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Resilience Engineering - Theoretical and Practical Reflections on a 20-Year Journey

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Abstract: In 2004, within Resilience Engineering (RE), resilience, was understood as system's ability to sustain required system function prior, during and in the aftermath of an adverse event. By 2024, this understanding has evolved to view resilience as a "verb" and not a property, related to a systems's ability to perform under varying conditions and being able to respond to both disturbances and opportunities. Perceptions of what resilience is, what it does, what it applies to and how it can be fostered have diversified across disciplines, application domains and communities of practice. This paper critically discusses on the challenges and opportunities that arise from the wide application of the term "resilience", particularly within the RE community. The paper further investigates fundamentals, concepts, methods and practical applications related to RE. The main objective is to provide a critical overview of both the achieved progress and challenges in terms of impact to both theory and practice.

Keywords: Complexity, Trade-offs, Critical Infrastructures, Societal Resilience, Aviation, Maritime, Healthcare.

1. Introduction

As our society experiences multi-crises, with interdependencies across critical infrastructures, organisations and population, there is a need for more resilient and robust people, organisations and societies, "a whole-of-society and whole-of-government approach" and (Adini et al. 2017, European Commision 2024). In this context, Resilience Engineering (RE) contribution targets the urgent need to improve our ability to reveal, assess and manage resilience, both in everyday operations, and during crises. One of the most recent definitions of resilience within RE is a system that can "adjust its functioning prior to, during, or following changes and disturbances, and thereby sustain required operations under both expected and unexpected conditions" (Hollnagel 2011). Two decades have passed since the field of RE was introduced. This paper reports on its efforts to advance in theory and practice: *What is resilience and what is RE?* and *What is the contribution of RE to practice?*

RE is a relatively young field and it's the evolution reflects a discovery of resilience that have shaped its progress. At the beginning, RE contributed to the advancement of proactive safety by addressing specific interrelated concepts such as efficiency-thoroughness, acute-chronic trade-offs concerns (Hollnagel 2009a; Hoffman and Woods 2011) and the relationship, or mismatch, between work-as-imagined (WAI) and work-as-done (WAD) in operations. Today, RE is transdisciplinary, a different form of systems engineering with formal theoretical foundations (concepts and methods derived from empirical results) and practical applications. RE involves architecting and designing roles to enhance highly

adaptable sociotechnical systems working at different scales (individual, organizational and societal). The objective is that these systems will have capabilities to understand and navigate multiple trade-offs, interdependencies, conflicting goals, limited resources and continuous change, considering both short-term and long- term perspectives (Herrera et al. 2024).

2. Approach

The data for this article consists of focused reading a careful selection of books and articles from RE symposiums from core contributors in the field between 2004 and 2024, and systematic reviews related to resilience engineering. Furthermore, the paper combines the authors' collective experiences gained from their involvement in national, European and global initiatives. It is important to note that this article is not a systematic literature review, issues related to resilience and risk are not covered. Instead, it provides a critical overview of RE's progress and contributions to safety science.

As critical discussion helps refine theoretical and methodological frameworks, allowing for a more nuanced understanding of complex issues (Popper 1992), the analysis has been conducted by questioning the foundations and evaluating the practical implications. The discussion section includes a critical reflection on two levels of abstraction. Firstly, the examination covers progress, inconsistencies, limitations, and tensions that arise when RE is implemented within the existing work system or when current practices are applied. Secondly, a foundational critique analyses the underlying principles, assumptions, and values upon which RE rests. This level seeks to question the very basis on which RE's logic or methodologies are constructed, exploring whether the foundational assumptions remain relevant or need to be re-evaluated in light of new challenges and insights. This dual approach allows a comprehensive critique of the challenges and opportunities that arise from the application of RE, identifying not only where improvements can be made but also whether RE's core assumptions and structures remain valid in a changing context.

3. Fundamentals and concepts

3.1. *Evolution of resilience understanding*

RE emerged partly as a critique of traditional linear accident models in safety management (Le Coze 2022). These critical reflections within the RE community and research are still present. They build upon insights and concepts from Cognitive Systems Engineering (CSE) and complex socio-technical systems within safety-critical operations and human-machine interaction. Following the first "symposium" on Rein 2004, resilience was seen as the ability of an organisation to keep or recover to a stable state, being able to continue operations during or after a major mishap (Nemeth 2008). For the 10th RE anniversary, a special issue reflecting on the field' progress was published (Nemeth and Herrera 2015). In this issue Woods discusses the diverse understandings on resilience as 1) rebound, returning to a stable state; 2) robustness, ability to managed increasing stressors and challenges (he argues that confounding robustness, a well-established term, with resilience is misleading; 3) graceful extensibility, extending the performance when dealing with surprises and reorganising to continue operations and 4) sustaining adaptability, managing adaptation to future surprises as conditions evolve in a interdependent layered network. He argues the scope and contribution of RE lies in graceful extensibility and sustain adaptability (Woods 2015). A 2019 special issue on safety science focused on the organisational strategies, fostering a discussion on the commonalities and difference between High Reliability Organisations (HRO) and RE (Wears and Roberts 2019). The issue includes discussions on the understanding of resilience as a concept. It highlights the differentiation between Safety-I and Safety-II, as an important contribution of resilience engineering to safety, where the emphasis is on what goes well in everyday operations. However, this view has been criticised in terms that is not possible to study what goes well without understanding things that go wrong (Haavik et al. 2019). Moreover, since resilience is hyper-popular, Dekker (2019) has reflected on inherent traps: 1) reductionism: focusing on targeting specific operations, 2) moral: promoting flexibility and adaptation are promoted, with operators being accountable for safety; and 3) normative: viewing local adaptations as safety promotion. The last point is, however, not the case for all industries as, for example, in fisheries, where the argument for flexibility is not for safety but for the acceptance of danger (Dekker 2019). The shift in the

understanding of resilience has contributed to enhancing the scope of RE from safety-critical domains to societal challenges covering micro-individuals, meso-organisations/domains and macro-societal interrelated aspects. 20 years after its inception, RE is considered a perspective, theory and field that centres around how systems sustain required functionality during both expected and unexpected conditions. With its contemporary views of "resilience as a verb" (Woods 2018) where RE is now a field of research and practice addressing questions related to how to identify, assess and improve resilient performance (Hollnagel and Nemeth 2022).

3.2. *Four potentials, RAG and FRAM*

Hollnagel developed the four cornerstones of RE, now named as the "four potentials" or essential system abilities for resilient performance: 1) knowing what to expect (anticipation-factual); 2) knowing what to look for (monitoring-critical); 3) knowing what to do (responding-actual); and 4) knowing what has happened (learning-factual) (Hollnagel 2009b). The model is well-established within the RE community and underscores that resilience is a characteristic of a system's performance rather than of the system itself (Hollnagel and Nemeth 2022). The four potentials are mutually dependent, and while they are rooted in historical and contemporary accident analysis, Hollnagel (2011) emphasises that the model is founded on pragmatic reasoning rather than empirical data (Hollnagel 2011). In 2017, Hollnagel reflected on the need to complement the four potentials with additional capabilities, including the potential to plan, communicate, and adapt (Hollnagel 2018).

A method tightly connected to the four cornerstones or potentials is Resilience Analysis grid (RAG) (Hollnagel 2011), which was developed in the early 2010s, addressing the need to foster a deeper understanding of organisational performance and underlying mechanisms that enable resilient performance of a system. The RAG operationalises the cornerstones through a set of domain-specific questions, sometimes a questionnaire (Hollnagel 2018; R. Patriarca, Di Gravio, and Costantino 2017), which can generate a "snapshot" of an organization's potential for resilience here and now (Chuang, Ou, and Ma 2020). Another method frequently used within RE is the Functional Resonance Analysis Method (FRAM), with underlying principles exploring sociotechnical systems' functional architecture, which allows us to understand how systems actually work during both anticipated and unanticipated conditions (Chuang, Ou, and Ma 2020). FRAM has been applied across a multitude of domains such as healthcare, transportation, oil and gas and aviation, to explore resilient system performance.

3.3. *Theory of graceful extensibility*

Woods sees the scope of RE as dedicated to the systems' ability to continue to adapt to changing environments and extend performance when facing unforeseen or challenging changes (Hollnagel, Woods, and Leveson 2006). This brings attention to the theory graceful extensibility (TGE, Woods 2018) with foundations for architecting systems that expand the capacity to continue operations. It acknowledges that systems, organisations and societies operate with finite resources (time, people, materials); and that environments in which systems operate consciously change and evolve. TGE outlines fundamentals of networked adaptability to support graceful extensibility, such as: 1) managing risk of saturation by recognizing adaptive capacity of a single unit is finite hence requiring one to revise or modify adaptive capacity; 2) managing networks of adaptive units by enabling synchronisation of activities across multiple roles and layers of a network to scale responses to the scope of challenges; and 3) outmanoeuvring constraints by recognising that adaptive units are local with constrained positions with respect to others and there exist limits on perspectives, requiring one to to proactively shift perspectives to recognize and refine the understanding of local and others' capabilities and constraints.

TGE is still young, with growing academic-industrial collaborations exploring its application across diverse fields. One notable example is a case study exploration of adaptations in internet facing business context (Cook and Long 2021). It focuses on challenging incidents with specific characteristics in terms of tempo, duration and magnitude of challenges demanding ad-hoc sharing. By comparing diverse events and responses, this enables participants to reflect, improve practice and adjust distribution of adaptive capacity.

3.2. *Safety-II and Safety Differently*

Building on the foundational insights from CSE and the initial formulation of RE in 2004, RE researchers Erik Hollnagel and Sidney Dekker developed distinct but related approaches to safety.

Hollnagel introduced the concept of "Safety-II" as both a critique of traditional safety models, termed "Safety-I", and a new framework for understanding safety. In contrast to Safety I, which focuses on preventing things from going wrong (e.g., errors, accidents and failures), Safety II emphasises what goes right in daily operations. The premise is that safety is created through successful everyday performance, where systems and individuals adapt to challenges and variability (Hollnagel 2014).

Dekker's "Safety Differently" (SD) also builds on a critique of traditional approaches, but emphasises the problems of excessive bureaucracy and compliance-driven safety management. Dekker argues that focusing solely on rule-following and documentation hinders adaptability. Instead, SD addresses organisational leadership and governance, and proposes that safety emerges when people are empowered to take ownership of their work and adapt to complex environments) (Dekker 2015).

4. Domains of application

4.1. *Societal resilience*

The new scale of disruptive events has enabled recognition of the urgent need for an all-hazards approach, cross sectorial collaboration, inclusive "whole of society" and "whole-of government" involvement to address compound and cascade events (European Commission 2024). There are efforts to bring RE to the societal scale addressing both top-down and bottom-up. Here, societal resilience is understood as the potential of all societal actors (both formal, e.g. authorities, and informal, e.g. citizens, digital and analogue) to anticipate, adjust, adapt, and change everyday life, especially in the face of adverse situations (prior, during, and after) (adapted from (ENGAGE 2023)). Thrust level in government, coping skills, social norms, sense of community and preparedness at individual, community and societal levels are identified important contributors to resilience (findings from European projects within Disaster Resilience Societies). Bottom-up approaches include the essential role of citizens' needs, knowledge and capabilities to innovate, develop and synchronise local adaptive responses (UCPM project, Empower Citizens). Other efforts include development of processes, collaborative architectures and technologies (i.e., computational ethnography). These approaches have the potential to generate rich ethnographic results that reflect lived experiences and sentiments of large and diverse populations, which are difficult to consolidate using current qualitative research methods. This type of data can be used to inform more inclusive and flexible strategies (Public Engagement to Re-imagine Community Planning, PERCC Project).

4.2. *Critical infrastructure*

Critical infrastructure (CI) refers to the vital systems and assets essential for the functioning of society. Traditionally, CI is managed as separate sectors, such as energy, water supply, transportation, digital infrastructure, communication, healthcare and public administration, where disruptions can lead to significant societal consequences. It is argued that the sector approach is insufficient, as these critical infrastructure systems are interconnected, constantly evolving, and subject to new challenges and vulnerabilities (Woods and Alderson 2021). This is aligned with the RE view on critical infrastructure as interconnected complex socio-technical systems, possessing their organizational potential for resilient performance. Besides the sector approach, there is a strong focus on technology in analysis and measures. However, it is equally crucial to focus on organizational aspects of CI operators (Degerman 2021). In the European context, recent European directives such as Critical Entities Resilience (CER) and Network of Information Systems Directive 2 (NIS-2), aim to ensure that CIs are able to cope with diverse disruptive events of whether they are related to natural hazards, intentional or cyber and non-cyber risks.

4.3. *Aviation*

Since 2004, there has been a growing interest in RE within the aviation community, motivated by increased complexity, interdependence across systems and surprising events reminding the need for adaptation and continued safe operations. Flight operations, air traffic management (ATM), airport and ground operations, aircraft maintenance, organisational policy and rulemaking provide examples on efforts to investigate resilience (Muecklich et al. 2023). Developments include

studies broadening existing risk management and accident analysis approaches (Herrera et al. 2010). The operationalisation of Safety-II focuses on the understanding and enhancing things that go well in an environment with multiple, shifting goals, variable and undefined demands is implemented in airlines operations (ref). The approach combines: 1) new language; 2) observations, data collection analyses and tools; 3) programme structure; and 4) implementation and dissemination facilitating the understanding of WAI and WAD, as well as a group called Learning Improvement Teams highlining the importance of learning improving safety (American Airlines' Department of Flight Safety 2021). Within Air Traffic Management (ATM), RE principles have been integrated in a method to asses resilience in design, not addressing specific components by looking at ATM systems as a whole, including work as done; varying conditions; signals and cues; goal trade-offs; margins and adaptive capacity; coupling, interactions and cascades; timing synchronisation and time scales and under specification and approximate adjustments (Ivonne Herrera et al. 2015).

Advancing resilient performance through incorporating capabilities is important to deal with unexpected situations during training. New trends include cyber-resilience in ATM with a growing interest on the intersection between resilience and cybersecurity (EUROCONTROL 2018).

4.4. *Healthcare*

The application of RE in healthcare began around 2013 when Erik Hollnagel, Jeffrey Braithwaite, and Robert Wears initiated annual meetings through the "Resilient Healthcare Network". These meetings aimed to discuss and develop RE concepts and approaches in the context of healthcare viewed as a complex adaptive system. These gatherings brought together both researchers and healthcare professionals, introducing resilience thinking and methods into the field. The RE approach resonated strongly with healthcare professionals, as RE acknowledges the complexity of everyday work while offering concepts and methods suited to the constant adaptations required in healthcare operations.

Traditionally, the healthcare sector has focused on errors through a reactive approach to safety, emphasising adverse event reporting, sanctioning, blame, and linear investigations. RE and Safety-II were adopted as alternatives, emphasising the need to understand "WAD", the necessity of adaptation, and the reasons why healthcare providers succeed so often despite constant pressure and the inability to stop service provision – in a sector still struggling with high rates of adverse events (Bates et al. 2023).

Over the years, there has been an increasing number of studies and use of RE and Safety-II in healthcare research. Literature reviews (Righi, Saurin, and Wachs 2015; Berg et al. 2018; Iflaifel et al. 2020) and special issues on RE in healthcare (S. Wiig and O'Hara 2021) have highlighted that the multilevel perspective of RE is important in healthcare.

One of the key challenges in applying RE to healthcare is the need for validated frameworks and the operationalisation of theoretical concepts into practical tools. The healthcare sector focuses heavily on quality improvement and interventions, necessitating that RE approaches integrate quality considerations (Guise, Anderson, and Wiig 2020), as well as patient involvement, care coordination, and collaborative learning (Siri Wiig et al. 2020).

Large research projects have enabled the development of learning tools to translate RE concepts into practice, such as the "Resilience Learning Tool", "Resilient Performance Enhancement Tool", and the "Resilience Toolkit". These projects address literature review findings mentioned above, which called for intervention studies, multilevel research and the use of methods beyond single case studies. Translational studies, such as those conducted in Norway (Aase et al. 2020) and Sweden, show that these tools are well-received. They create reflexive spaces for improving practice and fostering understanding and discussions about successes in healthcare operations.

Increasing attention is being directed toward resilience in teams and the critical role of leadership in enabling conditions that promote resilient performance (Hybinette et al. 2023). The empirical scope of healthcare RE research has expanded to include studies on pandemics, leadership, mental health, general practitioners, primary care services such as homecare, nursing homes and population groups with special needs (Ekstedt and Cook 2014).

Additionally, methods from the field of Human Factors are being integrated into RE research, such as cognitive task analysis in emergency departments (Clay-Williams et al. 2014), co-design approaches and social network analysis. Lastly, a growing body of work focuses on the role of regulation in healthcare resilience (Øyri and

Wiig 2022) and the interplay between individual and system resilience.

4.5. *Maritime*

Within the maritime domain, work utilising concepts from RE started to appear in early 2010 where most of the published work discussed the potential of introducing a novel perspective on safety (Schröder-Hinrichs, et al. 2012) rather than presenting empirical findings.

Empirical research on RE emerged around 2015 when studies utilizing and operationalizing the cornerstones began to explore how shore-based services adapt during everyday work (Praetorius and Hollnagel 2014; Praetorius, Hollnagel, and Dahlman 2015; De Vries 2017). This work was tightly coupled with the increasing application of FRAM to understand complexity within maritime operations.

Another line of work has focused on RE as a means to enhance safety management (Størkersen 2015; Olsson and Praetorius 2021) with novel perspectives on how international regulation and operational perspectives open for understanding how safety is constructed rather than only managing it retroactively. This work has also inspired recent developments in autonomous shipping, where system resilience has become one of the required system properties for future system developments (e.g. Wrobel, Montewka and Kujala, 2017).

Applications of RE to understand onboard work and the complex interactions in everyday operation have so far been limited. Among others, explored (Ljung and Oudhuis 2016) explored the importance of the catering staff for passenger safety, (Praetorius and Lundh 2013) focused on how onboard personnel actively constructs safety through their actions. An example of how to uncover the intricate and interconnected work of onboard work is provided in (Riccardo Patriarca and Bergström 2017) who analysed mooring with the help of FRAM.

Further, the potential to enhance resilience in operations by training of maritime professionals has been the focus of work conducted by others (Wahl, Kongsvik, and Antonsen 2020; Griffioen, Praetorius, Hult, and Österman 2020). They all focus on how resilience can enrich current training regimes focusing on non-technical skills programs.

In conclusion, RE work in maritime operations has been quite limited to date. Although the referenced publications argue for the potential of RE to help to improve safety work, safety management and understanding the complexities of everyday work, including improving training for high-risk operations, the accounts seldomly provide empirical data and much of the work remains conceptual.

5. Discussion

The understanding of resilience and RE is ongoing and constantly evolving delivering fundamentals, concepts and methods with concrete contributions to safety. However, it also has inconsistencies and limitations. Advancements in RE are driven by the interplay between fundamentals, concepts, methods, practitioners and academics working on real world case studies.

5.1. *Theoretical implications*

While RE started as a critique to other perspectives paradoxically, there are limited critiques on RE within the community. Is RE's narrow perspective characterised by a limited community? There is a dependency on a few prominent RE researchers as being oriented in different ways; models and methods builder (Hollnagel), political (Dekker), and formal, pattern oracle (Woods) and raconteur (Cook, mentioned by Hochstein and adapted from Le Coze, 2019). The over-reliance on few individuals coupled with the lack of diversity in gender and disciplinary backgrounds hinders progress. While human factors and engineering initially dominated RE and its progress, fields such as sociology and political science are now contributing. A new generation of researchers and practitioners is emerging from world-wide organisations such as the Resilience Engineering Association and Resilient Healthcare Society, as well as from collaborations in European and other international projects. These individuals are joining industry-academic and policy-academic collaborations and are essential for shaping future directions of RE.

Currently, the predominant fundamentals, concepts and methods within RE can be seen as a repertoire with diverse lines of inquiry often lacking connection to each other. Safety-II looks to what goes well and TGE looks to events challenging boundaries. The tension between diverse and sometimes conflicting views encourages dialogue and drives progress.

However, while theoretical concepts have been evolving, the methodological approaches to RE are still limited to a certain extent. Most work is grounded in specific case studies, in which qualitative inquiry may be coupled to FRAM, RAG, or loosely with Safety-II as a safety management approach. However, there is a trade-off between capturing complexity, and easy-to-use and visualisation methods. Approaches based on TGE are beginning to show results in terms of providing strategies that improved adaptive capacity within software engineering and railway.

While RE advocates proactivity, its methods rely on reactive analysis and most findings are reported based on studies of what *has* been, analysing resilience after the event and as such looking back rather than forward.

Many studies also focus on front line operators, but it remains unclear how RE truly benefits their work. While there are concrete examples, there is a need for more solid empirical evidence on concrete measures suggested on management level that actually improve work as done. Furthermore, with Safety-II for management tools gaining attention, we see ta growing confusion between Safety-II and resilience.

Advancing the RE field encompasses both progress on scientific foundations and opportunities to derive empirical generalisations across different domains.

5.1. *Practical implications*

A question remains, will the concept of resilience becomes meaningless with so diverse views? Operationalising a shift in perspective is an important challenge. While there is an expectation for bottom-up change, RE risks being interpreted and implemented through the lens of prevailing perspectives, rather than genuinely embraced. This is due to the fact that underlying principles and fundamentals are often absent from current work systems today. In addition, RE research often focuses on front line operations, while training initiatives tend to focus on management, limiting the empowerment those in the front line.

Successful progress has been made in diverse domains through academic – industrial collaborations within aviation, healthcare and software intensive organisation. Studies the last years have been able to get large scale funding, addressing diverse critical infrastructures. There are now ongoing EU projects and international comparative studies due to networks started by the RE pioneers.

Within aviation the added value of RE lies in their systemic view that allows to understand activities and impact across interconnected levels at diverse scales, to understand adaptive capacity (Woltjer 2019)

Within healthcare, what was a narrow field in 2013 has developed to a strong research stream that also has impact at policy level. The translation of RE theory into policy has gained increased attention in recent years (Siri Wiig et al. 2024). Furthermore, several key documents in WHO, EU, in health ministries, Lancet reports and in national healthcare strategies currently incorporate RE principles and tools as ways in which healthcare should acknowledge and use to reduce the high number of patient harm and to create working environments that support resilience for workers, patients and informal caregivers.

While RE seems attractive for high-risk domains, but to a certain extent, especially as shown in the maritime application cases, it remains an exercise for a limited group of researchers rather than a practical approach for increasing safety in operations and safety management approach.

Overall, empirics from domains still show gender imbalance and lack of diversity, which could represent a gap for new generation to grow. Each domain has created its own understanding as natural evolutions combining traditional approaches with conflicting views, thereby not contributing to the progress of RE.

6. Conclusions

Resilience has succeeded in changing the way people think about safety and gained attention in specific domains predominantly healthcare, aviation, crisis management and lately software related projects. However, the focus remains on past events needing more forward looking methods. Within safety still, the added value is not widely recognised as a perspective. Furthermore, RE studies shown that safety cannot be considered in isolation within organisations. There is a need to integrate safety considerations within organisational theory as this perspective represents values and norms.

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