Peñaloza, G. A., Formoso C. T., and Saurin T. A. (2017). "Safety Performance Measurement Systems Based on Resilience Engineering" In: LC3 2017 Volume II – Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC),Walsh, K., Sacks, R., Brilakis, I. (eds.), Heraklion, Greece, pp. 903–910. DOI: https://doi.org/10.24928/2017/0326

SAFETY PERFORMANCE MEASUREMENT SYSTEMS BASED ON RESILIENCE ENGINEERING: A LITERATURE REVIEW

Guillermina A. Peñaloza[1], Carlos T.Formoso[2], and Tarcisio A. Saurin[3]

Abstract: The emergence of new technologies and new types of risks, in which the relationships between people and technology are complex and dynamic, challenge the models and techniques that have been used to measure safety performance. Traditional approaches are usually reactive and have little predictive value. Thus, this study discusses the design of safety performance measurement systems based on the Resilience Engineering paradigm, so that these are capable of monitoring and managing risks continuously throughout the life-cycle of the system. Resilience Engineering is relevant from the Lean perspective because it is useful to devise ways to balance safety and efficiency pressures, which otherwise can contribute to wastes and accidents. This paper presents the preliminary results of a systematic literature review of principles for designing safety performance measurement systems based on the Resilience Engineering paradigm. Five principles were identified: management commitment, awareness, anticipation, continuous learning and flexibility.

Keywords: safety performance measurement, resilience engineering, systematic literature review

1 INTRODUCTION

Safety performance measurement is an essential part of safety management systems, since it provides information on the performance of those systems, with the aim of supporting decision-making on safety issues. Traditional approaches to measure safety performance are based on statistical analysis of retrospective or lagging indicators, such as number of injuries, accident rates, accident costs and damages associated to poor safety performance (Sgourou et al., 2010). Lagging indicators are related to reactive monitoring, measuring the occurrence of unwanted events and undesired safety outcomes (Øien et al., 2011). Frequently, companies choose indicators that facilitate benchmarking with other organizations or that provide results in the short-term, often resulting in performance measurement systems that do not support decision-making related to the company strategies and to critical processes (Lantelme and Formoso, 2000). Those traditional approaches have been criticized for having little predictive value and for being of little use to drive system improvements (Carder and Ragan, 2003).

Moreover, there is an increasing complexity in many industrial operations, due to the growing number of different players and interdependences, and uncertainty both in processes and goals, which have a strong influence on the final safety outcomes. In turn, the emergence of new technologies and new types of risks challenge the models and

[1] PhD student at NORIE/UFRGS - Built Environment Innovation Unit, Federal University of Rio Grande do Sul. Av. Osvaldo Aranha, 99. Porto Alegre, 3o andar, RS, Brazil. CEP 90035-190. +55 51 33083518 arq.guillerminapenaloza@gmail.com

[2] Professor at NORIE /UFRGS formoso@ufrgs.br

[3] Associate at the Industrial Engineering and Transportation Department, UFRGS. saurin@ufrgs.br

techniques traditionally used to measure safety performance. The Systems' Theory perspective suggests that, in organizations whose stability is dynamically emergent rather than structurally inherent, safety is something that a system does rather than something that a system has, so accidents emerge from the complexity of people's activities in an organizational and technical context (Hollnagel et al., 2006). Although several scientific publications and industrial guidelines have proposed sets of indicators (e.g.: HSE, OECD, CCPS, OSHAS), there are different theories and models that can underlie safety performance measurement systems. Most of the traditional approaches to measure safety performance are based on the assumption that safety can be increased by guaranteeing the reliability of the individual system components (human as well as machine), and that if components or layers of defence do not fail, then accidents will not occur (Leveson, 2011).

In recent years, emphasis has shifted to system approaches driving the focus of safety to interactions between human, technology and environment (Dekker et al., 2009). Resilience Engineering is in line with this approach, being associated with the organization's ability to learn and adapt by creating safety in an environment of failures and losses while compensating decisions and multiple objectives (Hollnagel et al., 2006; Wreathall, 2006). Resilience Engineering has been a recurrent topic into IGLC community related to safety, uncertainty and variability of construction projects (Schafer et al., 2008; Leino and Helfenstein, 2012; Saurin et al., 2013; Saurin and Sanches, 2014; Saurin, 2015). From a lean perspective, all accidents are waste and add no value to clients. In turn, accidents add variability to the production process resulting in disruptions to the workflow. Resilience Engineering is aligned with the Lean perspective, as it look for evidence on how people at work fill the gaps in plans to create safety in a context of increasing production demands that needs reliable workflows. This paper presents preliminary results of a systematic literature review on principles to design a safety performance measurement system based on the Resilience Engineering paradigm. This systematic literature review considered papers published over the last 10 years.

2 RESEARCH METHOD

The research question that guided this systematic literature review was: What principles to design a Safety Performance Measurement System are based on the Resilience Engineering paradigm? The first search was carried out on 6 databases: Science Direct, Web of Science, Scopus, Taylor and Francis Online, American Society of Civil Engineers and Emerald Full Text. These databases include the main journals on Safety Management and Resilience Engineering. The keywords used in the databases were: Safety Performance (Safety and (measurement system or measures)); Principles (or criteria or attributes) and Resilience (or Resilience engineering). Initially, 102 papers were selected. Inclusion and exclusion criteria were then applied in relation to the title and summary of the papers in order to refine the selection list. For inclusion, the articles had to be written in English, focus on a set of measures or criteria for safety performance measurement and introduce the concept or foundations of Resilience Engineering. The excluded papers focused on other aspects of "safety performance measurement" or "resilience", for example, referring to composite properties of materials, stability of skeletal structures, among others. After this refinement, 63 articles were selected. A second analysis was then carried out, based on the field of application, method and findings. A literature coding was performed in a database, including: paper title, publication year of each paper, journal title, country or region (in which the studies were conducted) and principles or criteria of resilience engineering. The first round of evaluation over the principles was performed by the first author, and it was cross checked by the third author by random sampling. In case of discrepancies, authors discussed to arrive at a consensus and replicated the same decision rules across all the papers collected. Out of the 63 articles, 27 were finally selected.

3 RESULTS

3.1 Data analysis

Regarding the origin of papers, 17 papers came from the United States, United Kingdom, Norway and Brazil, 5 came from Iran, Denmark and Sweden, and 5 papers came from, Netherlands, Australia, Lebanon, Poland and Spain respectively. The data analysis also indicated that the resilience engineering paradigm has become increasingly adopted in the last 10 years, especially since the first Resilience Engineering Symposium in 2006, as those events concentrate a large number of studies in this area. Concerning to the journals, 27% of them came from Safety Science, 16% from Reliability Engineering and System Safety, 14% from Journal of Loss Prevention in the Process Industries, 12% from Journal of Safety Research, 10% from International Journal of Industrial Ergonomics and 10% from Cognition, Technology & Work. The remaining 11% are from symposiums proceedings. Another characteristic of the analysis is that the majority (68%) of the papers were based on qualitative approaches and empirical data. Other significant result of the systematic literature review is concerned with the different areas of expertise found.

The distribution of principles is across six domains such as: chemical and petrochemical industry (28%), aviation and air transport (25%), nuclear power and electricity distributor (21%), railways and road transport (12%). Those domains are well-known for their complexity and hazardous technologies, which make them, target fields for the use of resilience engineering. Nevertheless, other domains regarded as complex are still under explored, such as construction (8%), manufacturing industry and health care (6%). Thus, five principles of resilience engineering have a broad consensus across the domains as contributors to improve safety performance because they are able to identify potential concerns, focus on proactive aspects of safety rather than only reactive, identify vulnerabilities and provide information about effectiveness of safety management, such as: management commitment, awareness, anticipation, continuous learning and flexibility (Table 1).

Table 1: Resilience engineering principles to improve safety performance

Study	MC	AW	AN	LR	FL
Flin (2006)	x	x			
Wrethall (2006)	x	x		x	x
Hale and Heijer (2006)		x			
Woods (2006)	x	x		x	
Leveson et al. (2006)		x	x	x	
Hollnagel et al. (2006)		x	x	x	
Dijkstra (2007)	x		x	x	
Carvalho et al. (2008)	x		x	x	x
Costella et al. (2008)	x	x		x	x
Dekker et al. (2009)		x	x	x	x
Johnsen et al. (2009)	x	x	x	x	
Øien et al. (2010)	x	x	x	x	x
Lekka and Sugden (2011)	x	x	x	x	
Dinh et al. (2012)	x				x
Huber et al. (2012)	x	x		x	x
Shirali et al. (2012)	x	x		x	
Saurin and Carim Junior (2012)	x	x		x	x
Saurin et al. (2013)	x	x		x	x
Shirali et al. (2013)	x	x		x	x
Woltjer et al. (2013)			x		x
Vincent et al. (2013)			x	x	
Saurin et al. (2014)		x	x	x	x
Azadeh and Zarrin (2015)	x	x		x	x
Labaka et al (2015)	x	x	x	x	
Peciłło (2015)	x	x	x	x	
Ray-Sannerud et al. (2015)			x	x	
Wehbe et al. (2016)	x	x		x	

MC management commitment; AW awareness; AN anticipation; LR learning; FL flexibility

3.1.1 Top Management Commitment is essential for an effective Safety Performance Measurement System (SPMS)

One core principle for effectively measuring safety performance is having the commitment of top management, in which safety is considered as one of the main goals of the organization (Rasmussen and Svedung, 2000). Recent studies in the aviation and air transport industry suggest that manager's commitment should be based on a systemic approach so that all the interactions between system components and external factors are considered. It is necessary to model how the system elements and activities interact to produce the expected safety outcomes, identifying the strengths and weaknesses of the system (Leveson, 2004; Woltjer et al., 2013). In an empirical study in construction industry, Saurin et al. (2013) suggest that safety management is inseparable from the management of other dimensions of the organization, such as production management. In this sense, management commitment in all dimensions of the organization can contribute, for example, to assess the trade-off between safety and production. Studies in the petrochemical industry (Lekka and Sugden, 2011; Azadeh and Zarrin, 2015) described situations in which workers and senior management were genuinely committed to improve safety. In that context, the leadership of top managers and their commitment to safety have resulted into effective initiatives, such as re-designing the organisation procedures and the development of measures to monitor management commitment (e.g. resources invested in safety; decisions informed by safety concerns rather than production, among others).

3.1.2 The SPMS should enhance the system awareness of variability

Managers and employees should be aware of the current state of the defences in the working environment as well as the system's boundaries (Hollnagel et al., 2006). In a study undertaken in the manufacturing industry, Costella et al. (2009) concluded that awareness is critical for the assessment of sacrifice judgments and for the anticipation of future changes in the environment. Results from interviews indicated the lack of support by managers and resources, and the lack of awareness of some hazards resulted in the absence of safety planning from the early conception of products and processes. Based on a study carried out in the chemical industry, Shirali et al. (2013) proposed, an indicator that attempts to measure the degree of awareness, based on a survey, (e.g. awareness of organizational, human and technological risks and awareness of all safe ways to do a job). The study of Lekka and Sugden (2011) in an Oil refinery highlights good practices to increase the levels of awareness. For instance, the organization provided safety awareness workshops, which contributed to the consciousness of the differences between process safety (described in terms of ‘leaks’ or ‘spills’) and occupational health and safety (such as trips or slips). Another initiative identified in that investigation was renewing the procedure system, drawing on relevant national and international guidelines, clarifying the purpose of the different types of procedures and training staff in writing procedures to ensure that the documents were clear and brief. This process led to a reduction in the number of procedures (from 14,000 to 1000) and an acknowledgment that the procedures were an accurate reflection of the job. Huber et al. (2012) devised a method for develop safety and resilience indicators for an air taxi system. The principle of awareness was the basis of some indicators such as: information sources to assess the current state of operations, and frequency for updating information about the current state of operations.

3.1.3 The SPMS must offer insights into how to deal with the unexpected

This principle is related to the principle of awareness, as anticipating threats and the preparation for coping with them is necessary to be aware on the performance of the system and the state of the barriers against accidents. Awareness also allows the anticipation of changes in risk situations. Wehbe et al. (2016) evaluated the safety performance and network resilience to risks by studying safety interactions among the construction team in three mega-projects in Middle East. Results indicated that networks with better interaction and structure have higher resilience to anticipate risks. In the chemical industry, Shirali et al. (2013) proposed some measures related to this principle such as: workshops in the areas of safety and resilience to expect potential problems in the future. The results of the interviews revealed that many units did not have a comprehensive plan to cope with failures related to the future. The study of Dinh et al. (2012) in the chemical industry assessed the resilience of a design process or operation by using a set of measures: ability to recognize abnormal conditions and execute appropriate actions; number of re-design processes; number of safety needs during an operation; inherently safer design to neutralize potential failures (e.g. interlocks); among others. Øien et al. (2010) proposed a method for the development of early warning indicators based on Resilience Engineering for the offshore industry. Potential indicators were proposed in a series of workshops with scientists with various backgrounds (engineering, psychology, organizational theory and human factors). The early warning indicators regarded to anticipation were: risk and hazard identification; lessons learned from own and others experiences and accidents.

3.1.4 The SPMS should encourage Continuous Learning not only from incidents, but also from normal work

According to Reason (1995), the best way of minimizing failures is by learning how to detect and assess the significance of latent failures before they combine with other contributors to produce unwanted outcomes. Pęciłło (2015) assessed the learning level of six manufacturing enterprises in Poland, through a set of questions based on resilience principles. That study concluded that values of learning level did not have significant variation in enterprises with occupational health and safety management system and without it. This reveals that learning referred not only to the procedures and motivation programs, but also to the significance of the participation in the learning process. Lekka and Sugden (2011) applied a qualitative approach to explore the types of resilience practices implemented in an oil refinery in the United Kingdom. That organization was working towards a learning organization by encouraging incident reporting and systematically analysing near misses and incidents. For instance, to ensure that accidents and near misses were communicated to staff across all hierarchical levels, toolbox talks were implemented. They were used as a means of disseminating the key learning points arising from previous incidents to the workforce. The organization also had corporate systems in place to capture and share knowledge about past incidents, such as a repository of root cause analysis.

3.1.5 The SPMS should monitor the System´s abilities to adjust to variability

Some authors refer to this principle as flexibility, while others refer as adaptive capacity and redundancy. Woltjer et al. (2013) in the air traffic sector, define adaptive capacity as the flexibility to get the information that enable attention management, problem detection and balance goals using different means and methods. Costella et al. (2008) and Saurin et al. (2013), adopt this principle arguing that, since resilience engineering assumes that error are inevitable, the system must be tolerant to them and should be able to discern between positive and negative variability, so that the former is reinforced, and the second, minimized. Costella et al. (2008), in the manufacturing industry, indicate the lack of flexibility in the absence of fail-safe devices in machines with the highest risks, which would make the limits error-tolerant. Saurin et al. (2013), conclude that the system design should support the natural human strategies for coping with hazards, rather than enforce a particular strategy. This implies studying what people actually do and then considering whether it is possible to support that through design. For instance, a mechanism to comply with this principle is to design error-tolerant boundaries, adapt procedures through the differences in the execution method specified in trainings and the methods used in practice, and encourage autonomy of the teams to make important decisions without having to wait for management instructions. Johnsen et al. (2009) in railway sector adopt the principle of flexibility as the redundancy of the system in having different ways of performing a function. Some recommendations were developed, in order to improve flexibility such as, redundancy implemented in technology (e.g. the GSM-R switch used to transmit data between trains and railway regulation centres) and redundancy in organizational or human abilities (e.g. by increasing permanent manning in safety critical areas, improve common mental models of risks between stakeholders and prioritize daily training, in order to increase knowledge, experience and flexibility).

4 Discussion and Conclusions

This paper discusses how the Resilience Engineering paradigm can contribute to improve safety performance measurement systems, by proposing a set of principles to design them. The literature review pointed out that this paradigm is a way to understand how people create safety in complex systems, especially in contexts of growing uncertainty, by developing capacities to anticipate and absorb pressures under variations.

The principles proposed complement criteria that any performance measurement system should meet (e.g. the need for indicators to have goals or targets; develop indicators simple and easy to use) (Kaplan and Norton, 1992; Neely, 1999; Lantelme and Formoso, 2000; Bourne and Neely 2003). However, those generic criteria do not address the particularities of safety and place more emphasis on the design of specific indicators (often inconsistent with company strategy), rather than address the overall design of the performance measurement system. Five resilience engineering principles have been explored in studies carried out in different industries to improve safety performance: management commitment, awareness, anticipation, continuous learning and flexibility. Those principles are interrelated and reinforce the need to design and use measurement in continuous improvement cycle as the lean thinking advocates. It also set up the possibility to embrace both paradigms towards better levels of safety performance. The principles of management commitment in a systemic approach and awareness are aligned to the lean principle which aims the whole system optimization though a broad thinking rather than local optimizations. To achieve this, the company must to be aware of the state of the safety defences and system's boundaries. The commitment and awareness in all dimensions of the organization can contribute to assess the trade-off between safety and production as well as to identify issues and problems related to human performance to take appropriate decisions to eliminate or limit them. One key factor to assess the trade-off between safety and production could be thought risk management concept by proactively managing and understanding the various types of risks.

Because awareness allows the anticipation of constraints and threats to cope with the unexpected, commit to the look ahead process can contribute to establish more reliable safety projects and leveling resources, anticipate hazards, recognize abnormal conditions and progress deviations as well as helps to develop leadership skills to reinforce pertinent attitudes and behaviours to complete the work. Another important aspect of this principles regards to the organisation's procedures which must to be an accurate reflection of working safely, recognizing the positive and negative variability that arises in daily operations. A lean production tool that helps to reduce the negative variability in the work flow and improves safety and learning culture is the standardized work, by capturing the accumulated learning from workers best's safety practices, not only from incidents and accidents but also from normal work, to improve upon safety standards and procedures. So, this learning can be adapted to the needs of the specific context to improve the organizations ability in addressing uncertainties flexibly (Alves et al., 2012) and leading to resilience capabilities. In this sense, the principle of flexibility, as the redundancy of the system in having different ways of performing a function, becomes a key factor to adjust to variability by adapting procedures through the differences in the execution method specified in trainings and the methods used in practice. Another lean production tool that contributes to flexibility is autonomation, which implies encouraging the teams to make important decisions and use the worker's perception and inputs for evaluating the aspects of safety. However, monitoring all these principles in a daily basis contributes to continuous improvement and turns the company a learning organization.

In order to reduce performance losses against disruptions and uncertainty, the integration of lean thinking and resilience perspective into a management system seem to be promising since both pursue similar continuous improvement initiatives. The literature review showed that there is no repertoire of safety principles and indicators based on resilience, which are broadly adopted in the academic community. Although some principles have been successfully applicable in aviation and process industries, further studies are necessary in other domains regarded as complex systems, which are still underexplored, such as the construction industry. Based on this literature review, some important trends can be proposed for this research topic: (i) as resilience engineering has been advocated as an alternative for the management of safety in complex socio-technical systems, understand the nature of the complexity of construction projects will be promising in order to investigate how resilience could be supported and (ii) analyse how these principles can contribute to the reinterpretation and improvement of the safety management practices in construction projects.

5 ACKNOWLEDGMENTS

We would like to thank the research project "Technologies for Sustainable Construction Sites of Social Interest Housing (Cantechis)" which is financially supported by the Funding of Studies and Projects (FINEP).

6 REFERENCES

Alves, A.C., Dinis-Carvalho, J., Sousa, R.M. (2012), “Lean production as promoter of thinkers to achieve companies’ agility”, The Learning Organization, Vol. 19.

Azadeh, A., Motevali S., Salehi V. (2015) Identification of managerial factors in a petrochemical plant by resilience engineering. J. of Loss Prev. in Process Indus. 36.

Carder,B., Ragan, P.(2003) A survey-based system for safety measurement and improvement. Journal of Safety Research, 34(2).

Costella, M., Saurin, T.A, Guimaraes, L. (2008). A method for assessing health and safety management systems from resilience engineering perspective. Safety Science.

Dinh, L., Pasman H., Gao X., Mannan S. (2012). Resilience engineering of industrial processes.Journal of Loss Prevention in the Process Industries, Volume 25.

Hollnagel, E., Woods, D., Leveson, N. (2006). Resilience engineering precepts. Resilience Engineering: Concepts and Precepts. Ashgate, Epilogue, London.

Lantelme, E.; Formoso, C.T. (2000). A performance measurement system for construction companies in Brazil. International Project Management Journal, Vol. 6.

Lekka, C., Sugden, C., (2011). The successes and challenges of implementing high reliability principles. Process Safety and Environmental Protection 89.

Leveson, N.(2004). A New Accident Model for Engineering Systems.Safety Science 42.

Leveson, N.(2011). Engineering a safer world: Systems thinking applied to safety. MIT.

Øien, K., Massaiu, S., Tinmannsvik, R.K., Størseth, F, (2010). Development of early warning indicators based on resilience engineering. Int. Safety Manag. Conf., Seattle.

Pęciłło, M. (2015). The resilience engineering concept in enterprises with and without occupational safety and health management systems, Safety Science, Volume 82.

Rasmussen J, Svedung I. (2000) Proactive risk management in dynamic society. Karlstad (Sweden): Swedish Rescue Services Agency.

Reason, J.(1995).Understanding adverse events: human factors. Quality in health care, 4.

Saurin, T.A., Famá, C., Formoso, C.T. (2013). Principles for designing health and safety performance measurement systems. Production Journal, 23.

Sgourou, E.;Katsakiori, P.; Goutsos, S.; Manatakis, E. (2009). Assessment of selected safety performance evaluation methods.Safety Science 48.

Shirali, G.A., Mohammadfam, I. (2013) A new method for quantitative assessment of resilience engineering.Reliability Engineering & System Safety 119.

Wehbe, F., Al Hattab, M., Hamzeh, F. (2015). Exploring associations between resilience and construction safety performance in safety networks, Safety Science 82.

Woltjer, R., Pinska, E., Laursen, T.(2013). RE in Air Traffic Manag. Proceed. SESAR.