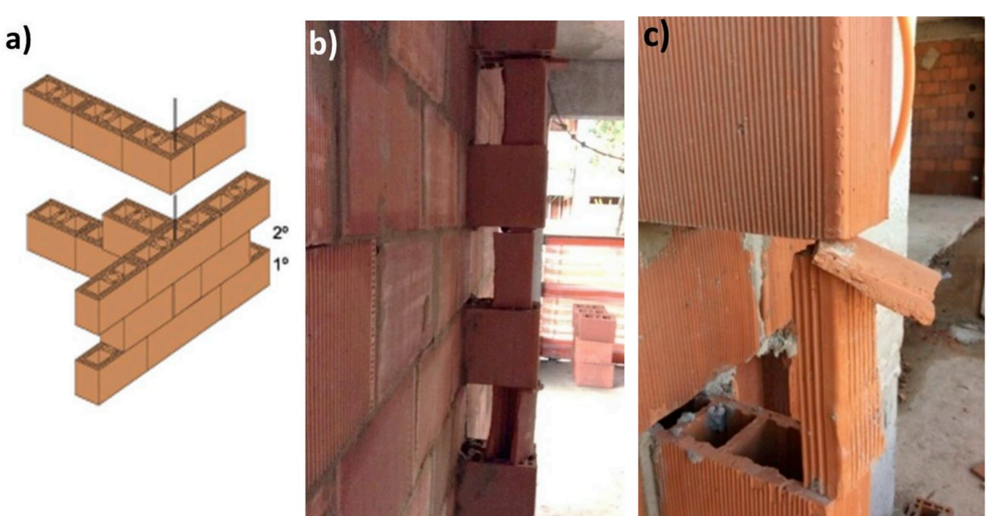

Fig. 3. a) wall intersection according to design; b) execution method performed by workers; c) improvised mechanisms to hold bricks distance.

Table 11
Sources of environmental complexity.

Project	Sources of environmental complexity that influence safety performance	Associated hazards and benefits
A	**(-)** Uncertainty in weather conditions (e.g. heavy rains and floods)	Absence of emergency plans and procedures
B	**(-)** Uncertainty of the political and economic situation of the external environment	Reduction on safety investments and resources
C	**(±)** Interactions with neighbours and municipality laws	Productivity pressures due to district controls. Increased awareness on health and safety conditions besides the construction site

Note: (+) positive and (-) negative influence on safety performance.

be framed as chronic sources of complexity, which usually exist during the whole construction stage.

In turn, other sources of complexity may have a more acute and highly contextual nature. For example, in Project B, the uncertainty brought by the upcoming presidential elections had a detrimental effect on the willingness of management to commit resources in general, including safety.

Only one source of project complexity was perceived as more ambiguous, both supporting and hindering safety – i.e. the environmental complexity related to the location and surroundings of Project C, as mentioned in Table 11. In this respect, a possible source of complexity that was not reported by the managers of projects A and C were the unintended safety consequences of the physical proximity of different production processes (Perrow, 1984). These projects involved the construction of high-rise buildings in relatively small land plots (17.000 m2 and 22.000 m2, respectively), which was in contrast with the horizontal nature of the building in project C (80.000 m2).

4.3. The four resilience potentials

4.3.1. Respond

Fig. 4 presents the results of RAG for the "respond" potential in each construction project. In all projects, there were regular threats and events that required preparation to "respond", such as hazards that are traditionally associated with accidents in the construction industry (e.g. falls from height, cave-in, and overexertion injuries). Another similarity is that, both in Brazil and Chile, the safety inspections carried out by government officers were perceived by managers as very strict, which encouraged a focus on compliance with regulations in order to prevent the shutdown of the construction site.

In **Project A,** the 6 functions related to this potential had an average overall score of 3.3, considering three respondents. For example, function number 6 (updating the indicator list and contents accounting for changes in the nature of hazards) had an average score of 2.3. The interviewees reported that the updating of the indicators list was difficult given the frequent recent changes in regulations. For instance, six months before the beginning of this study, five new requirements related to aerial work platforms and two others related to electrical shock prevention were added to the NR-18, and therefore were also added to the checklist. In this case, the risk perception by the regulator has changed, rather than the risks themselves.

In **Project B**, the average score of all functions was 4.1, considering two respondents. Functions 1 (safety and production planning meetings) and 2 (collaboration with front-line workers and team leader of subcontractors) can be mentioned as examples of positive practices adopted in this project. Regarding function 1, reports of near misses supported decision-making in the safety and production planning meetings, which had the participation of representatives from subcontractors and other departments, thus accounting for function 2. In fact, these practices benefited from the use of the Last Planner System, which demands collaborative planning and facilitates communication between stakeholders. A comment by one of the engineers illustrates this point:

> "The frequency of meetings and the visualization mechanisms (e.g. visual reminders and visual aids in the schedules) provided by the

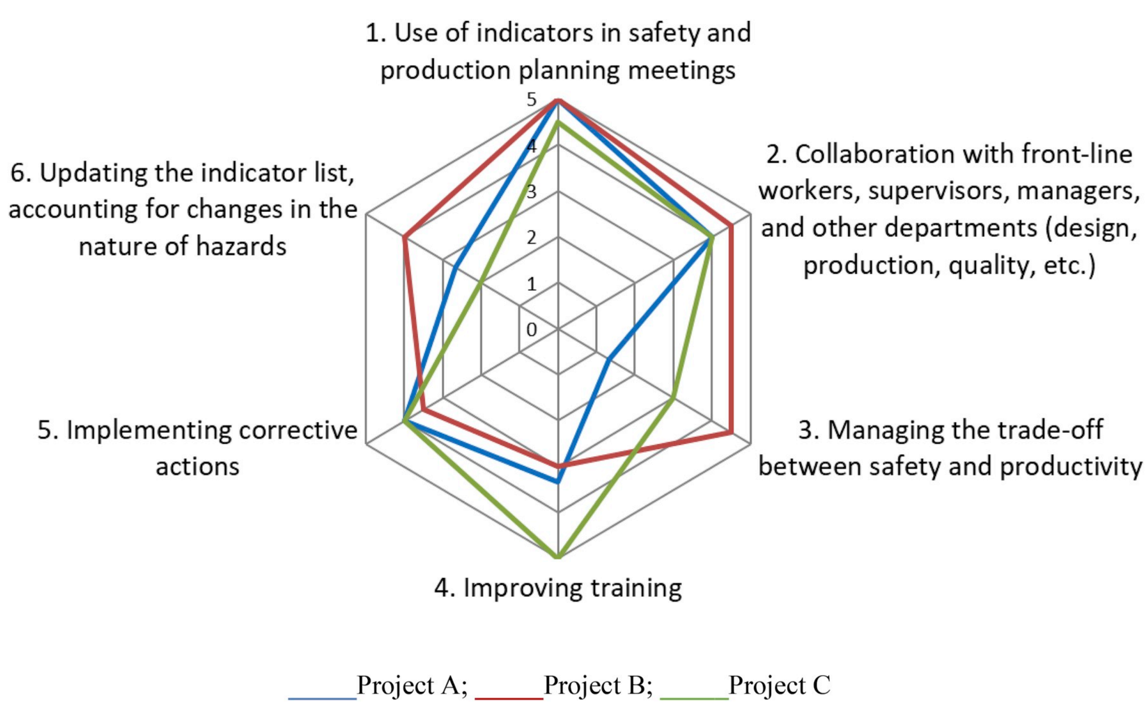

Fig. 4. Mean scores assigned to the "respond" potential.

Last Planner System are very useful in this case, in which there are many construction phases in parallel"

In **Project C**, this potential had an average overall score of 3.8 (two respondents). For example, regarding function 3, the respondents considered that the trade-offs between safety and productivity were informally discussed in the field, involving the safety engineer, team supervisor and project manager. However, the management of these trade-offs was not based on safety indicators and decision-making did not account for the viewpoint of workers. According to the safety engineer of that company:

"A stop work decision requires a convincing argument, as well as a contingency plan to cope with the consequences of the decision. Very often the project manager and team supervisors disagree on whether or not a task should be stopped. When we cannot reach an agreement, I can ask for the support of the safety coordinator and the general safety manager who are in a higher position in the control chain".

Decision-making related to these trade-offs could be supported by existing information, such as the historical data from accidents, lost time injuries and reasons for the non-completion of work packages. In fact, those reasons can point out recurring problems that have not been addressed due to production pressures, which in turn prevent work to be stopped when it should be.

4.3.2. Monitor

Fig. 5 shows the assessment of the "monitor" potential in each construction project. In **Project A**, the four functions related to this potential had an average overall score of 3. The general perception about the monitoring of everyday work (function 7) scored 3.3, mostly due to the checklists for the control of operating conditions of equipment and physical protections. However, reasons for the gap between prescription and practice were not explored as well as there was very little concern with understanding subtle informal work practices that contributed to desired outcomes. Similarly, function 9 (use of proactive measures) was rated as 3.6 because three safety indicators were used proactively as they provided opportunities to foresee the possible threats related to the non-compliance with documents and regulations as well as the fines imposed by the government inspection.

In **Project B**, the average score was 3.5. As to function 10 (decentralization of collection and dissemination of data), the opinion of respondents was positive (score 3) in terms of the number of employees on site for collecting safety related data, such as, the safety engineer, the safety technician and the insurance company representative. Regardless of this, there were reports of dissatisfaction with the administrative workload associated to safety management. The following report by the safety technician illustrates this point:

> "Tools such as mobile applications which can automatically synchronize, share and compare results would benefit those responsible for monitoring safety, by reducing the need for handling a lot of paperwork and photos"

In **Project C**, the average score was 3.6. Regarding the use of proactive indicators (function 9) the interviewees argued that other proactive measures are necessary in addition to those related to compliance to regulations. They reported the need for indicators that can be used to monitor risky processes in real-time, such as formwork or demolition. For function 8, which is related to workers involvement in monitoring, there was a mail box as a channel to encourage workers communication of incidents. According to the interviewees, many of the voluntary reports came from experienced workers, when they perceived alcohol or drug abuse in the construction site.

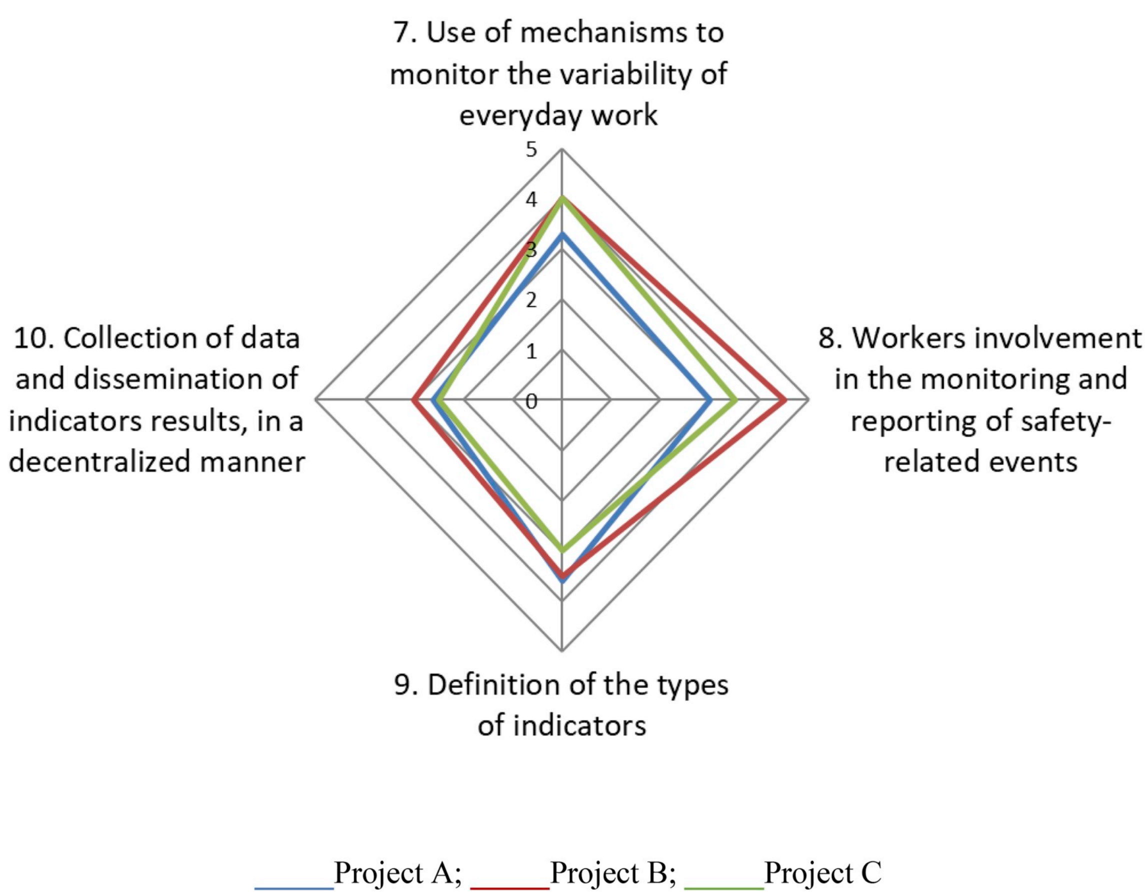

Fig. 5. Mean scores assigned to the "monitor" potential.

4.3.3. Learn

Fig. 6 summarizes the assessment of the "learn" potential in each construction project.

In **Project A**, the "learn" potential had an average overall score of 2.1. Regarding function 12 (lessons learned from failures), interviewees considered that the quality of the accident investigations and safety inspection reports was good enough, but the time that they take to be completed and produce feedback to managers is too long.

Examples of lessons learned that could support changes in the SPMS were identified when discussing function 14, which scored 2. The project manager and safety engineer reported an unexpected condition involving strong winds that caused the facade system to collapse. This event resulted in significant financial losses, but with no personal injuries. As a result of this event, the assembly process was revised and the list of hazards monitored by the SPMS was updated.

When it comes to learning from successful events (function 11) the interviewees from **Projects B** and **C** highlighted the advantage of having a large percentage (around 70%) of company's own employees on site. Thus, the turnover was low and newly hired workers had the possibility of working under the supervision of more experienced colleagues who could transmit knowledge of successful (and unsuccessful) work strategies.

In **Project B**, the average overall score was 2.5. Despite this, the respondents agreed that lessons were properly implemented (function 12, score 3.5) through changes in procedures and site layout, but those improvements were still not reflected in the SPMS (function 14, score 1.5).

In **Project C**, the overall perception associated with the potential to "learn" was rated as 2.7. Regardless of this low score, there was an innovative practice at corporate level that had been recently implemented, referred to as "close-up meetings". These meetings involved all the managers of a specific project after its completion in order to discuss lessons learned, not only those related to safety. According to the interviewees, lessons learned should be transferred from one project to another. However, they recognized that data were not systematically disseminated within the organization and were not used to feed the SPMS (function 14, score 2).

4.3.4. Anticipate

Fig. 7 summarizes the assessment of the "anticipate" potential in each construction project. In **Project A**, the overall average score of the anticipate potential was 2.3. Regarding function 17, although future threats and opportunities were discussed in a monthly managerial meeting, the results of this discussion were not widely communicated to all interested parties within the company (e.g. managers from other departments and the front-line workers). From the viewpoints of both the project manager and safety technician, the main threat was a shutdown of the construction site by government inspectors.

In **Projects B** and **C**, anticipation also had fairly low scores, (2.7 in B, and 2.8 in C), even though the interviewees stressed the role played by the Last Planner System as an anticipation mechanism. They reported the use of information from other departments (function 15) in the development of the look-ahead planning, which supported the early identification (up to 5 weeks before starting the activity) of risks and the provision of the necessary control measures.

Also, the respondents pointed out that the workers and subcontractors' perspectives were considered, to some extent, in decision-making (function 16). For example, in **Project B**, a group of workers suggested to the safety engineer a new equipment to handle tools during work at heights. After the introduction of the equipment in the construction site the safety engineer observed that workers movements were being compromised, recognizing that the innovation was introduced too fast and in the wrong order. Therefore, the conclusion was made that the evaluation of the equipment considering workers performance should be undertaken before implementation.

In **Project C**, highly skilled workers were consulted by foremen

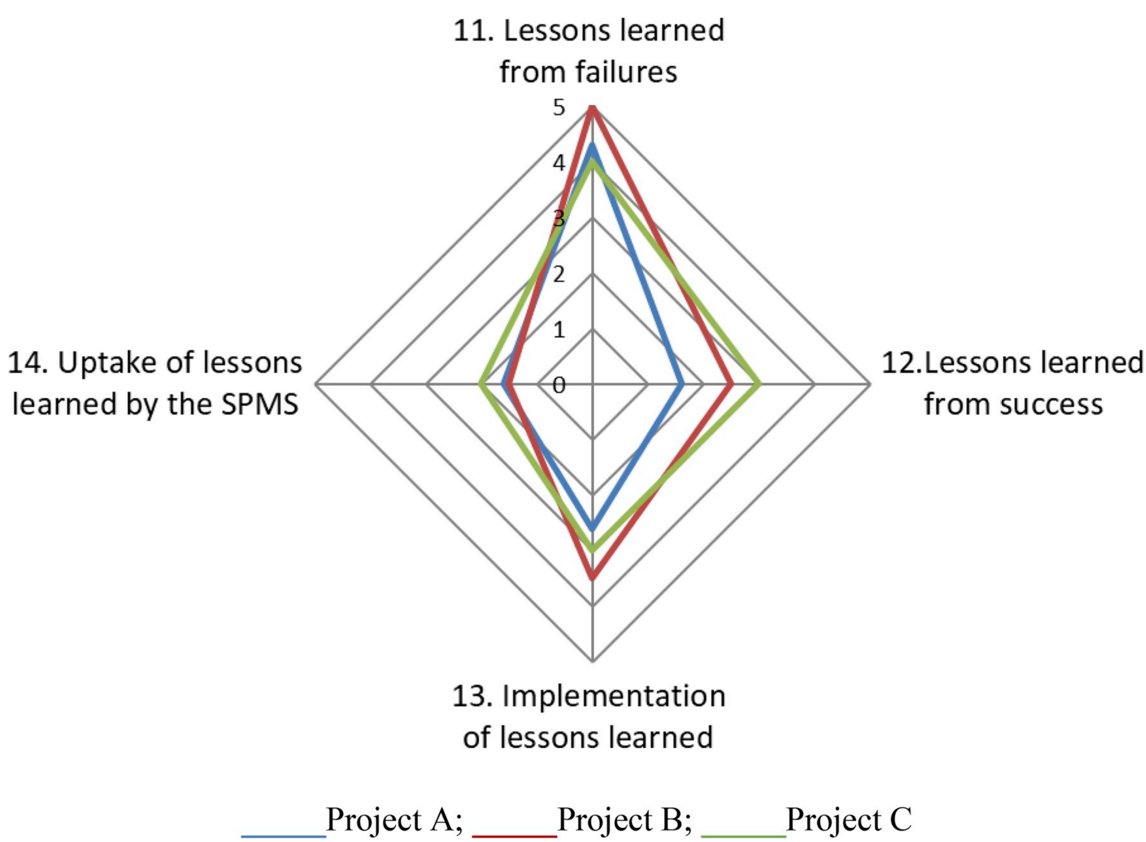

Fig. 6. Mean scores assigned to the "learn" potential.

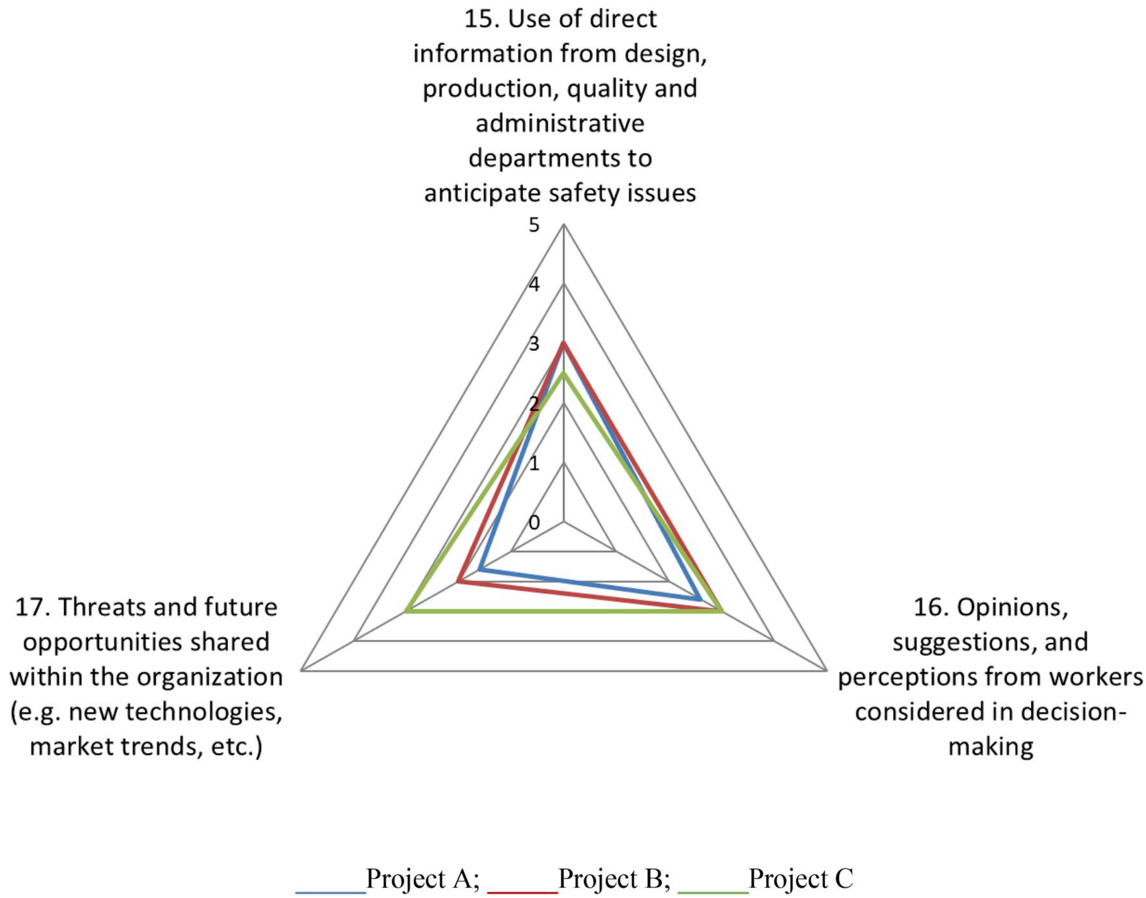

Fig. 7. Mean scores assigned to the "anticipate" potential.

before deciding the best way of carrying out some operational activities (e.g. interlocking pavement blocks). As a drawback reported by the safety engineer in project B, these suggestions were not always properly tested in a pilot study before full implementation, which introduced risks.

4.3.5. Cross-case analysis of RAG

Fig. 8 summarizes the scores obtained from RAG, in all construction projects. The results suggest that the respond and monitor potentials had a better performance in comparison with learn and anticipate potentials. An unbalanced performance across the potentials is not necessarily a drawback, as their relative importance is context-dependent (Hollnagel, 2017). However, a possible interpretation for the findings from this study is that safety management in the three construction projects is mostly reactive by focusing on recurrent problems that can be easily monitored and trigger known responses, not necessarily deployed in a

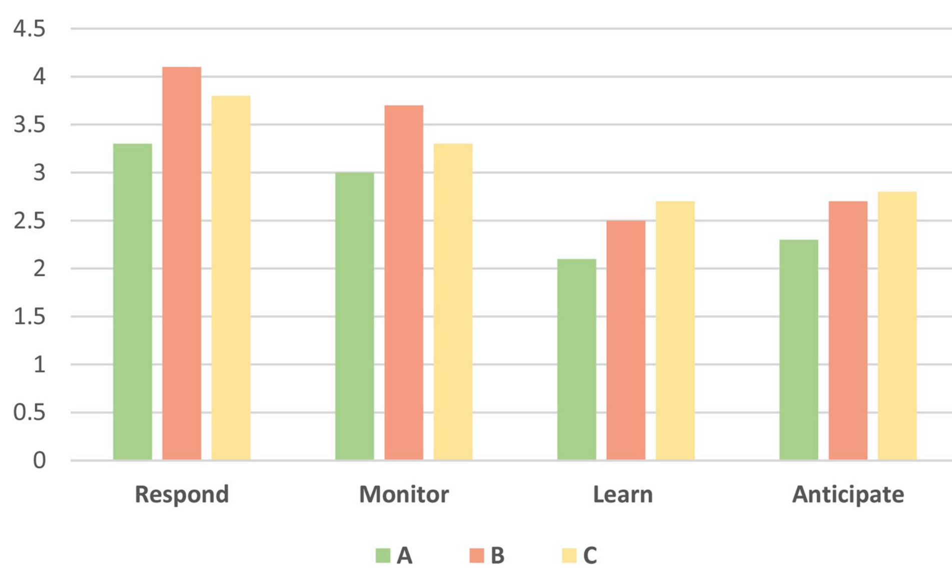

Fig. 8. RAG average scores for all construction projects.

timely and effective manner. For instance, the strong focus of project A on compliance with regulations narrowed the SPMS scope for monitoring and responding, and, at the same time, limited the effort spent in learning and anticipating.

In turn, in projects B and C, the Last Planner System supported many of the SPMS functions related to the resilience potentials. For example, the safety and production planning meetings involving the collaboration of several stakeholders benefited the potential to respond and anticipate by facilitating the identification of conflicting goals (Ballard and Howell, 2003). Also, look-ahead plans devised as a schedule of potential assignments (Ballard, 2000) supported the early anticipation of risks.

4.4. Improvement opportunities for the SPMS

Table 12 presents 16 improvement opportunities that were identified in the SPMS of the three companies, based on the application of RAG and TOE. Those opportunities address gaps that were identified in those systems regarding the identification of some sources of complexity and the assessment of some resilience potentials, as discussed in the previous sections. Those 16 improvement opportunities were divided into three categories, presented below:

(i) Changes in other safety management subsystems, rather than in the SPMS (8 opportunities): those changes may produce useful information for monitoring and understanding safety performance without necessarily demanding new metrics. This category is based on two assumptions: the SPMS is inseparable, from a complexity thinking viewpoint, from the general safety management system; and the SPMS has an inevitable informal portion (i.e. a manifestation of resilience), which refers to the flow of relevant safety information that cannot or should not be translated into metrics. The improvement opportunity related to pre-task safety and production planning (Table 12) illustrates these points. While that type of plan may use information produced by the SPMS, the assessment of the planning effectiveness may also feed information back onto new plans and the SPMS itself;

(ii) Design of new metrics (6 opportunities): this is concerned mostly with monitoring of sources of complexity or assessing resilience potentials that have been neglected. For instance, the new metric referred to as "ratio between the working time during restricted work hours and the total working time" is cited as an improvement opportunity in Table 12. This metric could monitor the extent to which a resilient strategy (i.e. working in restricted hours) was deployed, as a compensation for a source of complexity from the external environment (i.e. interactions with neighbours and municipality laws). The underlying assumption of this metric is that the extent of work in restricted hours matters for safety, because it implies in overtime work that can increase workers' fatigue, in addition to increasing the exposition to risks arising from interactions with neighbours; and

(iii) Revision of existing metrics (2 opportunities): this type of improvement is mostly concerned with the changing nature of risks as well as with the cost-benefit ratio of the metric. If these two aspects (changing risks, costs of implementing metrics) are neglected, the SPMS may become a source of unnecessary complexity and produce unintended consequences (e.g. loss of credibility in the value of keeping a SPMS). The prioritization of the regulations and documents to be assessed, defining monitoring frequencies according to the priority level is an example of improvement opportunity, included in Table 12, which considers those two requirements. Similar insights have been obtained by earlier studies, such as Janackovic et al. (2017).

In addition to this, Table 12 offers insights into the types of complexity sources that were monitored by the existing SPMS. Considering the three empirical studies, only two out of the nine sources of

Table 12
Improvement opportunities arising from RAG and TOE assessments.

Sources of project complexity that influence safety performance	Was this complexity source addressed by the SPMS?	Which resilience potentials were mostly supported?	Improvement opportunities and implications for the resilience potentials
T (-) Large number and diversity of legal requirements and associated documentation to be controlled (Project A)	It was covered by the index of compliance with the NR-18 regulation and the index of documents compliance	Monitoring: there were standardized data collection routines. Responding: the responses for addressing non-compliances were well-known.	(RM) Prioritization of the control items, and definition of different control cycles according to the item priority (*Monitoring*). Prioritization should be continuously reviewed as a result of learning. (RM) Changes in regulations could be anticipated to some extent, and incorporated into the existing metrics *(Anticipation and Learning)*
T (-) Interdependence between construction phases and the non-linear interactions arising from these (Project A) **O (-)** Gap between construction methods as imagined and as done (Project A)	Not covered by the existing SPMS	None of the potentials is supported	(SM) Early identification of possible hazardous interactions between construction activities in production planning (*Anticipation*). (NM) Pre-task safety and production planning, and assessment of plan completion, involving managers, supervisors and workers *(Responding and Learning)*
E (-) Uncertainty in weather conditions (Project A)	Not covered by the SPMS	None of the potentials is supported	(SM) Accounting for weather forecasts (short and long-run) when developing safety and production plans *(Monitoring and Anticipation)* (SM) Redesign responses based on their effectiveness in previous events of inclement weather (*Responding and Learning)* - e.g. drainage and pumping systems may need to be redesigned to cope with heavy rain

(continued on next page)

Table 12 (*continued*)

Sources of project complexity that influence safety performance	Was this complexity source addressed by the SPMS?	Which resilience potentials were mostly supported?	Improvement opportunities and implications for the resilience potentials
O (+) Diversity of stakeholders' perspectives and skills (Project A, B and C)	Although this source is not covered by the SPMS, it is dealt with by the safety and production planning meetings. These include the participation of team leader's subcontractors.	Mostly responding and anticipation, through communication of the hazards and follow-up of commitments assumed by stakeholders	(NM) The frequency of attendance of stakeholders in safety and production planning meetings could be monitored through a specific indicator *(Monitoring)* (NM) Communicate and revise the good practices and suggested alternative solutions for safety and production planning, with the participation of project members (*Anticipation and Learning)*
T (+) Dynamic interactions between project participants and clear goals shared between teams (Project B and C)	Same as above	Same as above	(NM) Social network analysis could shed light on the nature and frequency of social interactions relevant for safety management. Some metrics could be devised based on knowledge generated from these networks *(Monitoring)* (RM) Reflect on good practices in both verbal and written communication throughout the project. Review the clarity of goals with project teams on a regular basis (*Learning)*
T (-) Uncertainty in project scope due to changing client requirements (Project B)	Not covered by the SPMS	None of the potentials is supported	(NM) The number of incomplete designs and associated hazards could give rise to a specific metric (*Monitoring)* (RM) Educate the clients so as they can appreciate the impacts of their decisions on safety (*Anticipation and Learning)*
E (-) Political and economic uncertainty in the external environment (Project B)	Not covered by the SPMS	None of the potentials is supported	(NM) Slack resources (e.g. time buffers, financial savings, spare supplies) should be in place for coping with sudden threats from the external environment. The status of these resources could be monitored through specific metrics (*Responding, Monitoring and Anticipation)* (SM) Gather lessons from past situations which can be useful for sense-making when dealing with an uncertain external environment (*Learning and Responding)*
E (±) Interactions with neighbours and municipality laws (Project C)	The company conducted assessments of noise level on a regular basis.	Mostly responding and monitoring (noise levels)	(NM) There could be a specific metric for monitoring the total working hours during restricted work hours *(Monitoring)* (SM) Gather feedback from external parties to assess how well the construction project is performing in relation to their requirements. This could also give rise to new metrics *(Learning)*

Notes.
T: technical; O: organizational; E: environmental.
(-) negative influence on safety; **(+)** positive influence on safety.
(NM) new metrics; (RM) revision of existing metrics; (SM) other safety management sub-systems.

complexity were directly covered by the SPMS. In fact, the remaining sources were not monitored at all in any of the projects. This does not necessarily mean that these sources were neglected by management, but rather that they tend to be addressed reactively and probably too much based on the experience of individual managers. This may be interpreted as a possible overuse of reactive resilience, which is common in poorly designed socio-technical systems (Wears and Vincent, 2013).

5. Guidelines for the design for SPMS in construction

Based on the identification of improvement opportunities and also in the literature review, a set of guidelines for the design of SPMS in construction have been proposed. Those guidelines are intended to play a complementary role to those suggested in the literature (see Section 2.2):

(i) Benefits of using RAG and TOE on the design and implementation of SPMS:

The joint use of TOE and RAG may give rise to improvement opportunities of three main types, as discussed in Section 4.4: changes in other safety management sub-systems; new metrics for monitoring sources of complexity and resilience potentials; and the revision of existing metrics. This guideline suggests that RAG and TOE could be interpreted as meta-measurement tools and high-level elements of SPMS, which support carrying out critical reviews in those systems.

The use of those tools may support the analysis of whether SPMS produces useful information on key characteristics of socio-technical systems, which influence safety. In particular, the early identification of sources of complexity can indicate when and where resilience is likely to manifest as a compensation during the construction project, such as construction stages that have a high level of uncertainty, demanding *ad-hoc* solutions and ingenuity. This allows for the identification of priority areas for monitoring.

(ii) The influence of SPMS on complexity:

The influence of SPMS design on the sources of complexity may be either desired or undesired, and therefore it should be explicitly analysed. Regarding the former, the SPMS produces information that helps to increase the variety of controllers, which can be regarded as a proxy of complexity – i.e. the greater the controllers' variety, the greater their complexity. According to the "Law of Requisite Variety" (Ashby, 1991), effective system functioning requires that the variety of a controller (e.g. SPMS and its users) matches the variety of the system to be controlled (e.g. construction site activities). In this respect, a SPMS that is too narrowly focused on regulations does not have the necessary control variety. Regarding the latter, SPMS may create unnecessary complexity by adding much bureaucratic work and producing information that does not add value from a safety perspective.

Two approaches are proposed for managing the tension between adding variety to SPMS and avoiding unnecessary complexity. First, the adoption of an explicit safety management paradigm (e.g. resilience engineering), which defines the main beliefs regarding what is safety and how it can be obtained. This can help to decide what counts as a relevant metric. Second, the provision of organizational support to reduce perceived complexity (e.g. by using visual management and IT tools to disseminate safety information) and increase desirable dimensions of complexity (e.g. wider variety of controllers' skills as a result of education and training).

(iii) The influence of SPMS on resilience:

Similarly to complexity, the SPMS may either hinder or support the potentials of resilient systems. Regarding the former, by introducing unnecessary complexity, the SPMS may consume resources that otherwise could be useful for supporting resilience potentials. Besides, the SPMS may contribute to the unjustified unbalanced deployment of the potentials, possibly by overemphasizing monitoring and responding to the detriment of learning and anticipation, as it was observed in the three case studies. Regarding the latter, the SPMS may be a valuable source of information for understanding what resilience looks like in construction sites. In this respect, the case studies suggest that TOE and RAG produced insights into how resilience manifests in practice at higher organizational levels and with a low level of granularity. Other approaches, such as cognitive task analysis (Crandall et al., 2006), may be more appropriate for understanding the nature of resilience as deployed by front-line workers in construction sites.

Fig. 9 summarizes the conceptual relationships between the main constructs encompassed by the guidelines. These constructs appear in the boxes, while the nature of their relationships is explicit in the text over the connecting arrows. The central role played by TOE and RAG is highlighted, as these tools at the same time support the review of existing SPMS and are themselves a means for monitoring both complexity and resilience. Also, the bi-directional relationship between resilience and complexity is emphasized: complexity is assumed to be a trigger for resilience, while at the same time resilience can benefit from certain sources of complexity. The holistic nature of the guidelines is also highlighted in Fig. 9, which acknowledges that SPMS interacts with the overall project management system.

6. Conclusions

The combined use of two existing tools – RAG and TOE - have been proposed in this investigation for monitoring the factors that affect complexity and resilience in construction projects. The application of these tools is based on 95 questions (50 for TOE and 45 for RAG) that provide a holistic account of SPMS from a resilience engineering (RAG) and project complexity (TOE) lens. Given the systemic and managerial oriented nature of both tools, guidance is necessary for translating the findings from their application into practical improvement opportunities. The use of the tools in three construction projects suggested that these opportunities can be of three types: those related to changes in other safety management sub-systems, design of new metrics, and revision of existing metrics.

This research work also produced a set of guidelines containing higher-level recommendations for the design of SPMS. It is worth highlighting the role played by TOE and the associated attributes of complex systems, which require managers to think in terms of interactions and characteristics of the functioning of construction projects that may affect safety performance. This systemic approach is not exclusive with operational safety management concerned with coping with tangible hazards at the front-line. By contrast, it can be useful for refining safety management, as demonstrated by the practical nature of the improvement opportunities detected in the case studies.

Some limitations of this research must be highlighted. First, the improvement opportunities for the existing SPMS were not implemented and assessed in the scope of this study. Second, both TOE and RAG interviews were limited to representatives from managerial ranks, with no account of workers and supervisors' perspectives. Third, the evolution of the sources of resilience and complexity over time was not investigated in each construction project. This is probably a more relevant drawback in construction, in comparison to other sectors. Construction sites are known for significant changes across construction stages (e.g. from foundations to roofing), when different technologies and workers may be deployed. Fourth, the number and nature of the construction projects investigated in the case studies may have influenced the findings – e.g. the implications of using TOE and RAG could be different for SPMS with different maturity levels.

Based on the insights from this study, as well as on its limitations, some opportunities for further studies have been identified: (i) to consider workers and supervisors viewpoints when applying RAG and TOE, contrasting their perceptions with those from managers; (ii) to test other approaches for the adaptation of the RAG questionnaire to construction (e.g. focus groups with construction professionals) – in fact, the questions presented in Appendix A are not intended to be applicable to any construction site, but rather were considered to be useful questions for the purpose of this research study; (iii) to monitor the evolution of resilience and complexity over the whole life-cycle of construction projects, from design to the completion of the construction stage; (iv) to develop descriptive studies that offer a detailed account of what resilience and complexity look like in the construction industry, across different organizational levels (e.g. front-line operations and project management); (v) to carry out studies for exploring the nature and dynamics of cause-effect links between the sources of complexity and the resilience potentials, by combining quantitative and qualitative data; and (vi) to explore the contribution of other performance measurement systems (e.g. quality, production, environment) for the monitoring of

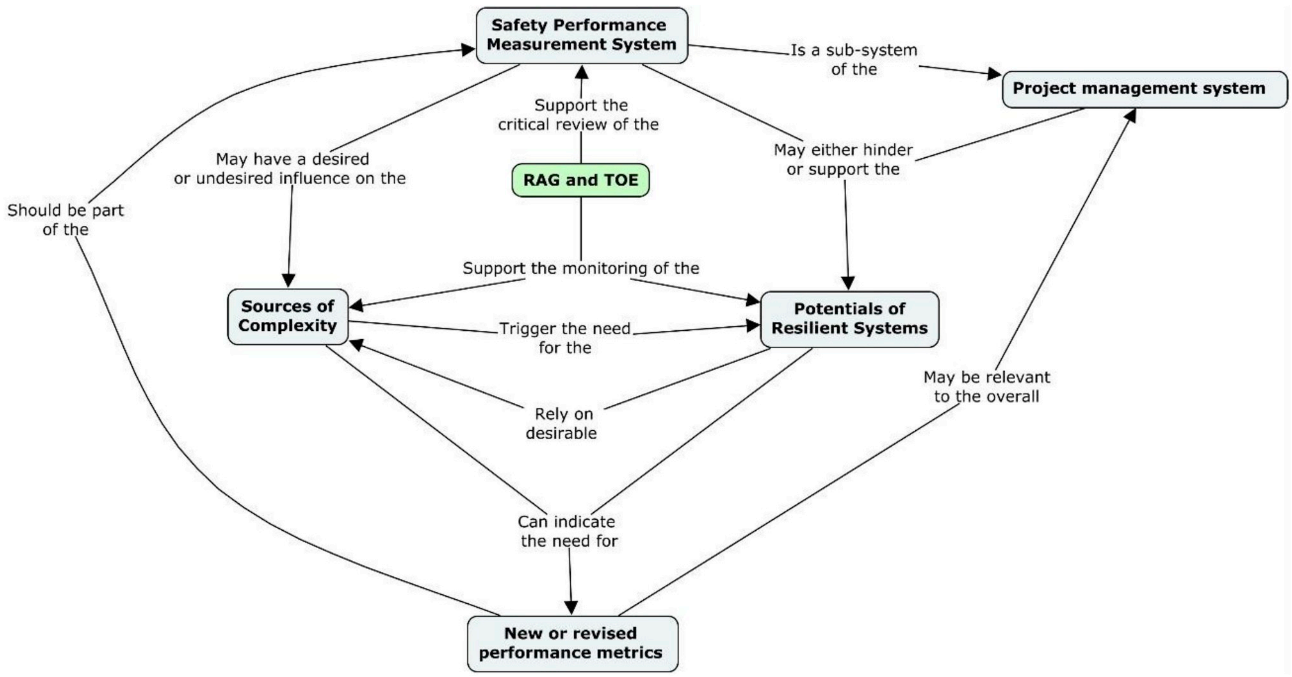

Fig. 9. Main conceptual relationships between the constructs encompassed by the guidelines.

sources of complexity and resilience.

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Appendix A. Resilience Assessment Grid (RAG) questionnaire. Notes: (i) questions referred to as "original" are those from the original RAG by Hollnagel (2011); (ii) questions referred to as "adapted" correspond to those from the original RAG by Hollnagel (2011), which were reworded as to facilitate their understanding in the construction context

	Functions of the SPMS	Questions	Sources
Respond	1. Use of indicators in safety and production planning meetings	1.1 Do results of safety indicators support decision-making in safety and production planning meetings? 1.2 Which safety indicators are used in these meetings? 1.3 How often are the indicators used in safety planning? 1.4 How often are the indicators used in production planning?	Hinze et al. (2013)
	2. Collaboration with front-line workers, supervisors, managers, and other departments (design, production, quality, etc.)	2.1 How are project participants involved in safety activities, such as job hazard analysis, planning meetings, and inspections?	Hallowell and Gambatese (2009)
		2.2 Who has the authority to stop work, without waiting for approval from site management? 2.3 How is the stop work authority put into practice?	Saurin et al. (2008)
	3. Managing the trade-off between safety and productivity	3.1 How are conflicts between safety and productivity managed? 3.2 In which construction phases are these conflicts more likely to occur?	Adapted from original *(Is there a trade-off between, e.g., safety and productivity?)*
	4. Improving training	4.1 Are the results from safety indicators used to improve training? How?	Hinze et al. (2013)
	5. Implementing corrective actions	5.1 How is the need for corrective actions identified? 5.2 Who is responsible for implementing corrective actions?	Choundry et al. (2008)
		5.3 How fast can an effective response be implemented?	Original
		5.4 How is the readiness (of workers and managers) to respond maintained and verified? Which type of training supports this readiness?	Adapted from original *(How many resources are allocated to the response readiness (people, materials)? How many are exclusive for the response potential?*
	6. Updating the safety indicators list, accounting for changes in the nature of hazards	6.1 When was the list created? How often is it revised? 6.2 Who is responsible for maintaining and evaluating the list?	Original
Monitor	7. Use of mechanisms to monitor the variability of everyday work	7.1 Are there mechanisms for monitoring the variability of everyday work?	Saurin et al. (2008)

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	Functions of the SPMS	Questions	Sources
		7.2 Are there mechanisms for monitoring the subcontractors' safety performance?	Hinze et al. (2013)
	8. Workers involvement in the monitoring and reporting of safety-related events	8.1 Are workers involved in the monitoring and reporting of safety-related events?	Hinze et al. (2013)
		8.2 Which practices support workers monitoring and reporting of safety-related events?	
	9. Definition of the types of indicators	9.1 How have safety indicators been defined (by analysis, by tradition, by industry consensus, by the regulator, by international standards, etc.)?	Original
		9.2 What is the nature of the safety indicators? Qualitative or quantitative? (If quantitative, what kind of scaling is used?)	
		9.3 How often are the safety indicators collected? Continuously, regularly, every now and then?	
		9.4 How many of the safety indicators are leading, and how many are lagging?	
	10. Collection of data and dissemination of indicators results, in a decentralized manner	10.1 What is the delay between measurement, analysis, and interpretation?	Original
		10.2 Are the results of safety indicators disseminated across all managerial and operational levels?	Saurin et al. (2008)
		10.3 Who is responsible for collection data and dissemination of results of safety indicators?	
		10.4 Is there a regular scheme or schedule for collection of data and dissemination of results of safety indicators? Is it properly resourced?	Adapted from original *(Is there a regular inspection scheme or -schedule?)*
Learn	11. Lessons learned from failures	11.1 Does the organisation try to learn from failures?	Original
		11.2 If yes, how are failures described?	
		11.3 Are there any formal procedures for investigation and learning form failures?	Original
	12. Lessons learned from success	12.1 Does the organisation try to learn from success (e.g. things that goes well, successful adaptations of performance, good practices)?	Original
		12.2 If yes, how are successes described?	Original
		12.3 Are there any formal procedures for investigation and learning from success?	
	13. Implementation of lessons learned (e.g. revision of procedures, redesign of tools, layout, etc.)	13.1 How are lessons learned translated into practical actions?	Adapted from original *(How are 'lessons learned' implemented? Regulations, procedures, norms, training, instructions, redesign, reorganisation, etc.)*
		13.2 What is the delay between learning a lesson and translating it into practical actions?	
		13.3 How are these lessons communicated to the interested parties?	
	14. Uptake of lessons learned by the SPMS	14.1 How often is the SPMS evaluated, in order to check that it keeps being relevant in face of the evolving nature of the socio-technical system?	Hinze et al. (2013)
		14.2 How does learning help to develop a balanced SPMS that is at the same time complete and easy to use?	
Anticipate	15. Use of direct information from design, production, quality and administrative departments to anticipate safety issues	15.1 Are indicators from other performance dimensions (e.g. quality, production, and cost) analysed from a safety perspective (e.g. providing input into safety planning meetings or risk analysis?	Saurin et al. (2008)
		15.2 If yes, which kind of indicators?	
	16. Opinions, suggestions, and perceptions from workers considered in decision-making	16.1 How are opinions, suggestions, and perceptions from workers considered in decision-making related to safety?	Saurin et al. (2008)
		16.2 How do these opinions, suggestions, and perceptions from workers support the anticipation of hazards?	
	17. Threats and future opportunities shared within the organization (e.g. new technologies, market trends, etc.)	17.1 Is information related to threats and future opportunities shared within the organization?	Adapted from original *(How are the expectations about future events communicated or shared within the organisation?)*
		17.2 If yes, which tools and practices support this information sharing?	

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A RESILIENCE ENGINEERING-BASED FRAMEWORK FOR ASSESSING SAFETY PERFORMANCE MEASUREMENT SYSTEMS: A STUDY IN THE CONSTRUCTION INDUSTRY

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Submitted

A Resilience Engineering-based framework for assessing safety performance measurement systems: a study in the construction industry

Abstract

Resilience engineering (RE) might provide a complementary perspective to traditional safety performance measurement systems (SPMSs), by accounting for the growing complexity of socio-technical systems. However, previous studies do not make it clear how that perspective could be translated into practice, nor the utility of that analysis. In order to address this gap, this paper presents a RE-based framework for assessing SPMSs in construction projects, which includes six stages : (i) obtain an overview of the existing SPMS; (ii) understand how complexity influences safety performance, based on the complexity assessment tool known as Technical, Organizational, and Environment framework; (iii) assess the four resilience abilities (monitor, anticipate, respond, learn), based on the Resilience Assessment Grid; (iv) assess the joint evidence from the previous steps in light of RE guidelines for SPMSs; and (v) identify improvement opportunities. The framework was tested in a construction site in Norway, based on interviews, observations, and analysis of documents. Results pointed out exemplar approaches for applying RE ideas to SPMSs as well as they shed light on how complexity may either hinder or support a SPMS.

Keywords: resilience engineering, safety performance measurement systems; complexity; construction.

1. Introduction

In the construction industry, safety performance is often assessed by using lagging indicators, which are based on past events, such as reportable accidents (Arquillos et al., 2012), number of near misses (Zhou et al., 2017), lost time, and non-lost time injuries (McVittie et al., 2009). Safety performance measurement systems (SPMSs) that rely only on those indicators are reactive and address only a fraction of everyday performance, i.e.

unwanted events. From this viewpoint, the goal of safety management is to keep the number of undesired outcomes as low as possible (Hollnagel, 2014).

In turn, the need for using leading indicators has been widely recognized in the literature on construction safety management, usually emphasizing the monitoring of activities believed to prevent accidents (e.g. safety inspections) (Hallowell et al., 2013; Guo and Yiu, 2015). This approach is proactive as it allows action taking before the occurrence of undesired outcomes (Hopkins, 2009). However, it might still focus on a fraction of everyday performance, instead of monitoring the variability of production activities in which hazards play out (Peñaloza et al., 2020a).

Whether reactive or proactive indicators are emphasized, previous studies usually do not frame these indicators as a part of a continuous improvement management cycle (Peñaloza et al., 2020a). This means that safety performance measurement often neglects other elements that would make up a system, such as the use of explicit criteria for the design and selection of indicators, the definition of protocols for data collection, processing and analysis, and the formulation of strategies for disseminating indicators and updating the system on a regular basis (Janicak, 2010). Furthermore, what counts as well-designed SPMSs is contingent to the chosen safety perspective (Reiman and Pietikäinen, 2012; Hollnagel, 2017).

The Resilience Engineering (RE) perspective is adopted in this study. RE is concerned with the observation, analysis, design and development of theories and tools to manage the adaptive ability of organizations in order to function effectively and safely (Nemeth and Herrera, 2015). From the RE viewpoint, SPMSs must contribute to the four abilities of resilient systems, namely monitoring, anticipating, responding, and learning (Hollnagel, 2017). Peñaloza et al. (2020a) proposed five guidelines to assess the extent to which previous research on SPMSs have adopted the RE perspective. According to that review, RE remains little explored in most SPMSs studies, even though it has been implicitly adopted in several cases.

This research study aims at contributing for making the use of RE in SPMSs explicit and intentional. For that purpose, a RE-based framework for assessing existing SPMSs is proposed, based on three premises: (i) the assessment of SPMS must provide useful information for its redesign; (ii) a RE-based SPMS must contribute to the aforementioned four abilities of resilient systems; and (iii) a RE-based SPMS must account for the complexity attributes of the construction project in which it is applied. This last premise is important as these complexity attributes account for key contextual characteristics of construction projects, which therefore might determine what is relevant to be measured through a SPMS and what is not.

The proposed framework is based on two existing tools, one of them focused on the four resilience abilities and the other focused on complexity. As for the former, the Resilience Assessment Grid (RAG) developed by Hollnagel (2017) is adopted for identifying how the four resilience abilities are deployed in a construction project, thus illuminating how these might be encompassed by the SPMSs. An adaptation of the RAG questions for the context of the construction industry, developed by Peñaloza et al. (2020b), is used. As for the latter, the Technical, Organizational and Environmental (TOE) framework, devised by Bosch-Rekveldt et al. (2011) was used for identifying sources of complexity and their influence on the safety performance. The TOE was also used for that purpose by Peñaloza et al. (2020b). Altogether, RAG and TOE might provide a comprehensive description of a construction project complexity, thus offering information for making a SPMS compatible with its contextual characteristics. However, RAG and TOE do not explicitly link complexity with SPMS design. This link, which was missing in the study of Peñaloza et al. (2020b), is established in this work by using the five RE guidelines for assessing SPMSs proposed by Peñaloza et al. (2020a). This paper presents the application of the framework in a construction site in Norway, which provided insight into both the utility of the framework and the nature of the relationships between complexity and SPMSs.

2. Literature review

2.1 The four resilience abilities and RE in the context of SPMSs

RE is concerned with factors that contribute to resilient performance mostly at the organizational level, stressing the adaptive capacity to cope with complexity (Woods, 2015). According to Hollnagel (2017), a resilient system should display four abilities:

(i) **Respond**: it refers to the system ability to adapt to regular and irregular events (challenges and opportunities) in an effective and flexible way. It involves strategies for supporting successful performance, e.g. deploying extra resources or identifying priority control areas;

(ii) **Monitor**: it means that the system is able to monitor internal and external conditions that may develop into challenges or opportunities. Effective monitoring can lead to increased readiness, thus, facilitating early responses and improving the use of resources.

(iii) **Learn**: it implies that the system is able to learn from past events by understanding why things go right and why they go wrong. Learning from performance adjustments in everyday work may benefit organizational knowledge and the development of skills; and

(iv) **Anticipate**: it indicates that the system can anticipate challenges and opportunities in the near and far future. It benefits from creative thinking by engaging people with diverse perspectives to anticipate knowledge or resources gaps and needs.

The Resilience Analysis Grid (RAG), developed by Hollnagel (2011) has been a frequently used tool for producing a resilience profile of organizations, based on those four abilities of resilient systems. RAG is based on the application of a questionnaire, which should be adapted to each industry sector. In construction, Peñaloza et al. (2020b) developed a sector-specific RAG questionnaire that was applied in three construction sites.

As for SPMSs, Peñaloza et al. (2020a) proposed five guidelines for their assessment based on RE (Table 1). These guidelines emerged from a thematic analysis of nine book chapters (Hollnagel et al.; 2006; Nemeth et al., 2008; Dekker et al. 2008; Hollnagel, 2009; Woods and Branlat, 2011; Hollnagel, 2014; Saurin et al., 2016; Hollnagel, 2017; Dekker, 2019) and three papers (Herrera and Hovden, 2008; Lay et al., 2015; Woods et al., 2015). Then, those five guidelines were used for analysing 43 research studies on SPMSs across different industrial sectors. It is worth stressing that these guidelines are not only useful to analyse indicators, but other elements of the SPMS, such as the dissemination of information to relevant stakeholders (e.g. guideline 2, concerned with the provision of feedback), learning (guideline 3), and continuous improvement (guideline 5).

Table 1 – RE guidelines for SPMSs assessment (adapted from Peñaloza et al. 2020a).

RE guidelines for SPMSs assessment	Description
(1) SPMSs should support the monitoring of everyday variability	RE assumes that the same variability sources that play out in everyday work may, sometimes, play out in accidents as well. Thus, by monitoring everyday performance an organization can better understand the nature of variability as an inevitable and sometimes necessary condition for the development of required outputs.
(2) SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities	As complex systems are continuously evolving, real-time monitoring is necessary, and ideally associated with feedback in real-time. The diverse perspectives of skilled workers and information technology may contribute to the use of this guideline.
(3) SPMSs should facilitate learning from what goes well, in addition to what goes wrong	From the RE viewpoint, "what goes well" is any situation in which there is presence of safety – this includes unsafe conditions or behaviours when people or systems keep the situation under control. Learning from what goes well can help organizations to maintain the desired outcomes as well as to understand why, sometimes, things goes wrong.
(4) SPMSs should offer insights into the management of trade-offs between safety and other business dimensions	Trade-offs are ubiquitous in complex systems and they are often triggered due to conflicting goals – e.g. between efficiency and thoroughness or safety.
(5) SPMSs should evolve due to the changing nature of complex socio-technical systems	The SPMS must be up-to-dated with the evolution and emergence of hazards and opportunities. This may imply, for example, in the periodic replacement of existing indicators and new approaches for their collection and interpretation.

3. Research method

3.1 Research strategy

Design Science Research (DSR) was the methodological approach adopted in this study. This research strategy involves the development of an artefact to solve practical problems while providing a prescriptive scientific contribution (Holmström et al., 2009). In this study, the proposed artefact is a framework for SPMSs assessment based on the RE perspective. The framework was tested in an empirical study, carried out in a construction project in Norway. Besides the willingness of the company to take part in this research there were three criteria for choosing that construction project: (i) there had been no serious accidents along the previous four years, since the project started; (ii) decentralized safety management mechanisms, which allowed the involvement of front-line workers and supervisors from lower hierarchical ranks; and (iii) low use of subcontracted workers, which could contribute to more consistent behaviours and attitudes regarding safety performance. These criteria were interpreted as proxies of resilient performance, which therefore could make the artefact more relevant for the construction project.

3.2 Research design

The research process consisted of the proposition, application and evaluation of the framework for SPMSs assessment based on the RE perspective (Figure 1). The proposed framework integrates the findings from Peñaloza et al. (2020a) and Peñaloza et al. (2020b). This integration consists of using the five RE guidelines for assessing SPMSs as a link between RAG and TOE, which jointly provide a description of a construction project complexity.

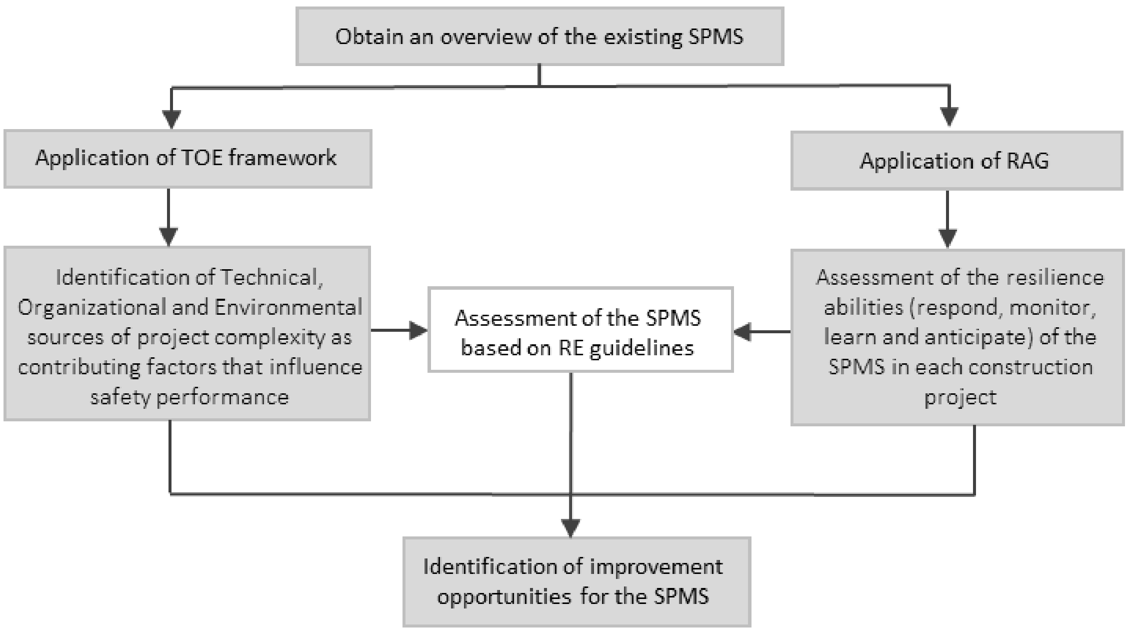

Figure 1 – Framework for SPMSs assessment based on the RE perspective

The application of the framework consisted of five stages: (i) obtain an overview the existing SPMS of the project; (ii) application of the TOE framework in order to understand how project complexity influences safety performance; (iii) assessment of the four resilience abilities by using RAG; (iv) assessment of the existing SPMS based on RE guidelines; and (v) identification of improvement opportunities. Based on the case study in Norway, the utility of the framework was assessed.

3.3 Data collection

Data collection followed five stages, corresponding to the framework´s elements presented in Figure 1. Stage (i) consisted of interviews in order to obtain an overview of the existing SPMS. Three semi-structured **interviews** were performed individually with the project manager, site manager, and safety coordinator, lasting on average one hour. Twenty questions related to the management of production and safety as well as performance measurement were applied. Also, concepts related to RE were introduced to the interviewees in order to establish a common ground. Two sessions of **participant observations** were carried out at this stage: one during a Gemba walk, lasting for two hours, and another during a short-term planning meeting, lasting one hour and a half. A Gemba walk is a management practice that is used by companies that implement Lean Production, in which people go to the place where the work is performed to understand how work is actually done (Womack, 2011). In the project investigated, once a week the safety coordinator randomly chose three workers and supervisors to join her in the Gemba walks. Also, safety related **documents** were analysed, including records of safety indicators, weekly safety reports, Health, Safety and Environment (HSE) deviations database, booklets, Job Safety Analysis, standardized operating procedures and the weekly work schedule. In general, those documents specified how the safety management system was expected to work from a legal and technical point of view.

Stage (ii) involved the application of **TOE** with the aim of investigating the most salient sources of project complexity that had an impact on safety performance (see Appendix A). It consisted of 50 questions across the technological (15 questions), organizational (21 questions), and environmental (14 questions) dimensions. Each question is associated with a source of complexity. The technical aspects account for interactions between technical processes, use of new technology, client requirements, quality specifications, variety and dependencies of tasks, as well as technical risks. The organizational aspects address the interfaces between design disciplines, the experience of the project stakeholders, availability of expertise and skills, contract types, resources, and organizational risks. The environmental dimension accounts for the interference with existing site, political and market influence, weather conditions and environmental risks, among others (Bosch-Rekveldt et al., 2011). Similarly to a previous application of TOE by Peñaloza et al. (2020b), complementary question to each TOE probe were added, as follows: *"does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects.*

In Stage (iii), an adaptation of **RAG** devised for construction projects by Peñaloza et al. (2020b), was used (see Appendix B). It consisted of 45 questions addressing 17 functions related to safety management and performance measurement. When answering the set of questions related to each function, the respondents were required to assign scores that indicated how well they thought the function was carried out. As suggested by Hollnagel (2017), scores were assigned in a six-point Likert-type scale: 0 (missing), 1 (deficient), 2 (unacceptable), 3 (acceptable), 4 (satisfactory), 5 (excellent).

TOE and **RAG** questionnaires were individually applied to a group of ten project participants: the project manager, the site manager, the safety coordinator, the foreman, and six front-line workers, including a team leader, a safety representative, and two carpenters and two concrete employees. These professionals were chosen for being strongly involved with both production and safety practices, such as planning, Gemba walks, and incident reporting. This approach differs from Peñaloza et al. (2020b), in which only the perspectives of production and safety managers were considered. Electronic and paper-based questionnaires – both in English and Norwegian language, were distributed to the participants so as they could choose one of these formats. The questionnaire had a brief introduction of core concepts, such as complexity sources and resilience abilities. After the examination of TOE and RAG findings, 13 sessions of **participant observations** provided additional data for the understanding of the complexity dimensions and resilience abilities. Seven of these were performed during Gemba walks, lasting on average two hours, in which the execution of concrete and timber activities was observed. Other six observations were performed during short-term planning meetings, lasting on average one hour.

In Stage (iv), the SPMS was assessed against the five **RE guidelines** based on the data collected from the previous stages. Next, based on the findings obtained from all stages, a set of improvement opportunities were devised for the SPMS (stage v). These opportunities were divided into three categories as suggested by Peñaloza et al. (2020b): new metrics for monitoring sources of complexity and resilience abilities; revision of existing metrics; and changes in other safety management sub-systems.

Table 2 provides a summary of the sources of evidence used along the research stages.

Table 2 – Overview of the sources of evidence

Sources of data	**Quantity**	**Research stages**				
		(i)	(ii)	(iii)	(iv)	(v)
Semi-structured interviews	3	x			x	x
Questionnaire to apply TOE framework	10		x		x	x
Questionnaire to apply RAG	10			x	x	x
Participant observations	15	x	x	x	x	x
Document analysis	7	x	x	x	x	x

Note: (i) obtain an overview the existing SPMS of the project; (ii) application of the TOE framework in order to understand how project complexity influences safety performance; (iii) assessment of the four resilience abilities by using RAG; (iv) assessment of the existing SPMS based on RE guidelines; and (v) identification of improvement opportunities.

3.3 Data analysis

Data from all sources were subjected to a content analysis (Pope et al., 2000), which encompassed transcripts from interviews, notes from observations and the excerpts of text identified from document analysis. The process of data analysis was structured in five themes (Table 3), each corresponding to a research stage previously presented in Figure 1.

Table 3 – Themes of data analysis

Themes of data analysis	**Exemplar information obtained from the sources of evidence**
Overview of the existing SPMS	Main activities of the SPMS, such as design and selection of indicators; collecting and analysing data; reporting and providing feedback; acting on findings (Kaplan and Norton, 1996; Neely et al., 2005).
Sources of project complexity that influence safety performance	Technical: project phases, construction methods, equipment/ machines, software. Organizational: composition of project teams, standards and procedures, behaviours, experience/skills.

<table>
<tr><td colspan="2"></td><td>Environmental: stakeholders, weather conditions, stability of exchange rates, raw material pricing</td></tr>
<tr><td colspan="2">The four resilience abilities</td><td>This assessment was based on a set of functions regarding the safety management practices and SPMS, such as: report and communication channels, learning style, mechanisms for problem-solving and action taking making</td></tr>
<tr><td rowspan="5">Assessment of SPMS based on RE guidelines</td><td>(1) SPMSs should support the monitoring of everyday variability</td><td>Indicators that provide information of work-as-done</td></tr>
<tr><td>(2) SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities.</td><td>Reporting mechanisms or indicators that provide real-time feedback.
Decentralization of data collection.</td></tr>
<tr><td>(3) SPMSs should facilitate learning from what goes well, in addition to what goes wrong</td><td>Indicators of desired outcomes (e.g. safe behaviours) and undesired outcomes (e.g. near misses, accidents). Organizational routines for sharing and discussing information from these indicators</td></tr>
<tr><td>(4) SPMSs should offer insights into the management of trade-offs between safety and other business dimensions</td><td>Organizational routines or indicators that support decision-making for coping with trade-offs (e.g. number of times that the stop work authority is exercised) between safety and other business dimensions</td></tr>
<tr><td>(5) SPMSs should evolve due to the changing nature of complex socio-technical systems</td><td>Changes or improvements made in SPMS with the aim to keep them up-to-date in a dynamic environment</td></tr>
<tr><td colspan="2">Improvement opportunities for the SPMS</td><td>Possibilities for adding new metrics to the SPMS or re-examining existing SPMS elements or producing changes in other safety management subsystems, accounting for the insights provided from RE guidelines, TOE and RAG assessments.</td></tr>
</table>

4. Results

4.1 Description of the project and safety management practices

The selected project belongs to one of the main construction companies in Scandinavia. The project involved eleven buildings to be built and delivered according to different deadlines over four years. During the development of this investigation, in 2019, seven out of 11 buildings were already inhabited – involving more than one hundred dwellers, while the other four were under different construction stages. There were various construction typologies, ranging from one to eight storey buildings, involving residential apartments, offices, and shops. These characteristics increased the circulation of people external to the construction site. Moreover, a number of technologies were used, such as cast in-place concrete, pre-fabricated concrete elements (e.g. balconies and beams), as well as wood and light steel frame.

Around 100 employees were working in this project at the moment of the study. The contractor´s own workers were divided into three teams - two for timber work and one for concrete. Each team was composed by a foreman, a team leader, a safety representative and around 15 front-line workers.

There was a collaborative planning system, based on the Last Planner System of Production Control (Ballard, 2000). This system increases planning reliability by assigning to the crews only work packages that have all necessary resources available, and therefore can be carried out (Ballard and Howell, 1998). The Last Planner System was implemented from the beginning of the project, involving seven planning and control levels. Figure 2 summarizes how the identification and evaluation of hazards were integrated to each planning level.

		Plan	Responsible	Setup	Safety management	Safety data source
Long-term planning	Level 1	Master schedule	- Project managers	Before project start-up	- Identify, visualize and communicate hazards in safety and envirmental plans	- Corporate database of past projects
	Level 2	Phase schedule	- Site manager - Safety coordinator	Phase schedule meeting	- Evaluate the level of risk on each construction phase - Identify hazards within activities - Visualize need for JSAs	- Corporate database of past projects - Risk assessment matrix
Medium-term planning	Level 3	Lookahead schedule (5 weeks)	- Site manager - Foreman - Safety coordinator	Operation meeting	- Detailing of activities - Identify and remove hazards - Communicate hazards between parallel activities - Decide which activities need JSAs	- Corporate database of past projects - HSE deviations database
Short-term planning	Level 4	Weekly work plan (2 weeks)	- Site manager - Foreman - Team leaders	Supervisors meeting	- Examine deviations and good practices reported - Identify and remove hazards - Examine activities for the upcoming week - Develop the required JSAs	- Weekly safety report - HSE deviations database
	Level 5	Team plan (upcoming week)				
	Level 6	Last check-out (every Monday or when necessary)	- Site manager - Safety coordinator - Foreman - All front-line workers including team leaders and safety representatives	Morning meeting, before operations start-up	- Examine deviations and good practices reported - Communicate hazards and risks - Decide final Team plan; - Encourage monitoring and reporting of HSE deviations	- Weekly safety report
	Level 7	Everyday operations	- Everyone	Daily conversations on site	- Encourage monitoring and reporting of HSE deviations - Feedback provided from managers or supervisors	- Safety app - Booklet - Gemba walks (Tuesday)

Figure 2 – Integration of safety management into the collaborative planning and control process

From levels 1 to 3, managers from top, middle and lower-levels made use of a corporate database of past projects and a risk assessment matrix in order to identify hazards and risks to be controlled.

From levels 4 to 6, managers from middle and lower-levels, in addition to front-line workers, made use of two main data sources to support planning meetings: the weekly safety report and the HSE deviation database. Weekly safety reports were performed during Gemba walks with the support of a safety app. Gemba walks were carried out once a week, lasting around two hours. Every week the safety coordinator randomly chooses three operational workers (e.g. foreman, team supervisors and front-line workers) to join him in the Gemba walks. The involvement of front-line employees not only provided an opportunity for learning from everyday work, but also helped the safety coordinator to build relationships and obtain direct feedback from them. During these walks, the safety app was used by the safety coordinator in order to take pictures and make short descriptions of both HSE deviations and good practices observed. In turn, the HSE deviation database consisted of the compilation of daily reports made by project participants. The HSE deviations were reported mostly through the safety app or through individual booklets that were available to all construction workers. The safety app allowed workers to record safety issues through the phone, make notes and then feed the HSE deviation database. The individual booklet was a pocket-size diary in which workers took notes of safety issues and delivered it to the managers or supervisors. Both tools had standardized fields such as the name of the reporter, date, hour, company, descriptions and keywords as well as the immediate corrective measures taken, if any. Each report was included in the database and the feedback from managers or supervisors to the involved parties was also documented. This database was mostly used by managers and supervisors in order to support medium and short-term planning meetings. However, the underlying causes of the events reported were underexplored.

4.2 Overview of the existing SPMS

Five safety indicators were collected on a monthly basis, namely: Accidents rate, Lost time injury rate, Attitude indicator, Focus indicator, and Housekeeping indicator. Two of these (Accidents rate and Lost time injury rate) are lagging indicators, while the other three are leading indicators. Table 4 presents the main characteristics of the SPMS.

Table 4 – Main characteristics of the existing SPMS

Safety indicators	Type	Sources of data collection
01. Accident frequency rate (AFR) $AFR = \frac{\text{Number of accidents x 1.000.000}}{\text{Total man hours}}$	Lagging	- HSE deviations database - Worksheet of total hours worked
02. Lost time injury rate (LTIR) $LTIR = \frac{\text{Number of lost time injuries x 1.000.000}}{\text{Total man hours}}$	Lagging	
03. Attitude indicator (AI) $AI = \frac{\text{Number of non confomities to HSE standard x 100}}{\text{Total number of HSE deviations reported}}$	Leading	- HSE deviations database
04. Focus indicator (FI) $FI = \frac{\text{Number of workers reporting HSE deviations}}{\text{Total number of workers}}$	Leading	- HSE deviations database - Monthly labour force data
05. Housekeeping indicator (HI) $TI = \frac{(a + b + c + d + e + f)}{\text{Total number of items}}$ Note: a = average score for temporary facilities b = average score for cleaning waste from using saw c = average score for materials and equipment not in use d = average score for storage and circulation areas e = average score for clearing own work f = average score for organized electrical cables	Leading	- Gemba walks

Although all indicators were collected on a monthly basis, the six items that formed the Housekeeping indicator were collected once a week during Gemba walks. Each item was assessed based on a scale ranging from 1 (very poor) to 7 (very good) and, therefore, the Housekeeping indicator was determined based on the monthly average of the six items.

The time lag for collection, analysis and processing of results varied from five to seven days. The results were processed separately for each building and disseminated by means of an electronic report to all project managers and supervisors. Another way of dissemination was a corporate system which summarized statistics for all construction projects of the company.

According to historical data of the project, only one serious injury had occurred on site since the beginning of the construction stage - from 2014 to 2019. The injury involved a cut in a worker's finger, which resulted in 14 days away from work. In turn, more than one thousand deviations were reported over four-years period of the construction project.

4.3 Sources of project complexity that influence safety performance

Table 5 presents four sources of project complexity, which were selected according to the criteria described in Section 3.4.

Table 5 – Sources of complexity that influence safety performance

Sources of complexity that influence safety performance		**Associated benefits or hazards**
T	Large number of simultaneous tasks at a certain phase of the project	**(+)** it encourages communication between production teams, supporting shared awareness of hazards; **(-)** it creates difficulties for housekeeping and waste sorting; **(-/+)** in order to compensate for missing components of scaffolds, workers performed adaptations that brought their own hazards
E	Interactions with dwellers and visitors to the buildings located in the construction site	**(-)** the inaccurate delimitation of public roads and sidewalks in in and around the construction site may lead outsiders to access hazardous areas
E	Inclement weather conditions	**(-)** slip and fall hazards arising from icy surfaces; **(-)** increased risk of damages to materials and equipment
O	Active collaboration and communication among project participants	**(+)** diversity of perspectives for making decisions (+) decentralized mechanisms for reporting

Note: **T**: technical; **O**: organizational; E: environmental **(+)** positive and **(-)** negative influence on safety performance

The **large number of simultaneous tasks at a certain phase of the project** was pointed out by all respondents to have influence on safety performance. As for the positive influence, the project manager reported that the parallel execution of structural works and exterior walls demanded coordination between the corresponding production teams. In his words, this implies "*extra-time in planning meetings to discuss critical tasks with the parties involved, before beginning any work*".

According to the site manager, the greater the number of simultaneous tasks, the more intense the communication between the interested parties. This communication was supported by booklets, safety app, Gemba walks, and collaborative planning meetings. These meetings also provided opportunities for information exchange between managers and front-line workers e.g. discussion of hazards stemming from simultaneous activities.

Regarding the negative influences of this source of complexity, the safety coordinator explained that the physical proximity of teams executing simultaneous tasks, sometimes, makes workers to neglect housekeeping and waste sorting. It means that precursor teams end up leaving the cleaning responsibility to the subsequent work team. Similarly, the team leader mentioned this source of complexity as one of the causes of the missing components of scaffolds. Scaffolds played a role both as work platforms and temporary edge protections, mostly during the construction of exterior walls. According to the team leader: "*sometimes the last team who uses it (scaffold) does not put all the components back at the storage area – therefore, when other workers need those components, they have to walk around the site to find them, and that takes time".* In order to cope with the aforementioned situation, workers used to make adaptations in the scaffolds, which allowed the continuity of work but created new hazards (Figure 3).

Figure 3 – Adaptations to compensate for the missing components of scaffolds. (a) pallets improvised as steps to access the working platform; (b) handmade stair to access the working platform

An environmental source of project complexity, namely the **interactions with dwellers and visitors to the buildings located in the construction site**, was also pointed out by all respondents to have an influence on safety. From a positive perspective, the site manager reported that:

"as the project progressed, the interactions with dwellers and visitors – e.g. in terms of incursions into dangerous or prohibited construction areas, led us to adapt the site plan in order to improve continuously the accessibility to the buildings in the site."

However, as the public roads and sidewalks in the construction site were changed regularly (e.g. for facilitating site logistics), their inaccurate delimitation could contribute to mistakes and unexpected behaviours from outsiders. The following report by that foreman illustrates that point:

"a neighbour entered the construction site because the fences were left open. He cycled into a trench because the sidewalk was blocked by cars. Furthermore, visitors commonly park in prohibited areas".

Similar reports were made by other interviewees. For example, the safety representative referred to the risks to the public when the construction site fences or gates are left open. This often occurred during the arrival or exit of deliveries from the site, in which the fences or gates, signals, and padlocks were removed and not replaced.

The **inclemency of weather conditions** was another environmental source considered by all respondents as negatively influencing safety performance. All examples given by participants were related to the winter period in which cycles of snow, rain and frost were common, resulting in slippery surfaces and damaging materials and equipment. The foreman, safety representative, team leader, and one front-line worker reported situations in this regard, such as workers which had slipped on ice and fallen on the elevator ramp while driving a trolley.

Concerning the sources of organizational complexity, the **active collaboration and effective communication among project participants** was pointed out by all respondents as having an influence on safety performance. The observations of daily activities and conversations during Gemba walks, in addition to routine planning meetings - by involving the content analysis of the HSE deviation database and weekly safety reports, were cited by respondents as the existing mechanisms that influenced positively the safety performance. It provided diverse perspectives for making decisions and supported decentralized mechanisms for reporting.

4.4 The four resilience abilities

4.4.1 Respond

Figure 4 presents the results of RAG for the “respond” ability. The average score for this ability was 2.9, considering ten respondents. Function 1 (use of indicators in safety and production planning meetings) had the lowest average score (0.8), indicating that the quantitative results of safety indicators rarely supported decision-making in collaborative planning meetings. However, the collaboration between front-line workers, supervisors, managers, and other departments (function 2) scored 4.9, reinforcing similar findings from the TOE application.

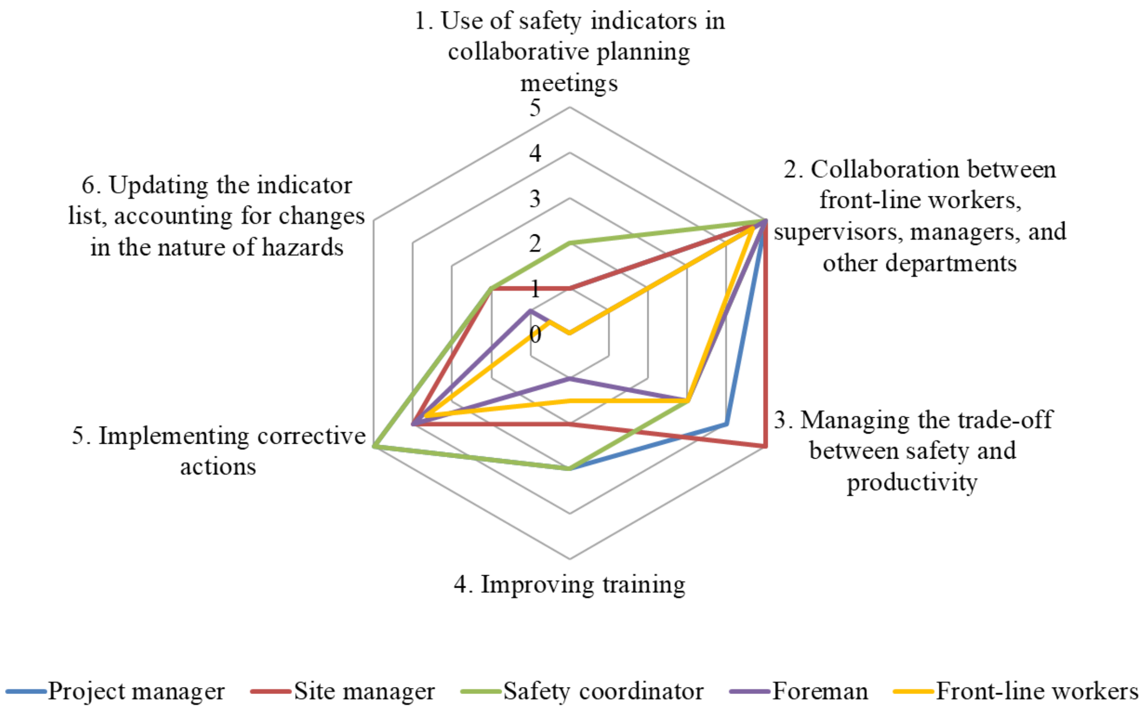

Figure 4 – Scores assigned to the "respond" ability

Function 3 (managing the trade-off between safety and productivity) scored 3.6. In general, respondents agreed that the stop work authority was put into practice in face of conflicts between safety and productivity. The project and site manager agreed that workers were encouraged to stop unsafe activities and have a "*safety conversation*". The site manager added that in these situations *"we sit down and find the best balance between safety and productivity"*. In turn, the safety coordinator reported that these conflicts often happened when *"there is a lot of sickness among teams (during the winter period) so, sometimes it gets very busy for some workers (increase in workload) and production goes ahead of safety"*.

4.4.2 Monitor

Figure 5 shows the assessment of the "monitor" ability. The average score for this ability was 3.4. All respondents recognized the importance of the safety app and booklets for monitoring the variability of everyday work (function 7, score 3.6). The site manager and safety coordinator also mentioned the importance of Gemba walks, as they provided "*opportunities for understanding the actual development of construction work"*.

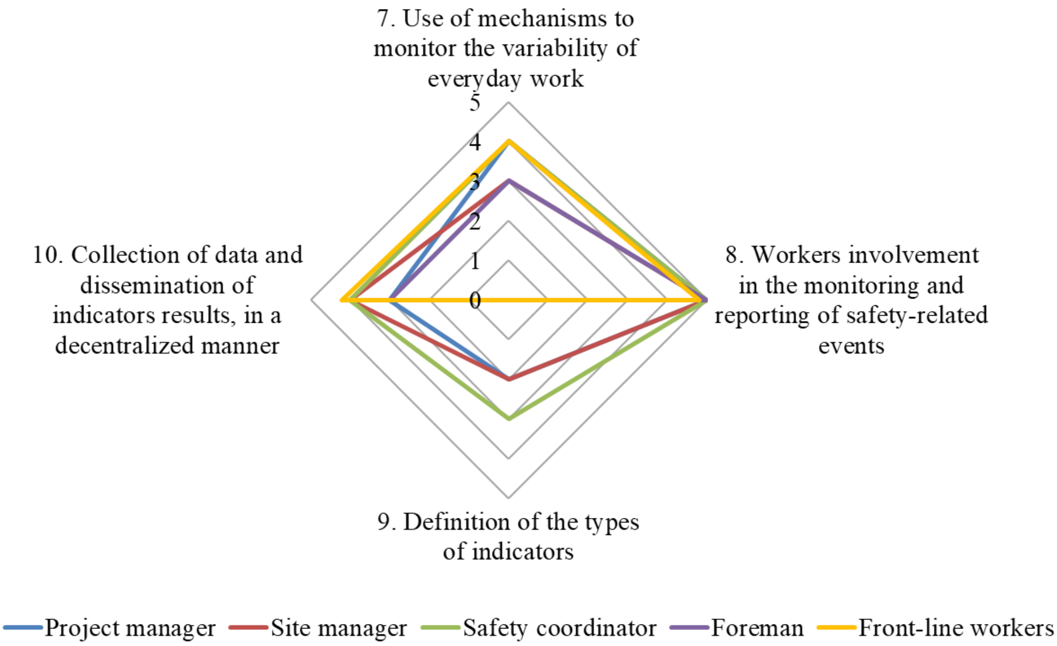

Figure 5 – Scores assigned to the "monitor" ability

The collection of data and dissemination of indicators results, in a decentralized way (function 10), also scored 3.6. However, the respondents strongly focused on practices that supported decentralized data collection across managerial and operational levels, such as the safety app, booklets or weekly work plans. Concerning function 9 (definition of the types of indicators, score 1.4) no responses were provided by the foreman and front-line workers. It suggests that although operational levels actively participated in data collection for some indicators, they were not aware of the reasons for choosing these metrics.

4.4.3 Learn

Figure 6 presents the assessment of the "learn" ability, which had an average score of 3.7. The respondents acknowledged that the frequency of learning from failures was higher than learning from success. According to the team leader, failures were interpreted as *"deviations from plans involving damages to people and goods"*. As for learning from successes, the project manager mentioned that a set of best practices from past projects, such as innovative construction methods, was compiled in a corporate database. In addition, he reported that *"close-up"* meetings were carried out when a project was complete and planning for a new project started. The purpose of these meetings was to gather feedback from front-line workers on improvement opportunities.

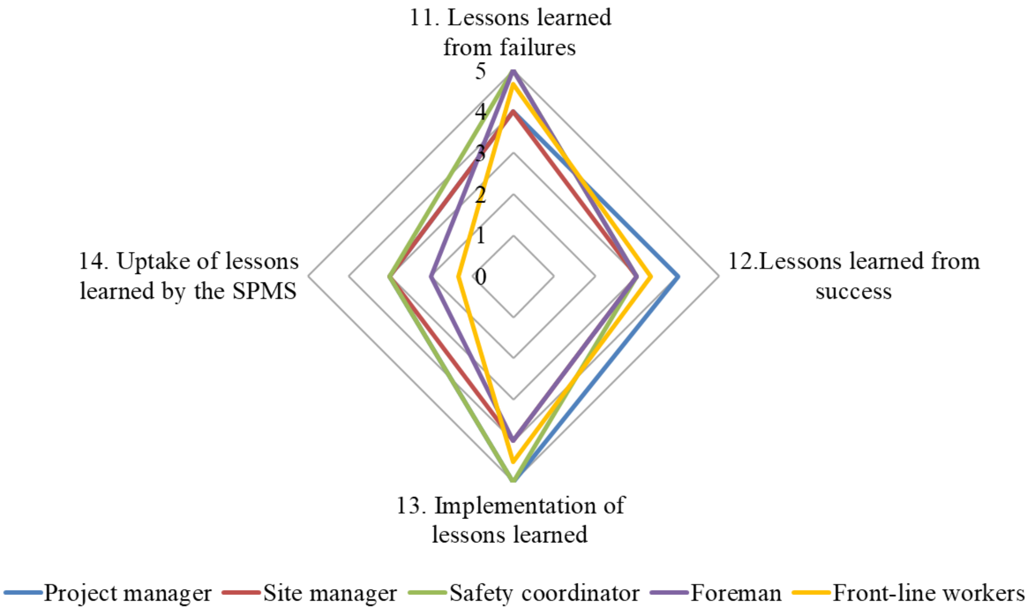

Figure 6 – Scores assigned to the "learn" ability

Therefore, the positive perception of the respondents about the implementation of the lessons learned (function 13, score 4.5) may stem from the close-up meetings. Function 14 (uptake of lessons learned by the SPMS) had low rating (2.4) and this may be consistent with the perception of the site manager, as he recognized that indicators results were mainly disseminated across managerial levels, rather than operational ranks.

4.4.4 Anticipate

Figure 7 shows the assessment of the "anticipate" ability, which had an average score of 3.5. On the one hand, all respondents had a very positive perception of function 15 (use of direct information from other departments to anticipate safety issues) and function 16 (opinions, suggestions and perceptions from workers considered in decision-making), which scored 4.3 and 4.6, respectively. In both functions, the role played by collaborative planning meetings was stressed. For example, the site manager and safety coordinator agreed on the importance of the look-ahead plan to anticipate safety issues: *"it (look-ahead plan) gives the chance to gather all necessary information concerning production, safety and environment in order to be prepared before execution"*.

From the viewpoint of the project manager, future threats and opportunities (function 17) were discussed during *"close-up"* meetings, while for the site manager and safety coordinator the look-ahead meetings had a crucial role. However, the low scoring given by front-line workers (0.5) suggested that they were not aware of the benefits of these practices in terms of recognizing the threats and opportunities that may develop in the near future.

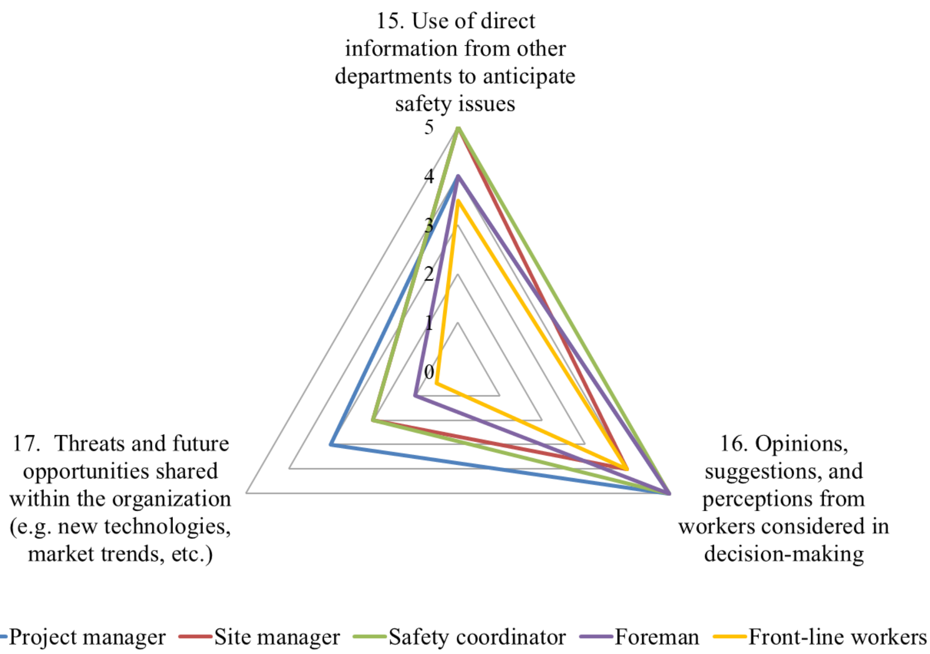

Figure 7 – Scores assigned to the "anticipate" ability

4.5 Assessment of the SPMS based on RE guidelines

4.5.1 SPMSs should support the monitoring of everyday variability

Two analysis emerged from the assessment of the SPMS against this guideline. Firstly, the process of data gathering for the attitude indicator, provided insights into the variability of everyday work. The data collected from this indicator shed light on both undesirable (i.e. non-compliances with HSE standards) and desirable everyday variability (i.e. immediate countermeasures taken by those who collected data). For instance, a front-line worker reported the impossibility of starting the assigned tasks due to ice covers on wall surfaces. As an immediate countermeasure, he described the use of steam for ice melting. In turn, the feedback provided by the supervisor was to "*consider the time of steam use on the wall, otherwise, consider safer mechanism for thawing*", but no alternative solutions have been described.

Secondly, an increase in the percentage of workers reporting HSE deviations (focus indicator) may indicate either a higher frequency of monitoring everyday variability or a wider dissemination of variability itself, to the point of being visibly by a larger number of potential reporters. A desirable performance of the focus indicator is when more than 50% of the total number of company own workers have reported HSE deviations. No formalized actions were taken if the percentage of reports decrease below target. However, the collaborative meetings played an important role for managers and supervisors in term of reinforcing the significance of communication and encouraging workers to report.

4.5.2 SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities

Real-time feedback used to be provided to those directly involved in production activities during Gemba walks. It allowed for observations of workers behaviours or conditions, immediately followed by feedback from the observer. Furthermore, the participants of Gemba walks provided feedback to dwellers and visitors who were in prohibited construction areas.

Other three mechanisms supported the provision of feedback, namely the safety app, the HSE deviation database, and the short-term planning attended by different stakeholders.

However, these three practices implied both a delay on the feedback provision and limited the feedback to managers and supervisors. For example, as the HSE deviation database was consulted mostly during weekly planning meetings, it provided feedback only to the participants involved in those meetings.

4.5.3 SPMSs should facilitate learning from what goes well, in addition to what goes wrong

The use of the weekly safety reports and the HSE deviation database in collaborative planning meetings, in addition to the Gemba walks, supported discussions about what went well and what went wrong on a daily and weekly basis. However, non-conformities with the standards were discussed more frequently than good practices.

As the Accidents and Lost time injury rates only accounted for losses, learning from them only accounted for what went wrong. Moreover, lessons learned from these two indicators were disseminated through a corporate database, reaching only managerial levels.

4.5.4 SPMSs should offer insight into the management of trade-offs between safety and other business dimensions

The housekeeping indicator provided quantitative evidence that the percentage of completed work packages (production indicator), at certain phases of the construction project, influenced the safety and environmental dimensions. However, there was no formal analysis of the correlation between these indicators.

Production work packages were set up in short-term planning meetings (level 4) and assigned to each team only when the packages have all necessary resources available, and therefore can be carried out.

During a two-months period, in one of the buildings, there were three construction phases being carried out in parallel: the structural phase, the exterior wall phase and the interior wall phase. However, as the completion of work packages in these three phases varied from 100% to 92% each week, the Housekeeping indicator decreased below target (≥ 6) 5,74 and 5,50. Similarly, the percentage of waste sorting (environmental indicator $\geq 90\%$)

decreased for the same period 68,11% and 73,03%. It indicates that a trade-off was being performed in which production prevailed over safety and environmental dimensions.

Besides, an increase in Accidents and Lost time injury rates, may indicate that production decisions prevail over safety. Nevertheless, the strong focus on the quantitative outcomes of these indicators do not help to understand the nature of trade-offs in everyday work.

4.5.5 SPMSs should evolve due to the changing nature of complex socio-technical systems

There was no evidence of formal mechanisms for updating the SPMS. However, it was observed that at certain phases of the construction project, some indicators were more relevant than others. For instance, during the parallel execution of critical phases, such as structural work and exterior wall activities, or during inclement weather conditions, managers reported to the researcher that the reporting of HSE deviations (focus indicators) was being reinforced in collaborative planning meeting and daily conversations on site. It indicates that communication between the involved parties play a significant role for monitoring and understanding the changing nature of every day construction work.

4.6 Improvement opportunities

Table 6 presents eight improvement opportunities identified based on the application of TOE, RAG, and RE guidelines. Although each opportunity may be related to different complexity sources and resilience abilities, the most salient relationships were listed. The improvement opportunities were divided into three categories:

(i) Design of new metrics (three opportunities): the new metrics might contribute to the monitoring and assessment of sources of complexity and resilience abilities that have been neglected in the studied construction project. For instance, there could be a metric to assess how safe the construction site is for dwellers and visitors, which findings pointed out as a relevant issue. This metric would account for a source of complexity (i.e. interactions with dwellers and visitors to the buildings located in the construction site) and for an existing resilient strategy (i.e. providing real-time feedback to dwellers and visitors who were in prohibited construction areas);

(ii) Revision of existing metrics (three opportunities): improvements of this type mostly imply the further analysis and reinterpretation of existing metrics. Although these metrics are quantitative, the qualitative information produced during data gathering may help to better understand how adaptations in plans and procedures contribute to desirable outcomes as well as provide insights into the management of trade-offs between safety and production. For example, the meaning of "HSE deviations", which is associated with the attitude and focus indicators, may be revisited by involving perspectives of various project participants and by accounting not only for hazards and failures, but also for deviations that contribute to successful performance.

(ii) Changes in other safety management subsystems, rather than in the SPMS (two opportunities): these changes imply the use of information gathered from SPMS as a basis for improvements in other safety management areas. For example, safety training programs and job safety analysis could benefit from an explicit consideration of the complexity sources, not only as threats (e.g. inclement weather) but also as assets (e.g. collaborative work) that should be further exploited by workers and managers.

Table 6 – Improvement opportunities identified from applying the proposed framework

Improvement opportunities	How is it related to the complexity sources?	How is it related to the resilience abilities?
(1) SPMSs should support the monitoring of everyday variability		
1. (NM) At a certain phase of the project, a formal model of work-as-done may lead to identify priority functions that contribute to desired outcomes. Then, candidate leading indicators can be associated to those functions – e.g. thawing or removing ice covers on surfaces by using safe methods.	By achieving balanced trade-offs between production and safety during the periods of inclement weather (environmental).	By identifying the available solutions or alternatives to cope with ice covers on surfaces involving managers, supervisors and front-line workers (*Monitoring)*.
2. (RM) The meaning of "HSE deviations" may be revisited by involving perspectives of various project participants and by accounting not only for hazards and failures, but also for deviations that contribute to successful performance.	By understanding the deviations arising from critical phases – e.g. the simultaneous execution of structural work and exterior wall activities (technical).	By discussing, in short-term planning meetings, the successful arrangements made by front-line workers (*Learning)*.
(2) SPMSs should provide feedback in real-time to those directly involved in the execution and supervision of production activities		
3. (RM) Definition of criteria for prioritizing production activities to be monitored in real-time	By considering the perspectives of the current group of participants involved in each Gemba walk (organizational).	By deciding in collaboration with supervisors and front-line workers the immediate corrective actions (*Responding)*.
4. (NM) Dwellers and visitors may be active agents for reporting and providing feedback in real-time. It may require new reporting mechanisms and a corresponding metric – e.g. number of reports from visitors and dwellers.	By accounting for the interactions with dwellers and visitors to the buildings located in the construction site (environmental).	By providing real-time feedback to dwellers and visitors who were in prohibited construction areas (*Monitoring).*
(3) SPMSs should facilitate learning from what goes well, in addition to what goes wrong		
5. (SM) Better exploit the collaborative planning meetings to explicitly discuss what goes well – e.g. after-action reviews.	By reviewing the performance of critical phases with the parties involved – e.g. the simultaneous execution of structural work and exterior wall activities (technical).	By understanding the variability of everyday work that lead to both desirable and undesirable outcomes (*Learning)*.
(4) SPMSs should offer insight into the management of trade-offs between safety and other business dimensions		
6. (RM) Analysis of the qualitative data produced from the collection of the safety indicators may provide insights into the management of trade-offs between safety and production.	Collaborative planning meetings offer an opportunity for the anticipation and discussion of trade-offs between safety and production (organizational)	By redesigning training and procedures, accounting for a variety of scenarios involving stop work decisions (*Responding)*.

7. (NM) The frequency of stop-work decisions may inform the balance between production and safety.	By understanding the nature of decisions taken during the periods of inclement weather conditions (environmental) or when the number of simultaneous tasks increase at a certain phase of the project (technical).	By managing the adequate balance between production and safety in collaborative planning meetings (*Responding)*.
(5) SPMSs should evolve due to the changing nature of complex socio-technical systems		
8. (SM) Definition of explicit criteria and frequency for updating the SPMS	By accounting for the positive and negative influence of complexity sources on safety performance (technical, organizational and environmental).	By discussing, in during close-up meetings, how the organization coped with changes over the project life cycle (*Anticipating)*.

Notes:
(NM) new metrics; (RM) revision of existing metrics; (SM) other safety management sub-systems

5. Discussion

An assumption of this study is that a SPMS aligned with the RE means that it is compatible with the complexity characteristics of the work environment. The findings from the case study offered insight into what that compatibility could look like.

In this respect, the joint application of TOE and RAG accounted for four attributes of complex systems widely described in literature (Saurin and Gonzalez, 2013; Hollnagel, 2012; Dekker et al., 2008; Cilliers, 1998) : (i) large number of dynamically interacting elements (Snowden and Boone, 2007), (ii) wide diversity of elements, (iii) unanticipated variability, and (iv) resilience.

On the one hand, TOE considered the first three attributes. Two sources of complexity are associated with a large number of dynamically interacting elements, namely the large number of simultaneous tasks at a certain phase of the project and the interactions with dwellers and visitors. The active collaboration and communication among project participants are clearly related to the wide diversity of elements, while the inclement weather conditions, is connected to unanticipated variability. On the other hand, RAG encompasses the fourth attribute of complexity, namely resilient performance and its corresponding four abilities: monitor, anticipate, learn, and respond.

Figure 9 shows the relationships between the four complexity attributes and the five RE guidelines for SPMSs assessment. These guidelines provide a conceptual and practical link between the complexity attributes and the SPMS, thus demonstrating how it might account for key contextual characteristics of construction projects. This is an important contribution as it translates into practice an idea that makes sense in theory but that lacks methods for implementation and investigation.

Some examples of how these relationships played out in the case study are described next. For instance, Figure 9 indicates that guideline 1 (supporting monitoring of everyday variability) is most clearly related to one complexity attribute (large number of elements in dynamic interactions) and one resilience ability (monitoring). Indeed, the case study demonstrated that the large number of simultaneous tasks at a certain phase of the project demanded a close monitoring of everyday variability, as this was amplified by unexpected interactions between production team working in the same area.

Similarly, guideline 2 (providing feedback in real-time) is also associated with the monitoring ability and the large number of dynamically interacting elements. However, this complexity attribute poses difficulties for providing feedback in real-time. For example, the decentralized mechanisms that encouraged workers to report HSE deviations (i.e. safety app, booklets, and collaborative planning meeting) produced lots of data, which were analysed by only one responsible, the safety coordinator. As a result, feedback to reporters used to be slow, or then only limited to managers and supervisors. Therefore, there was a mismatch between decentralized data collection and centralized data analysis and feedback.

Guideline 3 (learning from what goes well in addition to what goes wrong) is clearly related to the learning ability as well as to two complexity attributes (large number of elements in dynamic interactions, and wide diversity of elements). For instance, Gemba walks involved perspectives from different project participants, thus creating opportunities to understand what went well (e.g. countermeasures implemented on a previous Gemba walk were still in place) and what went wrong (e.g. non-compliances with standards). The Gemba walk seems to be an adequate practice to learn from what goes well, as it takes place "when" and "where" the work occurs involving people who are part of the work (Hollnagel, 2019).

The management of trade-offs between safety and other business dimensions (guideline 4) is related to the ability to respond and mostly associated with the complexity attribute unexpected variability of everyday work. As demonstrated in the case study, the unexpected interactions arising from the physical proximity of teams conducting simultaneous tasks created production pressures detrimental to safety (i.e. hindering housekeeping) and environmental dimensions (i.e. hindering waste sorting). Collaborative planning meetings played a role in both the creation of these production pressures and in managing them, as observed during the "last check-out" meetings (level 6). At this level, the site manager, foreman, safety coordinator and group of front-line workers reviewed the work plans before start operations as well as examined the deviations and good practices reported in the last week. Based on this, commitments were assigned and, when necessary, compensation strategies were discussed – e.g. rearrangement of timber teams to other construction areas in order to avoid risks (i.e. being struck by a fallen object) due to the proximity of their tasks with structural work activities.

Lastly, adapting the SPMS due to the changing nature of complex systems (guideline 5) is clearly related to the anticipating ability while benefiting from the wide diversity of elements, such as the participation of project participants from different organizational ranks in both collaborative meetings and Gemba walks. However, this potential was not fully untapped for the purpose of updating the SPMS across different construction stages. Indeed, during the eight months of the case study, no indicators were added to the SPMS and no existing indicator was removed from it. Data collection and analysis procedures also remained unchanged. Despite this, some existing indicators were more or less emphasized depending on project progress – e.g. more priority was given to the focus indicator during critical construction phases. These adjustments were made based on production plans, which allowed the anticipation of the changing nature of construction phases and their corresponding hazards.

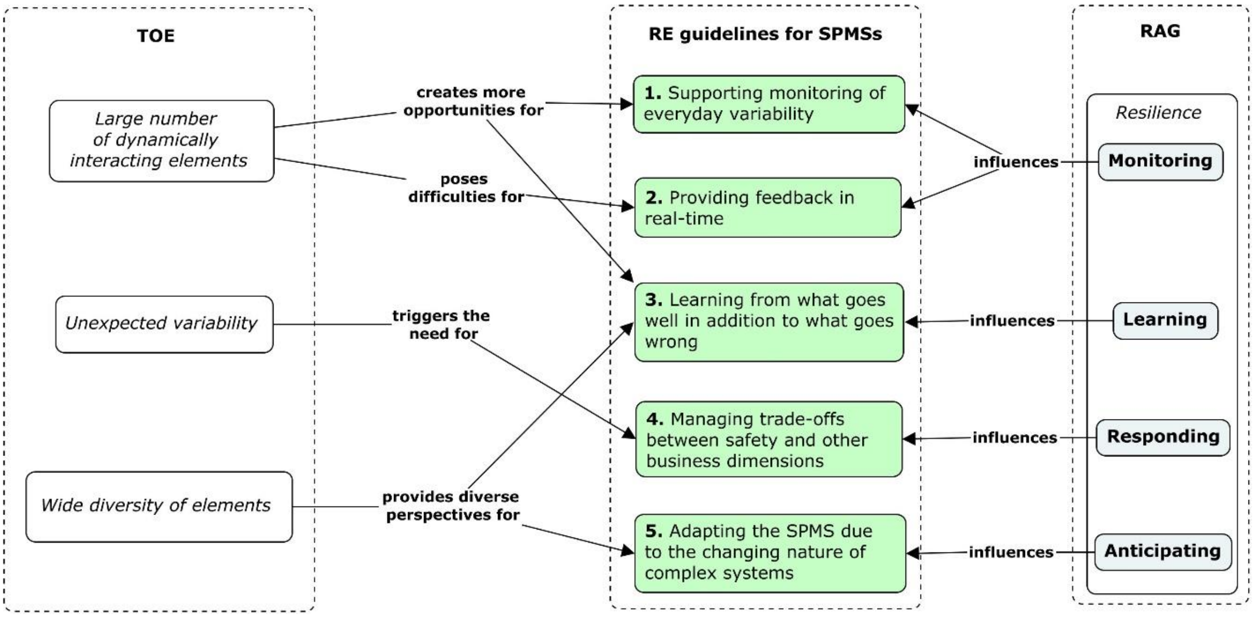

Figure 9 – RE guidelines as the link between TOE and RAG

6. Conclusions

Although construction projects are complex socio-technical systems, there is little guidance on how to assess whether existing management practices are consistent with that nature. This research study addressed this gap in the realm of safety performance measurement systems (SPMSs). Five resilience engineering (RE) guidelines were used as a proxy of what a SPMS compatible with complexity should look like. In order to produce data for the assessment of the guidelines, two existing tools were applied: the Technical, Organizational, and Environmental (TOE) framework, and the Resilience Assessment Grid (RAG). The practical utility of the proposed approach was demonstrated in a case study of a construction project. This case study highlighted the role of collaborative planning and decentralized data collection mechanisms, involving employees from different organizational ranks, for the emergence of safety and resilient performance.

Although the studied company had five safety performance indicators, these were not explicitly used as inputs in the formal production planning and control meetings, even though participants were likely aware of the indicators results and could implicitly account for these in decision-making. In fact, the process of data collection and subsequent feedback from managerial levels, suggested these were more important than the indicators themselves. Overall, this reinforces an initial assumption of this study, namely that a SPMS is more than a set of indicators; it is a participative managerial process that embodies the continuous improvement cycle. The case study also made it clear that the design and assessment of a SPMS must account for interactions with other management routines, such as production planning and control. This link has been underexplored by previous construction safety studies.

Some limitations of this study must be highlighted. First, the applicability of the guidelines in the assessment of the SPMS considering the whole project life-cycle was not addressed. Second, the improvement opportunities for the existing SPMS were not implemented and assessed in the scope of this study. Third, the application of TOE and RAG through a questionnaire format, without in-person contact with the researcher, limited the exploration of the underlying reasons for the answers.

Based on the insights from this research, as well as on its limitations, some opportunities for further studies have been identified: (i) to further explore the role of collaborative planning and decentralized safety management practices in the creation of safety and resilience in construction; (ii) to develop means for the further integration between the SPMS and production planning and control, using the proposed framework as a basis for establishing that integration; (iii) to test the utility of the framework in other SPMS; (iv) to test the use of other tools for complexity and resilience assessment, rather than TOE and RAG, for supporting the applicability of guidelines; (v) to develop indicators for assessing resilient performance in construction projects; and (vi) to assess existing construction safety management practices in light of the five RE guidelines, in order to assess their strengths and weaknesses from that perspective.

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Appendix A – Technical, Organizational and Environmental (TOE) framework. (adapted from Bosch-Rekveldt et al., 2011 and Peñaloza et al., 2020b).

1.	**The <u>Technological</u> dimension refers to "what" sources contributed to the complexity of the particular project. Please, select and describe the sources that contributed to the technical complexity and that have an influence on safety performance, according with your point of view.**
1.1	What is the number of strategic project goals? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.2	Are the project goals aligned? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.3	Are the project goals clear amongst the project team? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.4	What is the largeness of the scope, e.g. the number of official deliverables involved in the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.5	Are there uncertainties in the scope? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.6	Are there strict quality requirements regarding the project deliverables? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.7	What is the maxim number of tasks involved in a process? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.8	Does the project have a variety of tasks (e.g. different types of tasks)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.9	What is the number and nature of dependencies between the tasks? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.10	Are there uncertainties in the technical methods to be applied? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.11	To what extent do technical processes in this project have interrelations with existing processes? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.12	Are there conflicting design standards and country specific norms involved in the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects

1.13	Did the project make use of new technology, e.g. non-proven technology (technology which is new in the world, not only new to the company)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.14	Do the involved parties have experience with the technology involved? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
1.15	Do you consider the project being high risk (number, probability or impact of) in terms of technical risks? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.	**The Organizational dimension refers to "how" sources contributed to the complexity of the particular project. Please, select and describe the sources that contributed to the organizational complexity and that have an influence on safety performance, according with your point of view.**
2.1	What is the planned duration of the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.2	Do you expect compatibility issues regarding project management methodology or project management tools? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.3	What is the estimated financial investment of the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.4	What is the (expected) amount of engineering hours in the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.5	How many persons are within the project team? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.6	What is the size of the site area in square meters? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.7	How many site locations are involved in the project, including contractor sites? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.8	Is there strong project drive (cost, quality, schedule)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.9	Are the resources (materials, personnel) and skills required in the project, available? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.10	Do you have experience with the parties involved in the project (contractors, suppliers, etc.)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.11	Are involved parties aware of health, safety and environment (HSE) importance? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects

2.12 Are there interfaces between different disciplines involved in the project (mechanical, electrical, chemical, civil, finance, legal, communication, accounting, etc.) that could lead to interface problems? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.13 How many financial resources does the project have (e.g. own investment, bank investment, subsidies, etc.)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.14 Are there different main contract types involved? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.15 What is the number of different nationalities involved in the project team? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.16 How many different languages were used in the project for work related communication? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.17 Do you cooperate with partners in the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.18 How many overlapping office hours does the project have because of different time zones involved? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.19 Do you trust the project team members? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.20 Do you trust the contractor(s)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
2.21 Do you consider the project being high risk (number, probability or impact of) in terms of organizational risks? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3. The Environmental dimension refers to “who” sources contributed to the complexity of the particular project. Please, select and describe the sources that contributed to the organizational complexity and that have an influence on safety performance, according with your point of view.
3.1 What is the number of stakeholders (all internal and external parties around the table - e.g., project manager=1, project team=1, suppliers, contractors, governments)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.2 Do different stakeholders have different perspectives? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.3 What is the number and nature of dependencies on other stakeholders? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.4 Does the political situation influence the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects

3.5	Is there internal support (management support) for the project? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects.
3.6	What are the required local content requirements (policies imposed by governments that require firms to use domestically-manufactured goods or supplied services in order to operate in an economy)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.7	Do you expect interference with the current site or the current use of the (foreseen) project location? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.8	Do you expect unstable and/or extreme weather conditions; could they potentially influence the project progress? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.9	How remote is the location? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.10	Do the involved parties have experience in that country? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.11	Is there internal strategic pressure from the business? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.12	Is the project environment stable (e.g. exchange rates, raw material pricing)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.13	What is the level of competition (e.g. related to market conditions)? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects
3.14	Do you consider the project being high risk (number, probability or impact of) in terms of risk from the environment? Does this source of complexity influence safety performance? If yes, please specify how this influence plays out as well as its desired and undesired aspects

Appendix B – Resilience Assessment Grid (RAG) questionnaire (adapted from Hollnagel, 2011 and Peñaloza et al., 2020b).

Functions of the SPMS	**Questions** (please, mark with X the correct answer and give an example when necessary)	**How well this function is carried out?**
The ability to Respond means that the system is able to adapt to regular and irregular events (challenges and opportunities) in an effective and flexible way. It involves strategies for supporting successful performance, - e.g. deploying extra resources or identifying priority control areas.		
1. Use of indicators in safety and production planning meetings	1.1 Do results of safety indicators support decision-making in safety and production planning meetings? Yes ☐ No ☐	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	1.2 Which safety indicators are used in these meetings? Example:	
	1.3 How often are the indicators used in safety planning? Never ☐ Few times ☐ Sometimes ☐ Often ☐ Very often ☐	
	1.4 How often are the indicators used in production planning? Never ☐ Few times ☐ Sometimes ☐ Often ☐ Very often ☐	
2. Collaboration between front-line workers, supervisors, managers, and other departments (design, production, quality, etc.)	2.1 How are project participants involved in safety activities, such as job hazard analysis, planning meetings, and inspections? Example:	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	2.2 Who has the authority to stop work, without waiting for approval from site management? Example:	
	2.3 How is the stop work authority put into practice? Example:	
3. Managing the trade-off between safety and productivity	3.1 How are conflicts between safety and productivity managed? Example:	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	3.2 In which construction phases are these conflicts more likely to occur? Example:	
4. Improving training	4.1 Are the results from safety indicators used to improve training? How? Yes ☐ No ☐ Example:	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable)

		☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
5. Implementing corrective actions	5.1 How is the need for corrective actions identified? Example:	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	5.2 Who is responsible for implementing corrective actions? Example:	
	5.3 How fast can an effective response be implemented? Example:	
	5.4 How is the readiness (of workers and managers) to respond maintained and verified? Which type of training supports this readiness? Example:	
6. Updating the safety indicators list, accounting for changes in the nature of hazards	6.1 When was the list created? How often is it revised? Example: Never ☐ Few times ☐ Sometimes ☐ Often ☐ Very often ☐	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	6.2 Who is responsible for maintaining and evaluating the list? Example:	
Ability to <u>Monitor</u> means that the system is able to monitor internal and external conditions that may develop into challenges or opportunities. Effective monitoring can lead to increased readiness, thus, facilitating early responses and improving the use of resources.		
7. Use of mechanisms to monitor the variability of everyday work	7.1 Are there mechanisms for monitoring the variability of everyday work? Yes ☐ No ☐	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	7.2 Are there mechanisms for monitoring the subcontractors' safety performance? Yes ☐ No ☐	
8. Workers involvement in the monitoring and reporting of safety-related events	8.1 Are workers involved in the monitoring and reporting of safety-related events? Yes ☐ No ☐	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	8.2 Which practices support workers monitoring and reporting of safety-related events? Example:	

9. Definition of the types of indicators	9.1 How have safety indicators been defined (by analysis, by tradition, by industry consensus, by the regulator, by international standards, etc.)? Example:	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	9.2 What is the nature of the safety indicators? Qualitative or quantitative? (If quantitative, what kind of scaling is used?) Example:	
	9.3 How often are the safety indicators collected? Continuously, regularly, every now and then? Example:	
	9.4 How many of the safety indicators are leading, and how many are lagging? Example:	
10. Collection of data and dissemination of indicators results, in a decentralized manner	10.1 What is the delay between measurement, analysis, and interpretation? Example:	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	10.2 Are the results of safety indicators disseminated across all managerial and operational levels? Yes ☐ No ☐	
	10.3 Who is responsible for collection data and dissemination of results of safety indicators? Example:	
	10.4 Is there a regular scheme or schedule for collection of data and dissemination of results of safety indicators? Yes ☐ No ☐ Is it properly resourced? Yes ☐ No ☐	
The ability to <u>Learn</u> implies that the system is able to learn from past events and everyday work by understanding why things go right and why they go wrong and why.		
11. Lessons learned from failures	11.1 Does the organisation try to learn from failures? Yes ☐ No ☐	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	11.2 If yes, how are failures described? Example:	
	11.3 Are there any formal procedures for investigation and learning form failures? Yes ☐ No ☐	
12. Lessons learned from success	12.1 Does the organisation try to learn from success (e.g. things that goes well, successful adaptations of performance, good practices)? Yes ☐ No ☐	☐ 0 (missing) ☐ 1 (deficient) ☐ 2 (unacceptable) ☐ 3 (acceptable) ☐ 4 (satisfactory) ☐ 5 (excellent)
	12.2 If yes, how are successes described? Example:	
	12.3 Are there any formal procedures for investigation and learning from success? Yes ☐ No ☐	

<table>
<tr><td rowspan="3">13. Implementation of lessons learned (e.g. revision of procedures, redesign of tools, layout, etc.)</td><td>13.1 How are lessons learned translated into practical actions?
Example:</td><td rowspan="3">☐ 0 (missing)
☐ 1 (deficient)
☐ 2 (unacceptable)
☐ 3 (acceptable)
☐ 4 (satisfactory)
☐ 5 (excellent)</td></tr>
<tr><td>13.2 What is the delay between learning a lesson and translating it into practical actions?
Example:</td></tr>
<tr><td>13.3 How are these lessons communicated to the interested parties?
Example:</td></tr>
<tr><td rowspan="2">14. Uptake of lessons learned by the SPMS</td><td>14.1 How often is the SPMS evaluated, in order to check that it keeps being relevant in face of the evolving nature of the socio-technical system?
Never ☐ Few times ☐ Sometimes ☐ Often ☐ Very often ☐</td><td rowspan="2">☐ 0 (missing)
☐ 1 (deficient)
☐ 2 (unacceptable)
☐ 3 (acceptable)
☐ 4 (satisfactory)
☐ 5 (excellent)</td></tr>
<tr><td>14.2 How does learning help to develop a balanced SPMS that is at the same time complete and easy to use?
Example:</td></tr>
<tr><td colspan="3">The ability to <u>Anticipate</u> indicates that the system can anticipate challenges and opportunities in the near and far future. It implies in giving room to creative thinking by engaging people with diverse perspectives to anticipate knowledge or resources gaps and needs.</td></tr>
<tr><td rowspan="2">15. Use of direct information from design, production, quality and administrative departments to anticipate safety issues</td><td>15.1 Are indicators from other performance dimensions (e.g. quality, production, and cost) analysed from a safety perspective (e.g. providing input into safety planning meetings or risk analysis?
Yes ☐ No ☐</td><td rowspan="2">☐ 0 (missing)
☐ 1 (deficient)
☐ 2 (unacceptable)
☐ 3 (acceptable)
☐ 4 (satisfactory)
☐ 5 (excellent)</td></tr>
<tr><td>15.2 If yes, which kind of indicators?
Example:</td></tr>
<tr><td rowspan="2">16. Opinions, suggestions, and perceptions from workers considered in decision-making</td><td>16.1 How are opinions, suggestions, and perceptions from workers considered in decision-making related to safety?
Example:</td><td rowspan="2">☐ 0 (missing)
☐ 1 (deficient)
☐ 2 (unacceptable)
☐ 3 (acceptable)
☐ 4 (satisfactory)
☐ 5 (excellent)</td></tr>
<tr><td>16.2 How do these opinions, suggestions, and perceptions from workers support the anticipation of hazards?
Example:</td></tr>
<tr><td rowspan="2">17. Threats and future opportunities shared within the organization (e.g. new technologies, market trends, etc.)</td><td>17.1 Is information related to threats and future opportunities shared within the organization?
Yes ☐ No ☐</td><td rowspan="2">☐ 0 (missing)
☐ 1 (deficient)
☐ 2 (unacceptable)
☐ 3 (acceptable)
☐ 4 (satisfactory)
☐ 5 (excellent)</td></tr>
<tr><td>17.2 If yes, which tools and practices support this information sharing?
Example:</td></tr>
</table>

5. CONCLUSIONS

5.1 CONTRIBUTIONS OF THIS THESIS

The research conducted in this doctoral thesis was originated from a gap in literature concerning with how to use the RE perspective to assess SPMSs in construction. It was recognized that, even unintentionally, the existing SPMSs have partially adopted some core ideas of RE e.g. through the development of an organizational culture that values learning from what goes well. Moreover, it was acknowledged that systems-based perspective of performance measurement may contribute to the adoption of RE, and vice versa. As RE is concerned with the four abilities of resilient systems (monitoring, anticipating, responding, and learning) these can be logically associated with the whole cycle of defining, collecting, and learning from metrics.

The aim of this thesis is to propose a framework to assess SPMS for construction projects based on the RE perspective. One of the main contributions of this investigation is the variety of practical approaches adopted for the measurement of safety performance that were identified through the assessment of RE guidelines on previous SPMSs research (chapter 2). It may contribute to knowledge by providing a reference for researchers and practitioners interested in designing SPMSs based on RE. However, as the number of studies associated with strong alignment with the guidelines was low, this investigation has suggested that RE is far from being mainstream in SPMSs research, despite offering a new perspective.

Another contribution is the application of TOE to explore the influence of sources of complexity on safety performance and the adaptation of RAG for construction projects (chapter 3). Although RAG has been applied in different sectors, RAG was applied in this investigation for the first time in the construction sector. In addition, the combined use of TOE and RAG was another original contribution of this research, as these tools provided a holistic account of SPMS from the project complexity and resilience engineering perspectives. It may imply a comprehensive safety strategy – e.g. by encouraging project participants to think in terms of complex interactions that exist in construction projects, accounting for the emergence of both threats and opportunities.

The empirical orientation of this thesis also contributed to shed light on the utility of the proposed framework (chapter 4). As previous studies do not make it clear how to assess SPMSs based on the RE perspective, nor how it can be translated into practice, the framework was tested in a construction site based on interviews, observations, and analysis of documents. This application pointed out exemplar approaches for applying RE ideas to SPMSs as well as demonstrated how complexity may either hinder or support a SPMS.

Still, there are fundamental concepts related to RE that need to be explored and refined in the context of construction projects such as, “everyday variability”, “what goes well” and “trade-off decisions”. Moreover, the proposed framework may establish an integration between the SPMS and production planning and control, by assisting the organizations to grasp the context specific nature of the relationships between complexity, resilience and safety measurement over the construction project life cycle. Based on these interactions, SPMSs could be continuously revised and improved in order to maintain successful performance and promote desired outcomes.

5.2 LIMITATIONS

Some limitations of this thesis must be highlighted. First, there might be other guidelines or approaches that could be useful for SPMSs and complementary to RE, such as the principles of High Reliability Organization (HRO). The literature of RE and HRO demonstrated similar orientations in the ways of approaching safety, which might benefit the use of SPMSs – e.g. in high-risk organizations. Second, the limited number of empirical studies conducted in this thesis might not accurately represent the real diversity and approaches for SPMSs. Third, the improvement opportunities proposed for each SPMS were not implemented in the studied construction project nor assessed by the participants.

5.3 SUGGESTIONS FOR FUTURE RESEARCH

Further research could address the utility and applicability of the conceptual framework in the design or evaluation of SPMSs, considering different sectors, with distinct complexity characteristics. These are some suggestions that came out from this investigation:

(i) to extend the set of RE guidelines by exploring other RE principles suggested in literature, such as "graceful extensibility" or "sustained adaptability" taxonomies coined by Woods (2015);

(ii) to test the utility of the framework in other SPMSs as well as to test the use of other tools for complexity and resilience assessment, besides TOE and RAG, for supporting the applicability of guidelines;

(iii) to explore the contribution of other performance measurement systems (e.g. quality, production, environment) for the monitoring of sources of complexity and resilience;

(iv) to follow the evolution of resilience and complexity accounting along the whole project life cycle. This may point out priority areas in which each guideline become relevant;

(v) to further explore the role of collaborative planning and decentralized safety management practices in the creation of safety and resilience in construction. As observed in the studies carried out, the Last Planner System and Gemba walks may facilitate the understanding of everyday construction variability and may assist learning from what goes well;

(vi) to assess existing construction safety management practices in light of the five RE guidelines, in order to assess their strengths and weaknesses from that perspective;

(vii) to refine RE related concepts as well as to develop RE taxonomies within the context of the construction project – e.g. accounting for both threats and opportunities concerning "HSE deviations" or the classification of qualitative data produced form the collection of safety indicators, according with the five RE guidelines.

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