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Review

Resilience engineering: Current status of the research and future challenges

Riccardo Patriarca[a,*], Johan Bergström[b], Giulio Di Gravio[a], Francesco Costantino[a]

[a] Department of Mechanical and Aerospace Engineering, "Sapienza" University of Rome, Via Eudossiana 18, Rome, Italy
[b] Division of Risk Management and Societal Safety, Centre for Societal Resilience, Lund University, PO Box 118, Lund, Sweden

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ABSTRACT

This paper offers an extensive literature review on the field of Resilience Engineering (RE), encompassing 472 contributions, including journal articles, conference proceedings and book chapters. Adopting the numbers of co-citations as a metric of conceptual proximity, this paper details the application of Factor Analysis and Multi-Dimensional Scaling, as groundbreaking means to extract relevant research factors. A temporal analysis in a multi-variate two-dimensional space confirms the significance and relevance of the identified research factors. An in-depth analysis of the five research factors, labeled as *the need of RE*, *RE for modelling*, *defining and exploring RE*, *reflecting on RE*, *RE and improvisation*, guides the definition of future research paths and open research questions within the field and across several domains, suggesting the need for multi-disciplinary future studies.

1. Introduction

Resilience Engineering (RE) is a paradigm for safety management that focuses on systems coping with complexity and balancing productivity with safety. RE aims at providing tools to proactively manage risk, acknowledging the inherent complexity of system functioning and the correspondent need for performance variability. This perspective becomes crucial if linked to the risk-related needs of current socio-technical systems. In these systems, safety is not a constant or permanent property (Carayon et al., 2015); its presence or absence is a continuous function, i.e. emerges from, the interactive properties and activities of its constituent components. Safety is related to how system performs, generating the need to focus on whole system and the connection between agents, rather than individual agents (Bakx and Nyce, 2015). Risk and safety management for socio-technical systems shall not be reduced to tracking and analyzing roles and variables (Pava, 1986). Therefore, 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" (Woods, 2003). The concept of resilience is usually linked to terms such as robust, buoyant, elastic, and flexible. It can be intended as "[…] a feature of some systems that allows them to respond to an unanticipated disturbance that can lead to failure and then to resume normal operations quickly and with minimum decrement in their performance" (Fairbanks et al., 2014). Thus RE can be advocated as the discipline aimed at providing systems means to concretise these characteristics in response to external and internal perturbations (Hollnagel, 2006; Woods, 2006a).

This article aims to investigate the research domain of RE, by reviewing over twelve years of literature from 2004 to 2016 (and including articles published in 2017 but available online until October 2016). Starting from the confused consensus about RE argued in the first Resilience Engineering Association (REA) symposium in 2004 (Dekker, 2006), this paper aims at understanding the current state of the art of this research stream and its potential future directions. However, this is not the first literature review on the field: Righi et al. (2015) developed a systematic literature review to define the main areas and the agenda. Even if their review relies on a research protocol to reduce the subjectivity of the search, their work presents several limitations. Firstly, the inclusion and exclusion criteria, as the same authors acknowledge, incorporated the possibility for having neglected relevant studies and included a substantial portion of studies with little relevance. Furthermore, they suggested a frank critique of how they assigned papers to specific research areas, since many studies cut across several areas, thus reducing the relevance of the defined categories. Lastly, the same authors recognize the need to explore other meta-analysis techniques, (e.g.) using bibliometric indicators. Similar problems arise from another literature review on the field (Bergström et al., 2015), mainly focused on the domain of safety, which includes only papers from main journals related to resilience. The definition of main journals might be considered not completely objective since the authors define them as "the more generic journals on safety and resilience". Furthermore, the authors consider only seventy-one papers, i.e. filtering those papers where resilience was only a sub-topic. Those papers might as well contribute to the definition of the field, in a broader sense.

Starting from the inherent limitations of these two reviews, it is

* Corresponding author at: Via Eudossiana 18 - 00184, Rome, Italy.
E-mail address: riccardo.patriarca@uniroma1.it (R. Patriarca).

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possible to observe that a review on the wide topic of Resilience Engineering is currently lacking. Approximately twenty years after its first systematic definition (2004), this paper aims at providing a robust contribution to describe the current status and identify potential future challenges for the field.

According to these observations, we conducted the first meta-analysis on the field of RE. Our aim is to answer several research questions, including: What is the relevant literature in the field? How, and where, does the field define itself? Has there been an evolution of the field over the years? Which are the most and the less advanced research areas?

For this purpose, we adopt a groundbreaking and robust methodology, based on the bibliometric method of co-citation analysis, to ensure objectivity of the review and identify the intellectual structure of the research field. This latter has been discussed according to five relevant research domains, in terms of implications, limitations and future evolutions, adding also a time-reflective dimension to the research agenda.

2. Methodology

Understanding the intellectual structure of a research field can be a complex activity, especially in case of multiple, different and extensive amounts of contributions, where it is challenging even to restrict the literature review to a core dataset of publications. Analyzing citations as a starting point to evaluate co-citations represents a strategy to perform meta-analysis of the literature (Shafique, 2013). Co-citation analysis is a standard bibliometric method to examine relationships between articles, or even authors, in order to understand how they contribute to the development of a research field. This method relies on the assumption that if two contributions are often co-cited, the same contributions have to be linked somehow (Di Stefano et al., 2012). On this path, the more two documents are co-cited; the stronger the relationship between them, implying their belonging to a common research area, often referred as *invisible college* (Crane, 1969) in terms of authors' commonality.

The first step of our analysis consists of determining which documents are relevant in the field, i.e. related to Resilience Engineering, by a wide literature research, no restricting the search to any context.

The meta-analysis based on co-citations serves as an input to identify the intellectual research structure by Factor Analysis (FA). FA is a multi-variate technique useful for data reduction and it is compatible with the metric of co-citations, as a means to understand the not immediately visible relationships among documents (Pilkington and Meredith, 2009). For this purpose, we use the notion of *research factors* rather than invisible college, defining a research factor as a set of documents that analyze similar research interests concerning a specific field or sub-field with semantic commonalities.

However, since it is commonly acknowledged that an invisible college (and similarly a research factor) is not a one-dimensional construct, but rather a multi-faceted phenomenon, we consider it interesting to understand them and their relationships in a multi-dimensional representation. We use Multi-Dimensional Scaling (MDS), a multi-variate technique that graphically depicts the conceptual proximity between documents, based on co-citations metric (Ramos-Rodríguez and Ruíz-Navarro, 2004). Furthermore, we combine the results of FA with MDS to achieve an in-depth understanding of the research stream and interactions among research factors (Annarelli and Nonino, 2015; Costantino et al., 2016).

2.1. Searching and selecting the articles

The literature search of this study mainly used the Scopus database, which is the largest abstract and citation database of peer-reviewed literature. In order to avoid limitations in the search, we used a wide key-search analysis, searching for "resilience engineering" in the fields of title, abstract, keywords, i.e. TITLE-ABS-KEY ("resilience engineering"), including documents indexed until October 2016. We obtained 264 documents that refer to different subject areas, mainly "Engineering", "Social Sciences", "Computer Science", "Medicine", "Chemical Engineering", "Business, Management and Accounting", "Environmental Science", "Decision Sciences". As a final step, we performed a title and abstract reading in order to remove documents clearly outside the scope, duplicates, erratum and retracted articles.

2.1.1. Managing books

Since the set obtained by Scopus included in some cases both an entire book and its chapters, we performed specific analyses to evaluate their inclusion criteria. We removed those chapters of the books "Resilience Engineering: Concepts and Precepts", "Resilience Engineering in practice: A guidebook" and "Resilient Health Care", included in the original 264 documents, and the entire books. To maintain a systematic perspective and considering the relevance of these books for the analysis, we included their chapters as single documents. About the book "Governance and Control of Financial Systems: A Resilience Engineering Perspective" we decided to maintain it as a book, summarizing all the citations of the ten chapters (in total 12), which refer to RE in a single document. On the contrary, about the book "Oil and Gas, Technology and Humans: Assessing the Human Factors of Technological Change", we decided to evaluate the single chapters yet included in the original search, since not all the contributions in the books are related to RE.

We did not perform any further actions for the other book chapters included in the original 264 documents, in the following books: Human Factors in aviation", "Social Media and the Transformation of Interaction in Society", "Applications of Systems Thinking and Soft Operations Research in Managing Complexity: From Problem Framing to Problem Solving", "Pediatric and Congenital Cardiac Care: Volume 2: Quality Improvement and Patient Safety", "Numerical Methods for Reliability and Safety Assessment: Multiscale and Multiphysics Systems", "Reflections on the Fukushima Daiichi Nuclear Accident: Toward Social-Scientific Literacy and Engineering Resilience", "Risk Management in Life-Critical Systems", "Software Design and Development: Concepts, Methodologies, Tools, and Applications", "Simulator-based Human Factors Studies Across 25 Years: The History of the Halden Man-Machine Laboratory", "Robust Design Methodology for Reliability: Exploring the Effects of Variation and Uncertainty", "Designing, Engineering, and Analyzing Reliable and Efficient Software".

The choice to include book chapters in the analysis plays a relevant role for gathering emerging trends on resilience engineering, especially considering that book format is considered generally the best format to set innovative theories and approaches, thus contributing to an emergent discipline by a broad coverage of different aspects.

2.1.2. Managing proceedings

The original search included several relevant documents as proceedings (e.g. "Proceedings of the Human Factors and Ergonomics Society", "Proceedings of the European Safety and Reliability Conferences (ESREL)", proceedings of the "Probabilistic Assessment and Management (PSAM)" conferences). In addition, the Scopus database does not index the Resilience Engineering Association (REA) symposia papers, which represent significant contributions to the field of RE. We decided to include all the contributions related to the REA symposia. In particular, rather than including the proceedings, we included the relative chapters of the published books - where available - since they typically represent the same, or typically improved and more readable, peer-reviewed versions of the original conference papers. In order to maintain a systematic perspective and avoid duplicates, based on the correspondences sketched in Table 1, our analysis included all the chapters of the books "Resilience Engineering: Concepts and Precepts" (already included in the dataset, since included in Scopus, see Section 2.1.1), "Resilience Engineering Perspective Volume 1 –