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Review

A systematic literature review of resilience engineering: Research areas and a research agenda proposal

Angela Weber Righi [1], Tarcisio Abreu Saurin *, Priscila Wachs

Industrial Engineering and Transportation Department, Federal University of Rio Grande do Sul, Av. Osvaldo Aranha, 99, 5. Andar, Porto Alegre CEP 90035-190, RS, Brazil

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A B S T R A C T

Resilience engineering (RE) has been advocated as a new safety management paradigm, compatible with the nature of complex socio-technical systems. This study aims to identify the research areas and to propose a research agenda for RE, based on a systematic literature review that encompasses 237 studies from 2006 to 2014. Six research areas are identified: theory of RE; identification and classification of resilience; safety management tools; analysis of accidents; risk assessment; and training. The area "theory of RE" accounted for 52% of the studies, and it indicates that research has emphasized the description of how resilient performance occurs. The proposal for a research agenda is focused on: refining key constructs; positioning RE in relation to other theories; exploring other research strategies in addition to case-based studies; investigating barriers for implementing RE; and balancing the importance on describing and understanding resilience with the emphasis on the design of resilient systems, and the evaluation of these designs.

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* Corresponding author.
E-mail addresses: angelawrighi@yahoo.com.br (A.W. Righi), saurin@ufrgs.br (T.A. Saurin), priscilawachs@ig.com.br (P. Wachs).
[1] Tel.: +55 51 3308 4299.

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1. Introduction

Over the last decade, resilience engineering (RE) has been advocated as an alternative for the management of safety in complex socio-technical systems (CSSs) [1]. According to Woods [2] RE "uses the insights from research on failures in complex systems, including organizational contributors to risk, and the factors that affect human performance to provide systems engineering tools to manage risks proactively". As the name indicates, the assumption is that resilience can be engineered into a CSS, in order to support the use of adaptive capacity. RE recognizes that a portion of variability is unavoidable and beneficial, and due to this fact it should be managed rather than dampened [8].

The first publications mentioning the term RE can be traced back to 2003 [2,12]. However, RE became more widely known to the academic community in a meeting in Sweden in 2004 (the 1st RE Symposium), and also due to the publication of a book based on that meeting [1]. Since then, the interest in RE has grown as a result of both the theoretical merits of this discipline and the failure of existing approaches to move CSSs beyond the existing plateau of accident rates. Thus, in spite of being a fairly new discipline, the assumption of this paper is that studies on RE already exist in substantial quantity, quality and diversity. Therefore, it is necessary to make sense of the existing knowledge, characterizing what has been produced and identifying the main opportunities for future studies. Based on a systematic literature review, two research questions are addressed by this paper: (a) what are the main research areas of RE? (b) How should a research agenda for RE be structured? To the authors' knowledge, this is the first broad systematic literature review of RE, thus it has an exploratory nature. Previous to this, Van der Vorm et al. [34] had conducted a more limited systematic review, focusing on how the concept of resilience has been applied at the organizational, team and individual levels. Systematic reviews are strongly recommended for supporting the theoretical progress of scientific disciplines in general, as they identify over as well as under explored areas, in addition to constructs that should be refined [15,17].

2. Research design

2.1. Steps of the systematic literature review

A systematic literature review differs from a conventional review due to the use of a research protocol, so that readers can assess its rigor, completeness and repeatability; hence it reduces the effects of chance and increases the legitimacy and authority of the evidence found [17]. This review's starting point was the definition of the research questions, and subsequently three steps were followed: (a) defining criteria for selecting the studies; (b) defining the databases and selecting the studies based on the criteria; and (c) data analysis and discussion of selected studies. Regarding step (a), inclusion and exclusion criteria were defined as follows:

(i) Inclusion: the search was limited to papers in English, and "resilience engineering" was used as the keyword in the on-line search for papers. That keyword could appear in the title, abstract or the main body of the text. The keyword "resilience" was not adopted as the search would result in a much greater number of studies, since that concept has been investigated by several different disciplines, such as sustainability, psychology, economy and sociology. The search encompassed papers that had been published or were in press until October 2014. Moreover, the proceedings of the 2nd, 3rd, 4th and 5th Symposiums of Resilience Engineering were included, as they were the main academic events fully dedicated to RE so far.

(ii) Exclusion: conferences other than the RE symposiums, books, dissertations, thesis, and studies that only referred to the existence of RE, but did not focus on that subject. Moreover, both the annual workshops on the Functional Resonance Analysis Method (www.functionalresonance.net), and the annual meetings of the Resilience Health Care Network (www.resilienthealthcare.net) were not included, as they have not produced full papers.

The exclusion of certain sources from the on-line search for papers does not mean these sources were neglected by this review. It only means that these contributions were not included in the databases developed for supporting data analysis (see step "c", below), and therefore not included in the calculation of the distribution of papers according to categories such as the domains in which RE has been applied, and the adopted research designs. In fact, a number of additional sources, such as the books on RE e.g. [1,3,18,116,130], were used to support the analysis of the results obtained from the on-line search. In other words, although these sources did not count as "data", they had an important role both to enrich data analysis and characterize the research areas. Two papers published in this special issue were also cited [134,135] although they were not regarded as "data".

Regarding step (b), the chosen databases were those available from the authors' institution, namely: ACM Digital Library, ACS Journals Search, Academic Research Premier, Cambridge Journals Online, Emerald Fulltext, Highwire Press, IEEE Xplore, IOPscience, Nature, Oxford Journals, Royal Society of Chemistry, Science, ScienceDirect, Scielo.org, SpringerLink, and Wiley Online Library. Based on the inclusion criteria, 637 studies were identified, from 9 databases and the 4 Symposium proceedings. After checking for studies present in more than one database and applying the exclusion criteria, 237 studies remained.

Regarding step (c), a spreadsheet was developed to facilitate data analysis, including the fields presented below:

(i) Identification data: database(s) from which the paper was identified, journal's name, title, year of publication, institution of the first author, sector in which the study was developed;

(ii) Contents of the study: objectives, techniques for gathering and analyzing data, research strategy (e.g. literature review, case study, ethnography, experiments, etc.) and main results. Based on this information, six research areas associated with RE were identified, and the proposal for a research agenda was developed.

2.2. Framework for addressing the research questions

In order to address the research questions, it is necessary to develop operational definitions of what counts as a research area within RE as well as what characterizes a research agenda. A research area is defined mostly by the similarity of the objectives and the types of outcomes produced by a set of studies, regardless of the adopted research design. In turn, a research agenda refers to guidelines for the development of innovative practical and theoretical knowledge within and across research areas. To some extent, such an agenda is the result of the patterns identified in the research areas, and may also reflect the authors' biases. A source of bias is related to the fact the authors are industrial engineers conducting research in an Industrial Engineering program, and therefore concerns with the design of artifacts are possibly more natural than for researchers with other backgrounds.

3. Results

3.1. Main characteristics of the selected studies

Among the 237 selected papers, 158 (67%) are from the RE symposiums. Considering the remaining 79 journal papers, 24% of them came from Safety Science, 16% from Cognition, Technology & Work, and 11% from Reliability Engineering and System Safety. Another characteristic of the sample is that the majority of the papers (n=150, 63%) were based on empirical data. Table 1 presents the distribution of those studies across the domains in which they were conducted—the sum of studies in all domains is 158 because some papers report investigations in multiple sectors. Five domains account for 75% of the total: aviation (22%), healthcare (19%), chemical and petrochemical industry (16%), nuclear power plants (10%), and railways (8%). Those domains are well-known for their complexity and hazardous technologies [19], which makes them proper fields for the use of RE. Nevertheless, other domains widely regarded as complex are still under explored, such as military and information technology.

All studies focus on risk management, massively on personal and process safety-related risks. However, there are exceptions focusing on other types of risk, such as the collapse in financial services systems [84], terrorist acts in chemical plants [6], and natural disasters [129]. Impacts on other business dimensions, such as quality and efficiency, are usually dealt with jointly with safety impacts (e.g. the study by Lay and Branlat [86]). Although this approach is in line with the RE premise that safety is inseparable from business [8], it can also be a drawback as the full implications of using RE are not visible. It is also worth noting that there are many studies on the relationships and impacts of resilience on a number of areas not linked to safety—e.g. Creaco et al. [7] demonstrate how resilience can be an effective measure of the reliability of water distribution networks. As such studies were not presented within a RE framework, they were not included in this systematic review.

3.2. Methodological approaches

A substantial number of studies (n=87, 37%) were either literature reviews or conceptual papers. The studies which presented empirical data predominantly used case study as a methodological approach, and these accounted for 142 papers (95% of the empirical papers). Nevertheless, the use of action research [20,21], surveys [22], ethnography [23,24], experimental research [25], and design science [26] was also identified in the remaining empirical studies. It is worth noting that only 50 of the empirical papers explicitly stated their research strategy, and the strengths and limitations arising from that. In fact, underspecified research design is a methodological weakness of several papers.

Further evidence of methodological limitations in the empirical papers can be mentioned, for instance: (i) 33% of these papers (n=50) did not explain how the data were collected and, as a consequence, had no robust discussion on the reliability and validity of the results; (ii) procedures for the data analysis were stated only by 27 papers (18%)—content analysis was the most frequently cited data analysis technique (n=22, 15%); and (iii) 23% adopted only one source of data, such as documents (11%), interviews (11%), questionnaires (2%) or observations (1.3%). The use of two or more sources of data is always desirable, so as to increase credibility of results [27]. Of course, a possible explanation for the methodological flaws might be related to the fact that 105 out of the 150 empirical papers are from symposiums, which are by nature more succinct than journal papers.

3.3. Research areas

Six research areas were identified based on this systematic review. The distribution of the 237 selected papers across the areas was as follows: theory of RE (n=124, 52%); safety management tools (n=37, 16%); risk assessment (n=25, 11%); analysis of accidents (n=20, 9%); identification and classification of resilience (n=18, 7%); and training (n=13, 5%).

3.3.1. Theory of RE

This research area is focused on developing the theory of RE, and it includes studies based on empirical data. Papers that do not have any empirical data, in contrast, are not necessarily theoretical. In fact, an important criterion to categorize papers as related to the theory of RE was their emphasis on the development of constructs and models that presented the relationships among the constructs. This was a pragmatic criterion, since constructs and models are not sufficient for theory building [28]. Furthermore, from a broader perspective, RE theory has been built based on

Table 1
Distribution of empirical studies according to the domains studied.

Domains/research areas	Theory of resilience	Identification and classification of resilience	Safety management tools	Analysis of accidents	Risk assessment	Training	Total
Aviation, including air traffic control	**18**	**2**	**4**	**4**	**5**	**1**	**34**
Healthcare	**15**	**3**	**3**	**2**	**3**	**2**	**28**
Chemical and petrochemical industry	**9**	**4**	**6**	**4**	**1**	**0**	**24**
Nuclear power plants	**6**	**3**	**2**	**4**	**0**	**0**	**15**
Railways	**6**	**0**	**1**	**3**	**0**	**2**	**12**
Manufacturing	**2**	**0**	**4**	**0**	**2**	**0**	**8**
Natural disasters	**2**	**0**	**0**	**1**	**2**	**2**	**7**
Military	**3**	**1**	**0**	**0**	**1**	**0**	**5**
Construction	**2**	**0**	**2**	**0**	**0**	**0**	**4**
Electricity distribution	**1**	**0**	**1**	**0**	**0**	**2**	**4**
Road transport	**2**	**0**	**0**	**0**	**1**	**0**	**3**
Shipping	**3**	**0**	**0**	**0**	**0**	**0**	**3**
Meteorology	**2**	**0**	**0**	**0**	**0**	**0**	**2**
Financial services	**0**	**0**	**1**	**0**	**1**	**0**	**2**
Information technology	**2**	**0**	**0**	**0**	**0**	**0**	**2**
Fishing	**1**	**0**	**0**	**0**	**0**	**0**	**1**
Sector was not mentioned	**1**	**1**	**0**	**0**	**1**	**1**	**4**
Total	**75**	**14**	**24**	**18**	**17**	**10**	**158**

insights from all research areas identified in this literature review. As a matter of fact, we adopted a narrow view of "theory" by associating to this research area papers mostly devoted to the development of descriptive theory. According to Carlile and Christensen [15] descriptive theory is concerned with understanding what a phenomenon *is*. It involves observation, documentation, measurement and categorization of the phenomena in words and numbers. Normative theory stresses what *causes* the outcome of interest and it gives a manager unambiguous guidance about what actions will lead to the desired result, given the circumstance in which she finds herself [15].

As RE is defined by its seminal authors as a paradigm for safety management [1], the assumption of this paper is that RE theory is mostly about the development of safety management theory. The evolution of this theory was emphasized by five studies [13,22,29,30,31]. For instance, Re and Macchi [29] analyzed the evolution of Erik Hollnagel's assumptions on safety over his academic trajectory. McDonald [32] uses three criteria for the assessment of safety management theories, such as RE: focus of application (level of the system addressed by the theory); power of theory (extent to which the theory allows predictability and control of the system); and technological readiness (extent to which the theory was tested and evaluated). According to McDonald, RE performs better in the criterion focus due to its commitment to systems thinking, while more emphasis is necessary in the two other criteria. Madni and Jackson [33] proposed core objectives for RE: to support the management of trade-offs between safety and productivity; to measure resilience; and to develop mechanisms to promote resilience in organizations.

According to Back et al. [9] RE theory should be applied at three levels: individual, team and organizational. While empirical RE studies often describe the activities of front-line workers, researchers usually stress the identification of work system design factors, arising from organizational resilience, that influence individual and team resilience. The study by Dolif et al. [130] illustrates this approach of RE studies. Based on the investigation of the work of meteorologists in forecasting heavy rain, they identified a number of organizational and technical difficulties that hindered decision-making. However, the mechanisms through which resilience is linked across the individual/team/organizational levels are not yet well understood.

As previously mentioned, this research area emphasizes the definition of core constructs for the field, such as resilience and RE (Figs. 1 and 2). Some aspects of the definitions may be highlighted: (i) neither RE nor resilience are meant to be exclusively focused on safety; (ii) the ability of adjusting performance is the key aspect of resilience, despite the focus on individuals, teams, organizations or communities; and (iii) the major concern of RE is the scientific investigation and practical use of the concept of resilience, especially at the organizational level. Other constructs related to RE have also been investigated, such as robustness and regulation [36], stability [37], flexibility and robustness [38], unexpected events [39,40], disturbances [33], improvisation [41].

The links between RE and related disciplines have also been discussed, such as systems engineering [42], Normal Accidents Theory, High Reliability Organizations—HRO [13,43], safety culture [44], and complexity theory [45–50]. In particular, there has been sharp criticism on the extent to which RE differs from HRO theory (e.g. by Hopkins [13]), as commitment to resilience is a defining characteristic of HRO [51]. Indeed, it would be misleading to portray RE as radically innovative, since most of its core concepts and principles were borrowed from other fields and even RE seminal papers recognize inspiration from HRO [7,12]. However, HRO theory does not give a prominent role to the concept of resilience, as four other characteristics are equally emphasized: preoccupation with failure, reluctance to simplify interpretations, sensitivity to operations, and deference to expertise [51]. Furthermore, the choice of the term "high reliability" is criticized by Dekker [52], since it does not necessarily means safety. Dekker argues that a part can be reliable while the dynamics between parts can make a system unsafe.

Concerning the links between RE and complexity, Saurin et al. [46] discuss the role of resilience in the context of other characteristics of CSSs, as well as how the guideline to create an environment that supports resilience interacts with other guidelines for the management of CSSs. Zarboutis and Wright [49] describe how emergent phenomena, a core characteristic of complexity, may

Study	Definition
Grotberg [127]	"resilience is a universal capacity which allows a person, group or community to prevent, minimize or overcome the damaging effects of adversity"
Hollnagel [11]	"resilience is an organization's ability to adjust to harmful influences rather than to shun or resist them"
Wildavsky [10]	"resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back"
Woods [132]	"resilience, as a form of adaptive capacity, is a system's potential for adaptive action in the future when information varies, conditions change, or new kinds of events occur, any of which challenge the viability of previous adaptations, models, or assumptions"
Hollnagel [11]	"resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations even after a major mishap or in the presence of continuous stress"
Woods [134]	Four dimensions of the concept of resilience are identified: "(1) resilience as rebound from trauma and return to equilibrium; (2) resilience as a synonym for robustness; (3) resilience as the opposite of brittleness, i.e., as graceful extensibility when surprise challenges boundaries; (4) resilience as network architectures that can sustain the ability to adapt to future surprises as conditions evolve "

Fig. 1. Definitions of resilience [10,11,127,132,134].

Study	Definition
Woods and Hollnagel [5]	"resilience engineering is a paradigm that focuses on how to help people cope with complexity under pressure to achieve success"
Hollnagel and Woods [62]	"resilience engineering aims to enhance the ability of a complex socio-technical system to adapt or absorb disturbance, disruption and change"
Fairbanks et al. [133]	"resilience engineering is the deliberate design and construction of systems that have the capacity of resilience"
Resilience Engineering Association [14]	"resilience engineering looks for ways to enhance the ability at all levels of organizations to create processes that are robust yet flexible, to monitor and revise risk models, and to use resources proactively in the face of disruptions or ongoing production and economic pressures "
Anderson et al. [35]	"resilience engineering represents a philosophical shift in the science of safety. It is a proactive approach that focuses on the need for organizations to adapt to changes in the environment in which they operate, supporting workers in a safe adaption when necessary"

Fig. 2. Definitions of RE [5,14,35,62,133].

weaken resilience in aviation. CSSs are also known for the existence of many trade-offs, which often have to be managed on the spot by those working at the front-line. As the variety and number of trade-offs may be overwhelming, their management cannot rely solely on standardized operating procedures and, as a consequence, resilience is necessary. Partly as a result of the theme of the 5th RE symposium, some studies have addressed management of trade-offs [53–56]. Also, Patterson and Wears [135] discuss the tradeoff between the need to invest in adaptive capacity versus the need to invest in efficient production.

Some researchers are also interested in comparing the RE approach to resilience with the approach of other disciplines in which the same concept has been used. Le Coze and Capo [57], and Specht and Poumadère [58], identified similarities and differences between the psychological and the RE views of resilience. Those authors concluded that both RE and psychology value the role of past events as a basis for resilience. In fact, resilience is a concept that has raised interest of various disciplines. Longstaff et al. [59] found that the number of studies using that concept, in a broad range of disciplines, has doubled from 1995 to 2013.

Several studies of this area report stories of resilience, without being explicitly committed to the proposition of frameworks or methods e.g. [60,61,130,131]. This is not necessarily a drawback, as case studies perform an important role as a method of learning [16] and descriptions of resilience can give rise to prescriptions for safety management. The study by Le Coze and Herchin [115] illustrates how the description of the expertise of operators led to prescriptions that supported the re-design of standardized operating procedures in a high pressure gas transmission network. The strategic choice of cases is essential for conducting relevant case studies [16], and in general, studies of RE have adopted a consistent approach by investigating complex settings. For example, emergency departments (EDs) have possibly been the most frequent natural laboratory for the investigation of resilience in healthcare, which makes sense given the nature of these environments. One such study can be seen in Perry et al. [60] which identified resilient strategies adopted by a medical team in an ED. Furthermore, this study identified examples of sacrifice judgments and decision-making difficulties in EDs. Similarly, Wears and Perry [61] described how resilience can be designed, lost and restored in EDs, especially during periods of overcrowding and when the need for unexpected medical interventions arises.

3.3.2. Identification and classification of resilience

This research area is characterized by the development of guidelines, frameworks and methods for the identification and classification of resilience. On the one hand, these studies partially overlap with those belonging to the area "Theory of RE" as their results help to understand what resilience *is*. On the other hand, this area differs from "Theory of RE" as it focuses on the means to generate descriptive knowledge on RE, rather than on the descriptions themselves.

Furniss et al. [67] developed a framework for reasoning about resilience that requires representation of the level of analysis (from the individual to operational), a traceable link from abstract theory to specific observations, resilience mechanisms, and contextual factors. Hollnagel [18] presents the four abilities that characterize resilient systems, which have been widely adopted by RE researchers: anticipating, monitoring, responding, and learning. Rankin et al. [30] extended the frameworks by Furniss et al. [67] and Hollnagel [18], adding other categories and making an application in the analysis of high-risk work in different domains. Wears and Morrison [68] proposed the categorization of resilient behavior according to the type of response for an unexpected event: first level, characterized by a homeostatic response that eventually may be ineffective as it hides the need for deeper changes; second level, including not only responding, but also anticipating and monitoring the effects of the response; and third level, which is characterized by responses that take advantage of learning from second level responses. Saurin and Junior [69] developed and tested, in two air taxi carriers, a framework for the identification and classification of sources of resilience (SR) and sources of brittleness (SB), which allowed

Table 2
Categories adopted for classifying and describing resilience.

Categories/studies	[73]	[119]	[120]	[121]	[98]	[67]	[122]	[69]	[123]	[68]	[124]	[125]	[126]	[66]	[64]	[63]	[30]	Total
Ability of anticipating/being aware of hazards			X	X					X		X	X	X	X			X	8
Capacity of adapting to variability/being flexible		X	X		X		X		X			X		X				7
Ability of responding, restoring or limiting effects			X	X			X		X		X		X				X	7
Ability of learning			X	X							X	X	X				X	6
Resilient behaviors, resilient repertoire, resilience markers, cognitive strategies that support resilience[a]						X				X					X	X	X	5
Sources of brittleness (SB), vulnerabilities, or threats to resilience	X					X		X							X			4
Sources of resilience (SR) and opportunities	X					X		X										3
Capacity of absorbing variability/buffering capacity/ error tolerance		X			X		X											3
Ability of monitoring				X							X		X				X	4
Means of RE, resources and enabling conditions						X									X		X	3
Cross-scale interactions		X			X													2
Planning and preparedness									X			X						2
Goals of resilience															X		X	2
Sharp/blunt end; agents of resilience															X		X	2
Top level commitment												X						1
Just culture												X						1
The effectiveness of the SR								X										1
The opposite SR or SB								X										1
The risk from the SB								X										1
Origin of the SR/SB: internal/external; formal/informal								X										1
Mode of operation: the structure that a system adheres to						X												1
Forces and situational conditions																	X	1
Preventive or reactive resilience															X			1

[a] The category cognitive strategies that support resilience is divided into several sub-categories by Malakis and Kontogiannis [63].

identifying whether the SBs had correspondent SRs. The categories SR and SB were also used by others, such as Da Mata et al. [70] and Costa et al. [71]. While the former investigated safety of helicopter flights to and from off-shore oil platforms, the latter studied simulations of emergency situations in nuclear power plants.

Table 2 summarizes the categories for describing and classifying resilience that were proposed by the studies associated with this research area. The categories most frequently adopted are fully in line with the definitions of resilience and RE (see Figs. 1 and 2). It is also noteworthy that most categories, with the exception of those stressing sources of brittleness, risks and vulnerabilities, emphasize positive aspects of safety management. Indeed, this is consistent with the RE objective of understanding why things go right, rather than only why they sometimes go wrong [8]. Table 2 also indicates that there is room for the development of innovative frameworks that integrate the existing categories. The aforementioned work by Rankin et al. [30] is an example of a study moving in this direction.

3.3.3. *Safety management tools*

This research area aims at the development of innovative safety management tools based on RE premises. In fact, performance measurement through indicators and audits, which is a core aspect of safety management, is involved in the mainstream studies related to this area. Thus, differently from the research area "Identification and Classification of Resilience", the area presented in this section focuses on the management and measurement of resilience. Komatsubara [72], for example, proposed a safety management model which enables the identification of situations in which resilience is needed as well as the required resources for its furtherance. Pflanz and Levis [73] presented guidelines for the measurement of organizational resilience, based on proxy measures such as error-tolerance, capacity of responding to unexpected events and level of connectivity between system's elements. Siegel and Schraagen [74] devised a model for the measurement of resilience signals, based on three constructs: safety, capacity, and workload. Costella et al. [75] devised a method for the assessment of H&S safety management systems, whose requirements were explicitly related to RE premises. Øien et al. [76,77] designed a method for developing resilience based early warning indicators. The studies by Herrera and Tinmannsvik [78] and Herrera and Hovden [79], both in aviation, discuss how RE supports the design of innovative safety indicators.

Only a few studies do show concern with the design of safety performance measurement systems (SPMS) aligned with RE. This is a drawback, as SPMS are not limited to indicators. Indeed, guidelines and methods are necessary for selecting, disseminating information and learning from the results of indicators. In this respect, Saurin et al. [80] proposed six criteria for the assessment of SPMS based on insights from RE, and Woods et al. [81] devised a method for the selection of safety indicators, supporting the identification of misalignments, overlaps and false diversity among metrics. Huber et al. [82] discussed how to learn from indicators aligned to RE, based on an audit of the safety management system of a chemical plant.

3.3.4. *Risk assessment*

Studies associated with this research area emphasize the development of risk assessments from the RE view. Straeter et al. [83] criticize the traditional forms of risk assessment, especially the emphasis on measuring human performance based on the incidence rate of errors. This approach is in conflict with RE, which stresses the role of context for human performance, understanding errors as an inevitable by-product of CSSs.

Sundström and Hollnagel [84] used the Functional Resonance Analysis Method (FRAM) to assess risks in financial systems. The well-known Failure Mode and Effects Analysis method was used by Lhomme et al. [85] for the identification of resilient actions directed to the prevention of natural disasters. Lay and Branlat [86] carried out a risk assessment in a manufacturing plant, in order to identify ways of increasing resilience during demand surges. A risk assessment addressing the risks emerging from trade-offs in air traffic control was undertaken by Karikawa et al. [87], in order to identify threats to resilience. Cagno et al. [88] developed a method for the assessment of risks that may compromise the resilience of critical public services, such as gas and power supply, in the aftermath of disasters. Cabon et al. [89] assessed the risks of flight crews' fatigue, using insights from RE to identify the contributing factors and risk control measures. Anderson et al. [90] presented a classification of socio-technical risks that jeopardize resilience in the use of new technologies in healthcare. The assessment of risks arising from the increasing automation of CSSs has been dealt with by several studies, especially in aviation [91–94].

3.3.5. *Analysis of accidents*

In common, the studies associated with this research area stress accident investigations under the lens of RE. In fact, is argued by RE researchers that the analysis of accidents in CSSs should emphasize the dynamics and interactions among the contributing factors, rather than emphasizing the search for broken elements [95]. The need for recognizing and supporting second victims in accident investigations is emphasized by Dekker [128]. He argues that the relationship between a resilient second victim and a resilient organization is reciprocal. Four studies [96–99] used FRAM for re-interpreting major accidents. A core FRAM assumption is that accidents in CSSs result from the combination and resonance of normal variability, and that broken elements do not necessarily exist [8]. Praetorius et al. [97] did not identify any new contributing factors in an accident re-investigated using FRAM. However, they concluded that the use of FRAM allowed a better understanding of the dynamics among the contributing factors. In fact, it has been reported that the use of FRAM requires a high level of understanding of the theory underlying the method, and that obtaining insights is not a straightforward process [97]. Moreover, it seems that there is still under specification on how to use the method.

Major accidents have been re-interpreted in order to identify which lessons could be learned to improve the resilience of the affected CSS. By using FRAM to analyze a mid-air collision in Brazil, Carvalho [96] identified measures that could enhance the resilience of the air traffic control system. Westrum [100] proposed three recommendations to improve resilience of communities exposed to disasters similar to the one that devastated New Orleans in 2005: (i) removing latent conditions beforehand, as they cannot be tackled as the disaster unfolds; (ii) using decentralized controls, as centralization amplifies the effects of the high workload imposed on controllers in the aftermath of a disaster; and (iii) training small community-based teams, such as those related to NGOs, religious groups, and citizens in general, in order to operationalize decentralized crisis management.

This research area also addresses the issue of how the lack of resilience facilitated the occurrence of accidents. Shortcomings in the abilities of anticipating and monitoring disturbances, for example, were identified as contributing factors in two accidents in oil and gas production [101]. Perry et al. [102] demonstrated how the lack of resilience at the organizational level contributed to three accidents related to the administration of drugs in an ED. They concluded that a brittle process of purchasing and distributing drugs throughout the hospital hindered the benefits of existing resilience at the front-line. The insufficient use of RE principles also played a role in the Fukushima's nuclear disaster, according to Kitamura [103]. Yet, resilience prevented that the damages caused by that disaster were even greater. For example, soon after the plant was hit by the tsunami, a worker asked for immediate support from firefighters, anticipating the need for cooling the reactors by injecting water. Official investigations seem to have under appreciated the importance of similar resilient actions [104].

3.3.6. Training

This research area comprises the fewest number of studies (13), indicating that it has been less explored in comparison with the others. Overall, the implications of RE for training [26,105–108] and learning [109] have been investigated in this research area. Wachs et al. [106] re-interpreted the identification of non-technical skills (NTS) from the RE perspective. They proposed four procedures for the operationalization of the RE view on NTS identification: identifying work constraints which create the need for NTS as a means to adjust performance; identifying recommendations for re-designing the system, which could reduce the need for using NTS; regarding the identification of NTS as an opportunity to give visibility to adaptations; and classifying the NTS into categories which are meaningful for workers.

Due to the theoretical and practical implications of RE on NTS, Saurin et al. [26] proposed to use the expression “resilience skills”, which they defined as the individual and team skills of any type necessary to adjust performance. Ploquin et al. [109] discussed, in a healthcare setting, how the learning of RE premises could be supported by an incident reporting system. Lundberg and Rankin [107] proposed, based on focus group discussions with crisis response teams, guidelines for the design of training for taking improvised roles. One of the few studies involving the use of control groups in RE research was presented by Bergstrom et al. [3]. These authors developed scenarios for the training of resilient competencies of fire safety engineers involved in escalating situations, comparing the performances of control and experimental groups. The stress on how training should be designed to support the development of skills to deal with unexpected situations is a clear shared characteristic of the studies in this area. As a drawback, these studies do not always make it clear how the work system design may support the use of the skills practiced in training. Thus, it seems that more emphasis should be placed to make it explicit that, according to the RE view, the unit of analysis for designing and assessing training should be the joint cognitive system [65], rather than the individual worker.

4. Discussion and conclusions

The two research questions that guided this paper are discussed in Sections 4.1 and 4.2, respectively: (a) what are the main research areas of RE? (b) How should a research agenda for RE be structured?

4.1. Research areas

Considering the six research areas altogether, this literature review indicated that studies on RE: (i) usually adopt case-based research designs, accounting for the context-dependent nature of the management of CSSs; (ii) have a greater emphasis on the description of how resilient performance occurs in CSSs, in comparison with studies on prescribing, implementing and evaluating practices for the management of resilience; (iii) do not usually take advantage of the existing frameworks, guidelines and methods for the identification and classification of resilience, although there are exceptions [e.g. [30]]—due to this fact, a portion of the studies describing resilience are difficult to compare with other studies; and (iv) focus on domains in which hazardous technologies are used (e.g. aviation and healthcare), even though studies have also been conducted in non-safety critical domains, such as the financial sector.

Fig. 3 illustrates the relationships among the research areas. The area “Theory of RE” supports the others, to the extent that it involves the development of the core constructs and principles of RE, as well as their articulation. Of course, the relationship between this area and the others is bi-directional, since the more empirically oriented areas can provide insights that challenge theory and set a basis for its refinement. Fig. 3 also indicates that the research area “Safety Management Tools” has four branches that, due to their prominence, were regarded as research areas on their own. The area “Identification and Classification of Resilience” supports safety management as it helps to uncover where resilience is and how it looks like. As a result, it provides a basis for the design of practices to support the emergence of resilience and to eliminate its unnecessary portion due to ineffective processes. The relationship connecting safety management and the areas “Risk assessment”, “Analysis of Accidents”, and “Training” is straightforward, as those are traditional elements of safety management systems. It is also worth noting that the level of granularity of the adopted classification of research areas is low, so as they could be more fragmented. For example, the area “Theory of RE” involves studies of the evolution of safety management paradigms, stories of resilience, and discussions on the relationships between RE and other disciplines. As mentioned in Section 3.3.1, the common feature linking these studies, and that justifies their placement under “Theory of RE”, is the emphasis on understanding and describing core constructs for the discipline, such as resilience, RE, and safety.

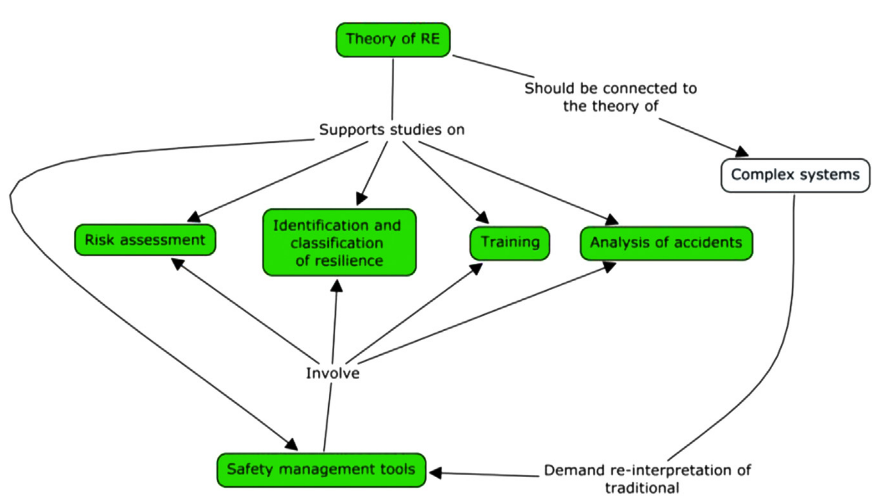

Fig. 3. Relationships among the research areas.

4.2. Research agenda proposal

Based on this review, some trends were identified in RE research, setting a basis for the proposition of a research agenda, focusing on:

(i) Refining key constructs that have been used in RE research (e.g. resilience, robustness, flexibility, adjustments, improvisation, adaptation, stability, variability), which may lead to a deeper understanding of their commonalities, differences, and relationships. In fact, each of those constructs can give rise to sub-constructs, as there is already substantial empirical evidence pointing out that resilience may have different manifestations—e.g. it changes across organizational levels, it may be more or less proactive, it may be sometimes simply a way of masking waste. The lack of well-defined constructs is a drawback for field studies, as it may not be clear which phenomena is to be measured. The development of a coherent body of knowledge may also be compromised, since comparisons between studies might become impossible.

(ii) Positioning RE in relation to other theories. This is important to prevent RE of becoming a self-contained discipline, which would be contradictory with the need for considering multiple perspectives when managing CSSs [117]. In particular, progress is necessary to articulate RE with other safety management paradigms (e.g. HRO) and system design theories (e.g. systems thinking). The lack of clarity of the conceptual links between RE and the theory of complex systems is also representative of such criticism. For example, it is possible that RE may not be equally relevant for all CSSs, as complexity is a multidimensional construct, and each dimension has different intensities in specific contexts [19]. In fact, there has been little discussion on when the use of RE might be counter-productive. One of the few exceptions is the study by Wears and Vincent [116], in which they discuss examples of overusing and misusing resilience in healthcare, and the resulting undesired side-effects, such as staff burnout. In a similar vein, Lundberg and Rankin [107] discuss the risk of resilience loss after an initially adaptive response, while Komatsubara [4] illustrates how the combination of individual resilient behaviors may lead to functional resonance type accidents. Moreover, it is unclear under which conditions should RE be more focused on reducing complexity or on managing the irreducible portion of complexity. While it is certain that both options (reduce and manage) can co-exist, an over emphasis on complexity reduction may equalize RE to a number of other management approaches dedicated to increase processes efficiency and reduce variability.

(iii) While the massive use of case-based studies is one of the strengths of RE, other research strategies have been under explored. In particular, quantitative methods, such as surveys, mathematical modelling, and computer simulations are not common to observe. While the complexity of real settings is difficult to be taken into account by those methods, they certainly have useful applications. For example, surveys could be carried out to investigate the extent to which RE principles have been implicitly used by industry, as well as to identify the perceptions of researchers in regard to where the school of RE should be heading. This type of study should also account for the academic background of researchers, as the RE community is multidisciplinary.

(iv) Balancing the current emphasis on describing and understanding resilience, which is represented mostly by the areas “theory of RE” and “identification and classification of resilience”, with the design of resilient systems, and the evaluation of these designs. In line with Le Coze and Herchin [115] this proposal also implies the need for developing guidance to researchers and practitioners, regarding how descriptions can be translated into prescriptions. In fact, Hollnagel [18, p. xxxviii] proposes that “RE should make use of existing methods and techniques, although seem from a RE perspective and in some cases be supplemented by new methods and techniques”. This conveys the objective of providing practical guidance to managers on how to design and operate resilient organizations. Thus, there is a need for the development of testable propositions related to RE (e.g. by supporting resilience through the use of a certain practice, under certain conditions, a certain dimension of performance is likely to improve to a certain extent), which can guide iterative cycles of design and evaluation.
The operationalization of proposal (iv) may benefit from the integration between RE and other management paradigms. For example, lean production shares a number of theoretical assumptions with complexity theory, and it has practices that could be useful for creating an environment that supports resilience [118]. Proposal (iv) may also benefit from the use of Design Science Research (DSR) as a research paradigm. The epistemology of DSR stresses knowing through making, and it is solution-focused, rather than problem-focused [111,112]. According to Hevner and Chatterjee [113] DSR is adequate for dealing with wicked problems, which are ubiquitous in CSSs, as it stresses the systematic development and rigorous evaluation of designed socio-technical artifacts. Horst and Webber [114] present ten characteristics of wicked problems, such as their unique nature, the fact that every problem is a symptom of another problem and the fact that they cannot be fixed, but only improved. When engineering resilience in a CSS, designers will be confronted with those and other characteristics of wicked problems. In fact, similarly to what happens with ergonomic interventions in general [110], “solutions” based on both DSR and RE are unlikely to provide generalizable proof of effectiveness, and this is why they should stress the identification of intervention elements and situations in which they are likely to work as intended. It is also worth noting that DSR is a type of case-based investigation aligned with the tradition of qualitative research, and so it does not imply major changes in the scientific values adopted by RE researchers familiar with case studies. For instance, by stressing the test of “solutions” in real environments, DSR recognizes the impact of complexity.

(v) Investigating barriers for the implementation of RE by industry as well as means for managing them. One of these barriers may be related to the fact that this review did not identify any report of companies formally using RE as their safety or business management philosophy, systematically integrating RE principles into a wide number of management routines—e.g. no reports were found of companies stating, in formal policies and programs, the need for using RE. This can become a bottleneck for the evolution of RE, as theory building would benefit from the observation of experiences of engineering resilience in large-scale in a company.

The academic origin of RE can be another barrier for widespread practical dissemination. A number of other organizational management paradigms (e.g. lean production) were born in industry, and strong theory building came after large scale practical experiences. Hence, some paradigms firstly proved to be effective in practice as to raise academic interest. RE has followed the other way around. Yet another barrier for the spread of RE in industry can be its questioning of some paradigms deeply rooted in practice—e.g. the view that the human being is the weakest link in a system, and therefore it should be replaced by reliable automation.

4.3. Limitations of this study

Some limitations of this study must be mentioned. First, the inclusion and exclusion criteria adopted for selecting papers imply that relevant studies may have been neglected. It is also likely that some studies of little relevance were included, especially because a substantial portion of the papers came from symposiums proceedings. Second, as several research areas were jointly reviewed, specific research questions associated with each area were not addressed. Third, the assignment of studies to research areas was a compromise solution, as there are studies that cross more than one area. In fact, those assignments are not free from the authors' biases, which may have also been evident in the studies chosen to illustrate each research area as well as in the proposal for a research agenda—e.g. as mentioned in Section 2.1 the authors have an engineering background, and so the suggestion for using DSR may be more natural for them than for other researchers. Thus, due to the exploratory nature and limitations of this research, an opportunity for further studies would be to undertake other systematic literature reviews and bibliometrics studies on RE. For example, narrower research questions could be defined and stricter criteria for sample selection of papers could be used—e.g. based on the number of citations and on the quality of contents as perceived by experts.

References

[1] Hollnagel E, Woods D, Leveson N. Resilience engineering: concepts and precepts. Aldershot: Ashgate Publishing; 2006.
[2] Woods D. Creating foresight: how resilience engineering can transform NASA's approach to risky decision making. Testimony on the future of NASA for committee on commerce, science and transportation; 2003.
[3] Bergstrom J, Dahlstrom N, Dekker S, Petersen K. Training organisational resilience in escalating situations. In: Hollnagel E, Paries J, Woods D, Wreathall J, editors. Resilience engineering in practice: a guidebook. Farnham, UK: Ashgate; 2011. p. 45–57.
[4] Komatsubara A. Resilience must be managed: a proposal for a safety management process that includes a resilience approach. In: Nemeth C, Hollnagel E, editors. Resilience engineering in practice: becoming resilient, vol. 2. Burlington: Ashgate; 2014. p. 96–109.
[5] Woods D, Hollnagel E. Prologue: resilience engineering concepts. In: Hollnagel E, Woods DD, Leveson N, editors. Resilience engineering: concepts and precepts. Aldershot: Ashgate Publishing; 2006. p. 1–6.
[6] Reniers G, Sorensen K, Khan F, Amyotte P. Resilience of chemical industrial areas through attenuation-based security. Reliab Eng Syst Saf 2014;131:94–101.
[7] Creaco E, Fortunato A, Franchini M, Mazzola M. Comparison between entropy and resilience as indirect measures of reliability in the framework of water distribution network design. Procedia Eng 2014;70:379–88.
[8] Hollnagel E. FRAM: the functional resonance analysis method—modeling complex socio-technical systems. Burlington: Ashgate; 2012.
[9] Back J., Furniss D., Hildebrandt M., Blandford A. Resilience markers for safer systems and organisations. In: Computer safety, reliability, and security (p. 99-112). Springer Verlag: Berlin/Heidelberg, Germany 2008.
[10] Wildavsky A. Searching for safety. New Brunswick: The Social Philosophy and Policy Center Transaction Books; 1989.
[11] Hollnagel E. Resilience—the challenge of the unstable. In: Hollnagel E, Woods D, Leveson N, editors. Resilience engineering: concepts and precepts. Aldershot: Ashgate Publishing; 2006. p. 9–17.
[12] Woods D, Wreathall J. Managing risk proactively: the emergence of resilience engineering. Institute for Ergonomics: The Ohio State University; 2003.
[13] Hopkins A. Issues in safety science. Saf Sci 2014;67:6–14.
[14] Resilience Engineering Association. Available at 〈http://www.resilience-engineering-association.org/〉; 2014 [accessed October 2014].
[15] Carlile P, Christensen C. The cycles of theory building in management research. Working paper 05-057, version 5.0, Boston University, Harvard Business School; 2004.
[16] Flyvbjerg B. Case study. In: Denzin N, Lincoln Y, editors. The Sage handbook of qualitative research, chapter 17. Thousand Oaks: Sage; 2011. p. 301–16.
[17] Tranfield D, Deyer D, Smart P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br J Manage 2003;14(3):207–22.
[18] Hollnagel E. Prologue: the scope of resilience engineering. In: Hollnagel E, Paries J, Woods D, Wreathall J, editors. Resilience engineering in practice: a guidebook. Farnham, UK: Ashgate; 2011. p. xxix–xix.
[19] Perrow C. Normal accidents: living with high-risk technologies. Princeton: Princeton University Press; 1984.
[20] Bracco F, Bruno A, Sossai D. Improving resilience through practitioners' well-being: an experience in Italian health-care. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[21] Johnsen S, Veen M. Risk assessment of critical communication infrastructure in railways in Norway. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[22] Steele K, Pariès J. Characterisation of the variation in safety beliefs across the aviation industry. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[23] Wahl A, Sleire H, Brurok T Asbjørnslett, BE. Agility and resilience in offshore operations. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[24] Takayama C, Nakatani M, Ohno T, Komatsubara A. Customer satisfaction plays an important role: a model to improve resiliency of ict service maintainer. In:Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[25] Blandford A, Back J, Curzon P, Li S, Rukšėnas R. Reasoning about human error by modeling cognition and interaction. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[26] Saurin T, Wachs P, Righi A, Henriqson É. The design of scenario-based training from the resilience engineering perspective: a study with grid electricians. Accid Anal Prev 2014;68:30–41.
[27] Patton M. Qualitative research & evaluation methods. London: Sage; 2002.
[28] Sutton R, Staw B. What theory is not. Admin Sci Q 1995;40:371–84.
[29] Re A, Macchi L. From cognitive reliability to competence? An evolving approach to human factors and safety Cogn Technol Work 2010;12(2):79–85.
[30] Rankin A, Lundberg J, Woltjer R, Rollenhagen C, Hollnagel E. Resilience in everyday operations: a framework for analyzing adaptations in high-risk work. J Cogn Eng Decis Making 2014;8(78):79–97.
[31] Benn J, Healey A, Hollnagel E. Improving performance reliability in surgical systems. Cogn Technol Work 2008;10:323–33.
[32] McDonald N. Challenges facing resilience engineering as a theoretical and practical project. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[33] Madni A, Jackson S. Towards a conceptual framework for resilience engineering. IEEE Syst J 2009;3(2):181–91.
[34] Van Der Vorm J, Van Der Beek D, Bos E, Steijger N, Gallis R, Zwetsloot G. Images of resilience: the resilience analysis grid applicable at several organizational levels? In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[35] Anderson J, Ross A, Jaye P. Resilience engineering in healthcare: moving from epistemology to theory and practice. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[36] Pavard B, Dugdale J, Saoud N, Darcy S, Salembier P. Design of robust socio-technical systems. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[37] Lundberg J, Johansson B. Resilience, stability and requisite interpretation in accident investigations. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[38] Nathanael D, Marmaras N. The interplay between work practices and prescription: a key issue for organizational resilience. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[39] Hémond Y, Robert B. Preparedness: the state of the art and future prospects. Disaster Prev Manage 2012;21(4):404–17.
[40] Epstein S. Unexampled events, resilience, and PRA. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[41] Grøtan T, Størseth F, Rø M, Skjerve A Resilience, adaptation and improvisation—increasing resilience by organising for successful improvisation. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[42] Jackson S, Ferris T. Resilience principles for engineered systems. Syst Eng 2012;16(2):152–64.
[43] Antunes P, Mourão H. Resilient business process management: framework and services. Expert Syst Appl 2011;38:1241–54.
[44] Chevreau F. Safety culture as a rational myth: why developing safety culture implies engineering resilience? In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[45] Hettinger L, Dainoff M, Robertson M, Huang Y. Sociotechnical systems issues in worker safety: implications for managing system tradeoffs. In: Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[46] Saurin T, Righi A, Henriqson E. Characteristics of complex socio-technical systems and guidelines for their management: the role of resilience. In: Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.

[47] Woods D, Branlat M. How human adaptive systems balance fundamental trade-offs: implications for polycentric governance architectures. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[48] Lalouette C, Pavard B. Enhancing inter-organizational resilience by loose coupling concept and complexity paradigm. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[49] Zarboutis N, Wright P. Using complexity theories to reveal emerged patterns that erode the resilience of complex systems. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[50] Boy G, Bradshaw J. Perceived complexity versus internal complexity: did we take into account expertise, reliability and cognitive stability? In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[51] Weick K, Sutcliffe K. Managing the unexpected: assuring high performance in an age of complexity. San Francisco: Jossey-Bass; 2001.
[52] Dekker S. Drift into failure: from hunting broken components to understanding complex systems. London: Ashgate; 2011.
[53] Bakx G, Nyce J. UAS in (inter)national airspace: resilience as a lever in the debate. In: Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[54] Di Cioccio, A, Morel, G. Trade-offs between safety and production during technical assistance of an aircraft. In: Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[55] Ferreira P, Wilson J, Ryan B, Sharples S, Clarke T. Trade-offs in the planning of rail engineering work. In: Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[56] Nathanael D, Tsagkas V, Marmaras N. Are trade-offs experienced and if yes, how? Studying organizational resilience through operators' dilemmas. In: Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[57] LeCoze J, Capo S. A conceptual and methodological comparison with the field of child resilience. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[58] Specht M, Poumadère M. Interrogating resilience: safety management, social structuralism and systemic adaptation. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[59] Longstaff P, Koslowski T, Geoghegan W. Translating resilience: a framework to enhance communication and implementation. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[60] Perry S, Wears R, Anderson B. Extemporaneous adaptation to evolving complexity: a case study of resilience in healthcare. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[61] Wears R, Perry S, McFauls A. Free fall—a case study of resilience, its degradation, and recovery in an emergency department. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[62] Hollnagel E, Woods D. Epilogue: resilience engineering precepts. In: Hollnagel E, Woods DD, Leveson N, editors. Resilience engineering: concepts and precepts. Aldershot: Ashgate Publishing; 2006. p. 347–58.
[63] Malakis S, Kontogiannis T. Cognitive strategies in emergency and abnormal situations training: implications for resilience in air traffic control. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[64] Hildebrandt M, Broberg H, Massaiu S, Dhillon B, Tarasewicz M. Resilience and the training of nuclear operators—a view from the shop floor. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[65] Hollnagel E, Woods D. Joint Cognitive Systems: foundations of cognitive systems engineering. Boca Raton, FL: Taylor & Francis; 2005.
[66] Johansson B, Lindgren M. A quick and dirty evaluation of resilience enhancing properties in safety critical systems. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[67] Furniss D, Back J, Blandford A, Hildebrandt M, Broberg H. A resilience markers framework for small teams. Reliab Eng Syst Saf 2011;96(1):2–10.
[68] Wears R, Morrison J. Levels of resilience: moving from resilience to resilience engineering. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[69] Saurin T, Junior G. A framework for identifying and analyzing sources of resilience and brittleness: a case study of two air taxi carriers. Int J Ind Ergon 2012;42:312–24.
[70] Da Mata T, Santos A, Abech M, Gomes J, Gilber J, Woods D. Goal conflicts in helicopter safety: dilemmas across maintenance, pilots, and management. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[71] Costa W, Voshell M, Branlat M, Woods D, Gomes J, Guimarães L. Resilience and brittleness in a nuclear emergency response simulation: focusing on team coordination activity. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[72] Komatsubara A. Resilience management system and development of resilience capability on site workers. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[73] Pflanz M, Levis A. An approach to evaluating resilience in command and control architectures. Procedia Comput Sci 2012;8:141–6.
[74] Siegel W, Schraagen J. Developing resilience signals for the Dutch railway system. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[75] Costella M, Saurin T, Guimarães L. A method for assessing health and safety management systems from the resilience engineering perspective. Saf Sci 2009;47:1056–67.
[76] Øien K, Utne I, Herrera I. Building safety indicators: Part 1—Theoretical foundation. Saf Sci 2011;49:148–61.
[77] Øien K, Utne I, Tinmannsvik R, Massaiu S. Building safety indicators: Part 2—Application, practices and results. Saf Sci 2011;49:162–71.
[78] Herrera IA, Tinmannsvik R. Key elements to avoid drifting out of the safety space. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[79] Herrera I, Hovden J. Leading indicators applied to maintenance in the framework of resilience engineering: a conceptual approach. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[80] Saurin TA, Formoso CT, Famá C. Criteria for assessing safety performance measurement systems: insights from resilience engineering. In: Nemeth C, Hollnagel E, editors. Resilience engineering in practice: becoming resilient, vol. 2. Burlington: Ashgate; 2014. p. 63–78.
[81] Woods D, Herrera I, Branlat M, Woltjer R. Identifying imbalances in a portfolio of safety metrics: the q4-balance framework for economy- safety tradeoffs. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[82] Huber S, Van Wijgerden I, Witt A, Dekker S. Learning from organizational incidents: resilience engineering for high-risk process environments. Process Saf Prog 2009;28(1):90–5.
[83] Straeter O, Leonhardt J, Durrett D, Hartung J. The dilemma of ill-defining the safety performance of systems if using a non-resilient safety assessment approach. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[84] Sundström G, Hollnagel E. Modeling risk in financial services systems: a functional risk modeling perspective. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[85] Lhomme S, Toubin M, Serre D, Diab Y, Laganier R. From technical resilience toward urban services resilience. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[86] Lay E, Branlat M. Sending up a FLARE: enhancing resilience in industrial maintenance through the timely mobilization of remote experts. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[87] Karikawa D, Aoyama H, Takahashi M, Furuta K, Ishibashi A, Kitamura M. A method for visualizing trade-offs in en-route air traffic control tasks. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[88] Cagno E, Grande O, Trucco P. Towards an integrated vulnerability and resilience analysis for underground infrastructures. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[89] Cabon P, Mollard R, Debouck F, Chaudron L, Grau J, Deharvengt S. From flight time limitations to fatigue risk management systems. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[90] Anderson S, Fairbrother P, Felici M, Hanley J, McKinstry B, Ure J. From hazards to resilience in socio-technical healthcare systems. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[91] Chialastri A. Resilience and ergonomics in aviation. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[92] Nemeth C, Wears R, Patel S, Rosen G, Cook R. Resilience is not control: healthcare, crisis management, and ICT. Cogn Technol Work 2011;13:189–202.
[93] Hoffman R, Lee J, Woods D, Shadbolt N, Miller J, Bradshaw J. The dynamics of trust in cyberdomains. Hum Centered-Comput 2009;3:5–12.
[94] Karikawa D, Takahashi M, Ishibashi A, Kitamura M. Design method of information display for pilot support with emphasis on resilience in highly automated flight deck. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[95] Hovden J, Albrechtsen E, Herrera I. Is there a need for new theories, models and approaches to occupational accident prevention? Saf Sci 2010;48:950–6.
[96] Carvalho P. The use of functional resonance analysis method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. Reliab Eng Syst Saf 2011;96:1482–98.
[97] Praetorius G, Lundh M, Lützhöft M. Learning from the past for pro-activity: a re-analysis of the accident of the MV Herald of Free Enterprise. In: Hollnagel

E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[98] Belmonte F, Schön W, Heurley L, Capel R. Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: an application to railway traffic supervision. Reliab Eng Syst Saf 2011;96:237–49.
[99] Woltjer R. Resilience assessment based on models of functional resonance. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[100] Westrum R. All coherence gone: new Orleans as a resilience failure. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[101] Andersen S, Albrechtsen E. Resilience abilities in recent blowouts in the petroleum industry. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[102] Perry S, Wears R, Spillane J. When worlds collide: two medication systems in one emergency department. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[103] Kitamura M. Precepts of resilience engineering as guidelines for learning lessons from the Fukushima-Daiichi accident. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[104] Takahashi M, Kitamura M. Actions contributed to disaster level reduction of the Fukushima accident. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[105] Fujino H, Horishita T, Sonda T, Yamaguchi H. Organisational factors for enhancing train drivers' proactive behaviors to maintain the normal operation of rail way. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[106] Wachs P, Righi A, Saurin T. Identification of non-technical skills from the resilience engineering perspective: a case study of an electricity distributor. Work 2012;41:3069–74.
[107] Lundberg J, Rankin A. Resilience and vulnerability of small flexible crisis response teams: implications for training and preparation. Cogn Technol Work 2013;28(1):64–85.
[108] Bergström J, Henriqson E, Dahlström N. From crew resource management to operational resilience. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[109] Ploquin J, Brown R, Clark B. Bridging professional silos in radiation medicine: the Ottawa hospital experience. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[110] Neumann W, Eklund J, Hansson B, Lindbeck L. Effect assessment in work environment interventions: a methodological reflection. Ergonomics 2010;53 (1):130–7.
[111] Vaishnavi V, Kuechler B. Design research in information systems, available at 〈http://www.isworld.org/Researchdesign/drisISworld.htm〉; 2007.
[112] Van Aken J. Management research based on the paradigm of the design sciences: the quest for field-tested and grounded technological rules. J Manage Stud 2004;41(2):219–46.
[113] Hevner A, Chatterjee S. Design research in information systems: theory and practice. New York, NY: Springer; 2010.
[114] Horst R, Webber M. Dilemmas in a general theory of planning. Policy Sci 1973;4(2):155–69.
[115] Le Coze JC, Herchin N. Describing and prescribing for safe operations within a large technical system (LTS): first reflections. In: Nemeth C, Hollnagel E, editors. Resilience engineering in practice: becoming resilient, vol. 2. Burlington: Ashgate; 2014. p. 13–32.
[116] Wears T, Vincent C. Relying on resilience: too much of a good thing. In: Hollnagel E, Braithwaite J, Wears R, editors. Resilient health care. Dorchester: Ashgate; 2013. p. 135–44.
[117] Page S. The difference: how the power of diversity creates better groups, firms, schools and societies. Princeton: Princeton University Press; 2007.
[118] Saurin T, Rooke J, Koskela L. A complex systems theory perspective of lean production. Int J Prod Res 2013;53(19):5824–38.
[119] Anders S, Woods D, Wears R, Perry S, Patterson E. Limits on adaptation: modeling resilience and brittleness in hospital emergency departments. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[120] Reis M, Borges M, Gomes J. Identifying resilience in emergency response stories. In: Hollnagel E, Pieri F, Rigaud E, editors. Proceedings of the third resilience engineering symposium. France: Antibes-Juan-Les-Pins; 2008.
[121] Macchi L, Reiman T, Pietikäinen E, Oedewald P, Gotcheva N. DISC model as a conceptual tool for engineering organizational resilience: two case studies in nuclear and healthcare domains. In: Hollnagel E, Rigaud E, Besnard D, editors. Proceedings of the fourth resilience engineering symposium. France: Sophia-Antipolis; 2011.
[122] Balchanos M, Li Y, Mavris D. Towards a method for assessing resilience of complex dynamical systems. Proceedings of the fifth international symposium on resilient control systems. 2008. p. 155–60.
[123] Dinh L, Pasman H, Gao X, Mannan M. Resilience engineering of industrial processes: principles and contributing factors. J Loss Prev Process Ind 2012;25:233–41.
[124] Rigaud E, Martin C. Considering trade-offs when assessing resilience. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[125] Grecco C, Vidal M, Cosenza C, Santos I. A fuzzy model to assess resilience for safety management. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[126] Ose G, Ramstad L, Steiro T. Analysis of resilience in offshore logistics and emergency response using a theoretically based tool. Proceedings of the fifth resilience engineering symposium. Netherlands: Soesterberg; 2013.
[127] Grotberg E. The international resilience project: findings from the research and the effectiveness of interventions. Proceedings of the 54th Annual Convention of the International Council of Psychologists 1997:118–28.
[128] Dekker S. Second victim: error, guilt, trauma, and resilience. Boca Raton: CRC Press; 2013.
[129] Becker P, Abrahamsson M, Tehler R. An emergent means to assurgent ends: societal resilience for safety and sustainability. In: Nemeth C, Hollnagel E, editors. Resilience engineering in practice: becoming resilient, vol. 2. Burlington: Ashgate; 2014. p. 1–12.
[130] Dolif G, Engelbrecht A, Jatobá A, Da Silva A, Gomes J, Borges M, et al. Resilience and brittleness in the ALERTA RIO system: a field study about the decision-making of forecasters. Nat Hazard 2012;65:1831–47.
[131] Mendonça D, Wallace W. Adaptive capacity: electric power restoration in New York City following the 11 September 2001 attacks. In: Hollnagel E, Rigaud E, editors. Proceedings of the second resilience engineering symposium. France: Juan-Les-Pins; 2006.
[132] Woods D. Escaping failures of foresight. Saf Sci 2009;47:498–501.
[133] Fairbanks R, Wears R, Woods D, Hollnagel E, Plsek P, Cook R. Resilience and resilience engineering in healthcare. Jt Comm J Qual Patient Saf 2014;40 (8):376–82.
[134] Woods D. Four concepts for resilience and their implications for systems safety in the face of complexity. in press. Special Issue on Resilience Engineering. Reliab Eng Syst Saf 2015. http://dx.doi.org/10.1016/j.ress.2015.03.018.
[135] Patterson M, Wears R. Resilience and Precarious Success, Reliab Eng Syst Saf, in press Special Issue on Resilience Engineering 2015, http://dx.doi.org/10.1016/j.ress.2015.03.014.