Engineering Resilient Complex Systems: The Necessary Shift Toward Complexity Science

Giuliano Punzo, Anurag Tewari, Eugene Butans, Massimiliano Vasile, Alan Purvis, Martin Mayfield, and Liz Varga

***Abstract*—This position article addresses resilience in complex engineering and engineered systems (CES). It offers a synthesis of academic thinking with an empirical analysis of the challenge. This article puts forward argumentations and a conceptual framework in support of a new understanding of CES resilience as the product of continuous learning in between disruptive events. CES are in continuous evolution and with each generation they become more complex as they adapt to their environment. While this evolution takes place, new failure modes arise with the engineering of their resilience having to evolve in parallel to cope with them. Our position supports the role of an overarching complexity science framework to investigate the resilience of CES, including their temporal evolution, resilience features, the management and decision layers, and the transparency of boundaries between interconnected systems. The conclusion identifies the value of a complexity perspective to address CES resilience. Extending the latest understanding of resilience, we propose a circular framework where features of CES are related to a resilience event and complexity science explains the importance of interconnections with external systems, the increasingly fast system evolution and the stratification of heterogeneous layers.**

***Index Terms*—Complex systems engineering (CES), complex networks, complexity theory, resilience, system resilience.**

I. Introduction

ENGINEERING systems are designed to specifications. In addition to functional requirements, a system's reliability, failure tolerance, or resilience form an integral part of the design parameters. In principle, a system's resilience should provide it with a capability to preserve its functionality over varying conditions of stress or for uncertainties arising from natural or human interventions [1].

For modern day engineering systems, designing for resilience or testing resilience at the design phase, poses a significant challenge. Due to the interconnectedness and embeddedness of these systems in a nested system of systems [2]–[4], it gets increasingly difficult to adopt the traditional approach of testing a system in isolation for resilience. Here, isolation refers to engaging with stress testing using a restrictive set of predetermined input parameters and system specific conditions [5]. The criticism of traditional, functional parameters and individual component-based failure testing approach is that it fails to account for the continuous evolution and adaptation that a system undergoes, in progressive generations, over its entire life span. Modern era systems are highly complex and have deeply coupled interdependencies that are difficult to account for in the design phase. It is an undeniable fact that modern day systems are more integrated, more interdependent, evolve at faster pace and, in a word, are more complex than the systems of the previous century [6], thus excluding the possibility of testing for resilience in isolation. We shall refer to these new class of evolving "living" systems as complex engineering systems (CES) and we further argue that there is a need to look for alternative paradigms and methodologies to approach these systems.

Supporting the argument for a need to develop alternative methodologies to approach engineering system resilience, Gheorghe and Katina [1] quote "the dwindling applicability of 'old' methods and tools cannot be expected to address increasing 21st century concerns." The underlying assumption to this assertion is that being complex, these systems demonstrate complexity traits such as adaptation, self-organization, and emergence; and these system traits inherently conflict with the purpose-driven approach of engineering system design that looks for convergence of behaviors and consistency of design and performance [7]. It is thus imperative for CES studies to resolve the debates around complexity and its influence on resilience.

A complexity perspective prompts engineering systems' research to reason why a system behavior exceeds what is intuitively the sum of its individual parts [8]. Prime examples of these, that will be expanded later on, are transportation infrastructure that not only connect existing places, but shape the commuting patterns, the supply chains, the emergence of new conurbation, and so on. Another question that may arise is whether embeddedness or interconnectedness is actually to be blamed for loss in resilience [9, p. 13]. Elsewhere in complex natural system research, it has been established that in natural

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ecosystems, which are proven to be highly nested and interconnected, there exists an inherent ability to survive and bounce back [1]. If this is the case, then how do CES differ from other similar man made or natural systems and what would be an apt approach to study CES resilience. Motivated by these debates, this article sets out to position the study of CES resilience in the wider extant literature on complexity and resilience. After establishing the positioning of CES in the interdisciplinary debates of complexity and resilience, the article aims to provide a synthesis of selected resilience examples from other related domains of CES. More centrally, we propose a conceptual framework that, acknowledging the circular nature of CES failures, identifies in the learning element a way to avoid failure replicas or escalations. To do so, we argue for complexity science to be fully embraced as a framework within which CES are to be designed and operated, widening the breadth of engineering understanding. Looking at CES with a complexity perspective will allow shifting the focus from the single components to their reciprocal interactions within the engineered system they belong and with its surrounding environment.

While the link between abstract science and engineering has been highlighted before [7], [10], [11], there is considerable scope for dialogue between the various fields of system engineering seeking to exploit complexity methods beyond the identification of failure mechanism, into the understanding of the system's dynamics. In this article, we argue in support of an application of complexity science in the design of engineering systems that, from commissioning to removal, coevolve with their environment to turn away from their designed shape. Our intentionally essential analysis of the literature is leveraged to show how complexity disciplines, such as network science, have so far either evolved in isolation or have found collocation as a tool repository in support of the research carried out in other domains, linking apparently distant fields, such as ecology and engineering. It is not our intention to deliver a comprehensive survey of the literature in this broad area. Using examples we show that engineering-led approaches trail behind, not considering real experience of system evolution. We hence argue that a step change is achievable if complexity science is used to guide the understanding of the system, with a system engineering approach to manage the resilience of the system in a time frame identified by the cyclical occurrence of disruptive events, for which we propose a new, 1-D, periodic model.

The key argument that differentiates this article from others is that we suggest resilience investigation to recognize the temporal element of evolutionary adaptation in CES, presented at the core of the article in the form of a resilience wheel, and incorporate it in their process of continuous resilience evaluation.

Understanding the impact of emergence, interdependencies and other characterizing CES features on resilience should not be done in the system's specific framework (in our case engineering) but in a complexity science framework that can provide a privileged position for applying the system specific tools.

II. Essential and Quantified Analysis of the Literature

Resilience has its etymological roots in engineering [12], but a bibliometric analysis of the literature suggests that ecology is currently leading the investigation of resilience. Avoiding duplication with literature reviews on the topic, in this section, we produce a bibliometric analysis showing how complexity enters the theme of resilience under different labels, with a lack of a holistic view. Research on CES resilience is often restricted to specific technical aspects, with complexity science perspectives often overlooked.

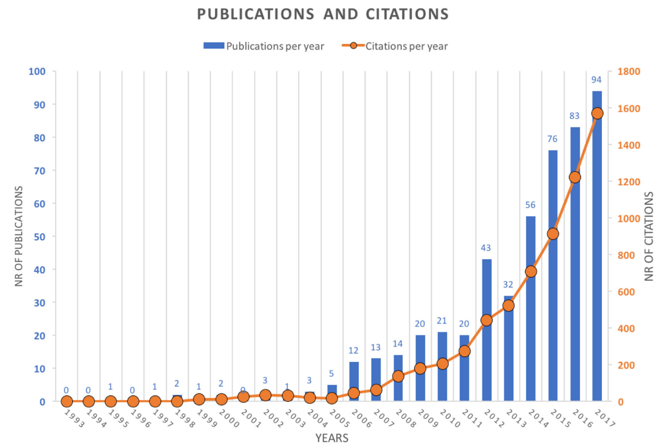

Fig. 1. Citations per year of the 503 elements found in the engineering subset (keywords *resilien**, *complex**, *engineering*). The last 25 years are considered.

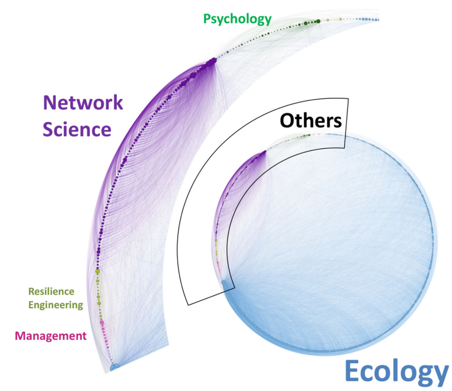

Fig. 2. Cocitation map for keywords "resilien*" and "complex*." Each pair of linked node is a pair of scientific papers cocited in one of the 8538 records returned by the research for the keywords.

A. Bibliometric Analysis

A literature search for the last 25 years (1993–2017) with keywords *resilien**, *complex**[1] identifies 8538 works (data webofknowledge.com). By adding the keyword *engineering*, the search identifies 503 works in the same period. The exponential growth that the field underwent can be measured through the number of works published and the citations they received (see Fig. 1). In order to classify both sets of works by their research areas, we performed a cocitation analysis, similar to the one in [13] for the field of industrial ecology. In a cocitation network, nodes can be authors, subject fields, or scientific publications. Nodes are linked if present or cited together in the same publication. A description of the cocitation method can be found in [14]. The visualization of the results (see Figs. 2–4) is obtained using Gephi [15]. We built two networks where nodes are scientific

[1]The * is a wild character to include all possible keywords starting with resilien and complex, e.g., resiliency, resilient, complexity, etc.

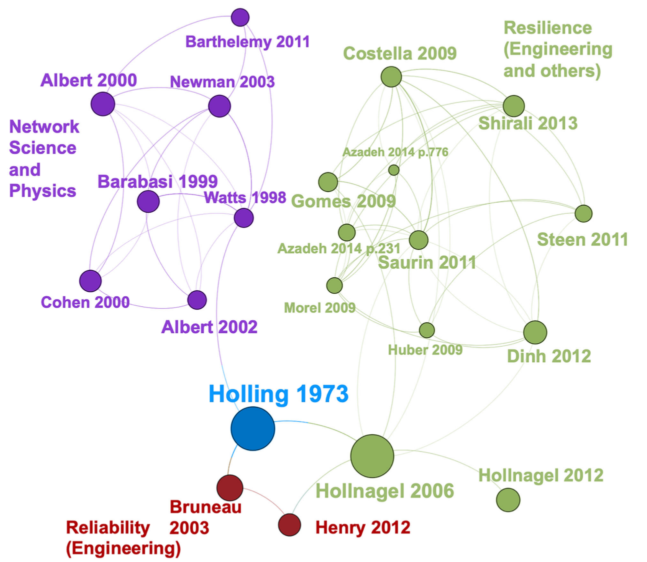

Fig. 3. Cocitation map for keywords "resilien*," "complex*," and "engineering." Each pair of linked nodes is a pair of scientific papers cocited at least five times the 503 records returned by the research for the keywords. The total number of nodes in this map is 22. For each node, the size indicates its degree while the colour indicates the subject group it belongs.

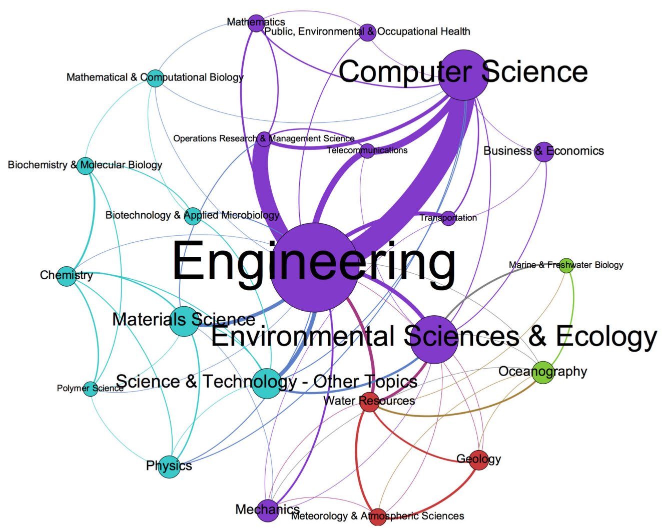

Fig. 4. Cocitation map for keywords "resilien*," "complex*," and "engineering." SC field, edge weight $\geq$ 5. Complexity does not appear and works in network science (present in the network of papers) is disguised under other labels.

works cited in the 8538 and 503 publications, where colours identify different subject fields while labels and authors were assigned by inspection.

The first cocitation map of the works referenced by the 8538 publications covering the topics of "complexity" and "resilience" is shown in Fig. 2. The field is dominated by ecology, meaning that works in complexity and resilience refer extensively to ecology research. Other important research areas are network science and psychology. Resilience engineering is a relatively small set in this collection.

Considering only the 503 publications of the engineering subset, a second cocitation analysis was performed. For clarity of representation, only publications cocited at least five times were considered (see Fig. 3). A fundamental work by Holling [16] that looks at ecological resilience is the center of this network and the strongest connection to engineering is through the work by Hollnagel [17], which sets the basis for the current understanding of resilience engineering.

Works framing the problem of resilience very well in its complexity, starting from engineering and moving beyond that, are those by Dekker, Perrow, and Vaughan in [18]–[20], respectively. These focus on catastrophic cascade failures and the role that a system's complexity plays in these. The fact that these works are cocited less than five times, and hence, do not appear in the network in Fig. 3, is possibly symptomatic of the field often looking at specific system resilience issues, abstracting them from the complexity attributes. In particular, already in 1984, Charles Perrow,[2] framed very well the problem of ensuring safe and reliable operations of systems that become hardly predictable due to their complexity. This is in part captured by the more recent work in [21] and some of the works in the resilience engineering cluster [22]–[28].

Papers in network science, such as the works by Watts and Strogatz [29], Barabasi and Albert [30], and Albert [31] are among the most cocited (hence, influential) documents in the set of publications. These works figure as highly influential despite their starting point being fundamental network science, rather than strictly engineering (examples considered come from biological and social networks, as well as the internet and the world wide web), and despite not explicitly referring to resilience, but rather looking at robustness instead. This, in turn, may suggest a possible explanation to the growth in publications and citations shown in Fig. 1 coinciding with the outbreak of network science in the late '90s. Moreover, it should be noted how resilience and robustness, although conceptually different, are related and often linked to other system's properties such as recoverability and reliability. The distinctions between these properties are not uniquely marked, and often the choice of referring to one or the other is field dependent [32].

We finally looked at the subject areas, as classified in the *webofknowledge* database (SC field), and made the cooccurrence map in Fig. 4, again cutting the weight of the edges (the number of times two fields are referred together to a single publication) to five. In the map, there is no clear indication of complexity-related disciplines, nor of network science that emerged clearly at single-paper level. These disappear under other labels used by the journals as interest fields, suggesting a secondary overall level of attention. This suggests the absence of a general framework of complexity science that is used as literature classification and that is a reference for the resilience of CES. Yet, through the scientific literature, the ideas of CES and resilience do emerge, if not clearly, at least in a discernible way. The next section will provide more details about these.

B. Link Between Complexity Science and Engineering

Engineering met complexity around the mid 20th century, with Wayne Weaver framing the problems of organized complexity as the new frontier for physics and Charles Perrow making evident in 1984 how engineering problems are of organized complexity nature [19], [33].

[2]The citation of Perrow's work [19] refers to the 1999 edition of his work. This was first published in 1984 through a different publisher

Baranger, Gell-Mann, and Bar-Yam in [34]–[36], respectively, are amongst those reinforcing the link and putting complex systems in relation with chaotic systems and entropy. Noticeably, Bar-Yam identified complex systems as an approach, as opposed to a family of systems, focussing on the relations and interplay amongst the system's parts and between the system as a whole and its part [37], [38], being supported by others in his conclusions [39], [40].

The approach prioritizing the interactions over the interacting parts was formulated through complex networks as a way of modeling complex systems, where the attribute "complex" indicates structures which are not fully regular (i.e., lattices) nor completely random. Starting from the seminal papers [29] and [30], many of the world's complex systems were modeled, associated, characterized, and explained through complex networks. From these it was just a short step to move into resilience themes, such as defining the propagation of a fault or the collapse of a network following the removal of some nodes [41], [42].

In recognizing characteristics, such as emergence, nonlinear interactions and, in many cases, continuous growth of the systems, engineers found themselves dealing with the problems that [33] classified as organized complexity, entering the realm of theoretical physics. Of the 43 metrics for complexity identified by Lloyd [43], measures used in engineering are mostly model-based, that is, they refer to a model of the system to capture features such as size, regularity, and interdependencies [44]–[46].

C. Resilience and How It Applies to CES

In engineering, a popular understanding of resilience points at the concept of bouncing back from disruptions, recovering some level of performance the system had before being hit by a shock [47], or exceeding the preshock performance after recovering [48]. The United Nations International Strategy for Disaster Reduction defines resilience more broadly as the system's ability to resist, absorb, accommodate, and recover from the effects of a hazard [49]. This definition is also shared by Linkov *et al.* [50] in their systemic approach to climate change, centered on uncertainty quantification and risk management. Adaptation to changing scenarios is a pronounced characteristic of organizational resilience that applies to individuals and communities facing adversities [51], [52].

With the breadth of engineering comprising a variety of systems as well as a variety of approaches, resilience can be captured generically as "*enduring disruption*." Irrespectively from how the definition applies to specific engineering domains, a common characteristic appears to be the lack of quantifiable *a priori* metrics. If the system has not yet experienced a performance loss, its resilience can hardly be quantified. In particular, it is difficult to account for the through-life aspects of resilience [53].

What makes CES resilience a complex matter on its own is that it exceeds the system boundaries. In Charles Perrow's fundamental work [19], opposite to expectations, added devices devoted to system safety, in fact, increase the level of complexity and failure sources. "Normal accidents" are, hence, endogenously generated within our society, and our engineering within it, in a rush toward higher and higher levels of complexity. Consider the example of a dam. The hydrogeological equilibrium of the catchment, the proximity of inhabited areas and the climate are some of the elements that make the dam something more than a water retaining structure. It is in all respects a CES, even in the case that the water retaining structure is the only engineered part of it. In 2011, the Brisbane river catchment was hit by persistent torrential rain for days before the January catastrophic floods. The rain and the inflow from other reservoirs filled the Wivenhoe dam, rapidly passing the levels between which dam operators could exert some discretion in deciding for water spillage. At the point that spilling was a necessity to avoid structural damages, all the surrounding water ways were already full and the spillage determined the catastrophic flood [54]. Operational procedures were followed without flaws by the dam operators, but the multiple, persistent shocks to which the whole ecosystem was subjected showed the lack of resilience in the associated CES [55]. Other relevant examples within and beyond water engineering are the 1967 earthquakes in Denver [56], the cases of the Kariba dam [57] and the Koyna dam, in India [58].

The ever-changing scenario, including both the environment surrounding the system and the system itself, is the fundamental aspect that appears overlooked by the current approach. The "Red Queen hypothesis" was first formulated in [59], again in an ecological context, establishing the link between species' resilience to extinction and their ability to quickly adapt to changed conditions. The ability of species to adapt to new environmental conditions faster than the rate of change of these could explain the survival of species and complement Darwin's natural selection law by including elements of adaptation. This concept translates to CES when considering the ability of systems to adapt to ever-changing operations and operational scenarios. The quicker CES achieve a new stable operating condition, the more resilient it will be. System adaptability during distress periods and before, while a system naturally evolves and new technologies are bolted onto old substrates, is hardly captured in traditional resilience engineering research.

D. Resilience for CES—The Example of Aerospace Systems

The design and operations of aerospace systems require high levels of reliability (the ability to perform under specified conditions and for a specified time) and robustness, because of the difficulty in recovering from degraded states or failures. Space systems have to operate without maintenance for several years in harsh environments. Launch systems (both expendable and reusable) need to achieve reliability over 90% for nonhuman-rated flights and over 96% man-rated flights. Robustness and reliability approaches in aerospace are described in [60]–[62].

An example of dealing with increased complexity due to increased autonomy is the failure detection identification and recovery (FDIR) system, which is able to detect (possibly predict) failure and can implement actions for system recovery. Beyond reliability and robustness, resilience is addressed in aerospace through the failure modes, effects, and criticality analysis (FMECA), an examination of the possible causes of faults and consequences from its propagation across subsystems [63]. This attention to the robustness and reliability of the aerospace products does not always guarantee the resilience of the larger system these products contribute to engineer.

Airplanes and spacecrafts are self-contained aerospace products and complex engineered systems. An important layer of complexity is added when these objects are coupled with other systems, where not everything is known and there is not necessarily a design envelope through which it is possible to define normal operations. As an example, the failure, and successive recovery of the Telsat Anik E-2 and Anik E-2 satellites, in January 1994, caused an interruption of cable TV, telephone, newswire, and data transfer services through Canada [64]. More recently, the eruption of the volcano Eyjafjallajokull paralyzed air traffic over the Atlantic and in most of Europe due to the unknown risk associated with it [65].

E. Common Resilience Problem Across Engineering Domains

Across all engineering systems, resilience suffers from the unpredictability of disruptions originating both outside the design domain but often within the wider system, considered as the engineered part and the environment in which it operates. The resilience of a system has and should be put in connection with its complexity, as pointed out for example in [66], yet when looking at the system complexity, one should look beyond the system boundaries. The environment can be a source of systemic threat, such as in aerospace systems with the presence of particles in suspension in the atmosphere. This overlooking of the wider system emerges from our bibliometric analysis, with resilience and complexity often restricted within more specific research fields. CES suffer from stratification and changing demand patterns that accelerate obsolescence making single nodes, designed in isolation, harmful to systemic resilience. The need to achieve multiple objectives (safety, affordability, etc.) as well as resilience is a defining characteristic. These considerations call for reconsidering resilience as a continuous process aimed at understanding the system in its complexity. This is the point of our next section.

III. Holistic Approach to the Resilience of CES

The literature offers numerous definitions for resilience and it is not our intention to impose a new one to win them all. However, it is our scope to explain our position about the problem of designing and managing CES. To be able to proceed, acknowledging the always increasing complexity of contemporary engineering systems, we provide a definition for resilience of CES.

Resilience of CES is the system ability to prepare by building system awareness, identify premonitory signs by monitoring key nodes and knowing their weaknesses, being robust at node level (component or subsystem) to avoid collapse during speculated adverse events, revise the system objectives by reconfiguring and/or exploiting redundancy through the complex interplay of its parts, and recover full service by reinstalling operations to meet reviewed system objectives.

In light of this definition, resilience becomes a defining feature of CES. It is a measure of how the different system parts subsidize each other and work together in reinforcing each other. Resilience intertwines with other characteristics such as the distributed and heterogeneous nature of complex systems, the need to gather meaningful information from a wide variety of sources and adaptation in respect of the system goals. This intersection between resilience and CES elicits the emergence of natural research questions related to the applications of research methods. How the rapid succession of multiple shocks is responsible for cascade failure and sudden collapse is probably the most evident of these. Also, how does the structure of the CES influence its resilience? What design mechanism is needed for CES systemic resilience? What are the resilience-critical nodes and the edges to consider for different types of shock? And so on. This list of questions is of course not exhaustive, but provides an idea of the breadth of the field that opens up at the intersection of resilience and CES. Even more than that, the questions highlight the role played toward system resilience by a thoughtful understanding of the complex structural and dynamical interactions within and across systems.

A. All-Round Resilience Concept

The engineering systems' literature recognizes the existence of strong coupling among engineering system components, natural surroundings, infrastructure availability, and interacting social systems, and argues that these complex interdependencies necessitate the study of engineering resilience from a complexity perspective. A complex system perspective provides the necessary theoretical foundation and analytical framework to study the dynamic and emergent nature of system resilience. It is often argued that system resilience can only be observed when a system is exposed to unfavourable events, perturbations or signals and inputs beyond normal operating or design conditions. Thus, a longitudinal study of the system and events over time provides the best opportunity to observe, measure, and comment on the resilience performance of the system design. Based upon this premise and on similar arguments from the literature (e.g., [19], [67], [68], etc.), we converge to a simple framework or concept of complex engineering system resilience. This is one dimensional and temporal. The framework arises from juxtaposing and consolidating existing literature, and has validity from a deductive perspective. It presents the building up of system resilience as a continuous learning process based on the analysis of the system, its weaknesses and occurred failures to prevent these from happening again. We shall call such framework the *resilience wheel*.

The resilience wheel frames resilience around the changing state of the system around a disruptive event, when passing from the normal operations to a series of contingency and recovery states. To each system state, the framework associates resilience objectives that the system has to achieve, functions to absolve, and event features to show resilient behavior. This way, the resilience wheel merges the phases and pillars for resilience introduced by Madni and Jackson [69] with the increasingly popular understanding of resilience as continuous application of risk management practices [70], which we argue to be the way resilience should be understood for CES. As we can see, the system sequentially passes through five distinct phases in response to a threat. Each phase provides a separate viewpoint to explore the phenomenon of resilience. The idea of a continuous cycle of improvement was recognized by Hollnagel [71] stating that a resilient system needs to know what happened

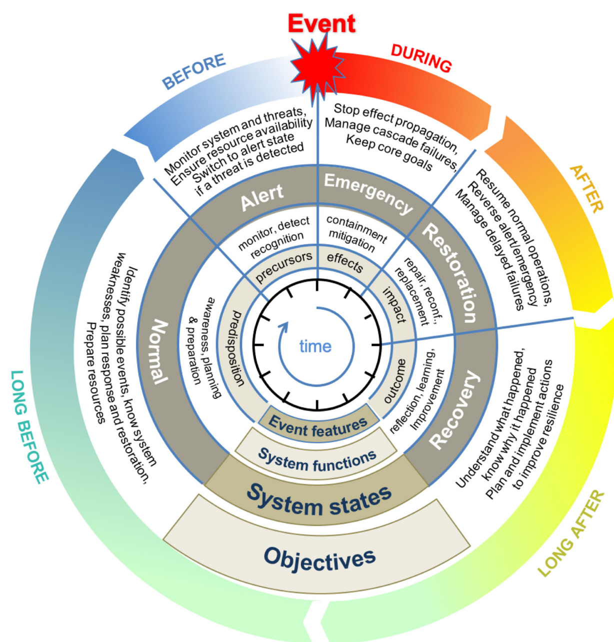

Fig. 5. Resilience wheel is a 1-D temporal resilience framework.

and learn from it. The proposed concept follows this approach by identifying learning that is achievable through a complexity perspective.

Referring to Fig. 5, the five phases are termed as long before, before, during, after, and long after. The phases are usually different in length, with the during phase being the shortest, and long before and long after phases being much longer than the rest.

In order to characterize the system, we are going to describe its resilience objectives and the way the system achieves them, i.e., system functions. In addition, the event features for each state are defined—predisposition, precursors, effects, impacts, and outcomes corresponding to the system states normal, alert, emergency, restoration, and recovery, respectively.

1) Long Before: The long before phase refers to the period where there are no active or impending threats to the system and the system is operating under normal design conditions. However, despite being at a performance optima, a resilient system will have processes constantly monitoring the system for anomalies and threats and would also maintain system resources and parameters to be sufficiently available in case of any eventuality or crisis situation. The system could be argued to have a degree of self-awareness and standby preparedness achieved through the observation of the system outputs and variable, only possible through the knowledge of what are the outputs and variables to observe.

2) Before: Engineering systems are designed for diagnosis and prognosis of threats and vulnerabilities originating within the components of the system. However, as CES are nested in other systems with several complex interdependencies extending far beyond their direct control or influence, it is far more important to monitor the vulnerability and threats originating in the extended network of systems. Often there is a lag between an event and its impact being felt on a connected system. The resilience wheel refers to this time period, from the time of detection of a vulnerability or threat to the time when this adverse event actually impacts the performance of the system, as the "before phase." A more resilient system would be capable of recognizing a threat earlier and would also be able to quantify the severity of the impact. Early detection, informed by prior system knowledge and training, can considerably reduce the response time and help restrict the severity of impact.

3) During: In this phase, the system is directly subjected to the negative effects of an unfolding threat and may lose its normal state functionality in part or in full. Adaptation plays a fundamental role in system resilience while disruptions are unfolding. This may include changes to system structure and operational procedures. An often overlooked aspect of adaptation is a change in system goals. Considering that the goals of the system have a significant impact on its functioning, they can be one of the most effective ways to adapt to changing conditions.

The functional focus of a system in an emergency state is to withstand the negative effects of adverse events by mitigating them and preventing propagation of effects and cascading failures through the system and beyond the system's boundary, a process known as containment. While doing that, the system needs to document the extent of damages as well as mitigation and containment actions to the best of its ability to be used later in the recovery and learning phase. To ensure an effective response, the system makes use of resources that were planned and allocated during the *long before* phase. Yet the system benefits from the processing of outputs observable during the distress phase. An understanding of what these outputs are is achievable only if the system knowledge is developed to the point of modeling the effect of a disruption ahead of this happening.

4) After: The after phase is concerned with recovery from disruptions caused by adverse events and exiting the alert and emergency states. As the recovery progresses, core goals are being supplemented and replaced by an extended goal set pertaining to normal functioning of the system. This extended set may be the same as the original set of goals in the long before phase, as the system "bounces back" to its original state [72], or "forward" to an adapted state, resulting in delivery of a new extended set of goals [73], [74]. To achieve the transition from core to an extended set of goals, the system can reconfigure, repair, or replace itself or one of its subsystems. After suffering an adverse event, there may be multiple equilibrium points requiring a coordinated recovery effort from interconnected subsystems [75]. Uncoordinated restorative actions may cause deadlocks in interconnected systems [76] and create cascading failures. Only an overall, systemic consideration of the system can deliver a coordinated action.

5) Long After: In the long after phase, the system operates in conditions that will be regarded as normal. However, in this phase, a resilient system would be simultaneously engaged with the process of analyzing and learning from the events that impacted the system. A complete analysis and assessment of system impact could take a very long time.

In a continuing process of resilience improvement, results from the analysis and deduced structural or process improvements are continuously adopted by the system to make it more resilient. While the system learns and adapts to past threats, this long after phase slowly slips into the long before phase, and the process continues in a cyclic manner.

B. *Examples of the Resilience Wheel in Action*

The resilience wheel posits the need for evaluation of changing system conditions and requirements over an extended period of time, which is often missed when an engineering system is designed and tested for reliability using a functional design approach and a range of scenarios. It is logical to argue that these scenarios are not capable of providing an exhaustive set of conditions, particularly the ones arising in nested systems of systems (comprising of weather, infrastructure, social systems, etc.). These system behaviors and conditions are path sensitive and need to be evaluated on a real-time basis using a resilience framework, such as the resilience wheel; failing to do so may result in a disaster. There are numerous examples of disasters that happened due to a lack of understanding of system resilience and its dependence on other connected systems. A full validation of the framework would require analyzing systems where this is implemented and comparing them to systems where it is not. Besides being difficult to achieve, this is outside the scope of this work. We shall nevertheless provide two examples of CES failures highlighting their links to the phases in the resilience wheel. The first is about the Challenger and Columbia disasters from the NASA space program—a program that, ironically, is considered to have popularized the reliability testing methods of engineering systems. The second is about the collapse of the air traffic network following the eruption of the volcano Eyjafjallajokull, previously encountered in Section II-D.

1) From Challenger to the Columbia: In the Challenger disaster, the low-temperature issue leading to the sealing failure of the "O-rings" [77] was known to the engineers but the consolidated practice of launches at low outside temperature reinforced the view that the risk was an acceptable one. Vaughan called the practice "normalization of deviance" which refers to the attitude of people becoming accustomed to behaviors, events, practices, and processes that they normally would have considered wrong or deviant from their own perspective [20]. Feynman described it as "when playing Russian roulette, the fact that the first shot got off safely is little comfort for the next" [78]. With the STS-107 Columbia disintegrating at re-entry, history repeated itself. The foam detachment issue at the origin of the problem was a well known risk, a recurring issue already noted in mission STS-7 and STS-112. It was classified as an "accepted risk" for STS-113, launched one month before the STS-107 Columbia [79]. The parallel with the Challenger disaster is evident [80], with the NASA blamed for negligence in official circumstances [79].

The Columbia incident lifted the curtain over a system far more complex than the space shuttles and space transportation system (STS) programme. Normalization of deviance did not occur at the vehicle level. It was an organizational problem showing a lack of resilience within the extended system, in which the shuttle was just a "component." The shuttle failure, at least in the Columbia case, was a consequence of the lack of resilience of the system (intended as organization) within which it was operating.

The events between the Challenger and Columbia accidents can be mapped to the resilience wheel 5, where we can consider the system to be the NASA, whose objective is to enable manned space flight within the STS programme. At the time of the Challenger event, in the *during* phase, the STS programme was halted causing a disruption to the western access to space. The *after* phase finished with the launch of STS-26-R Discovery on 29th September 1988. The restoration included a new safety paradigm and changes in the management at NASA, as it was clear how misjudgment more than a technical failure were the reasons for the explosion [20]. The *recovery* of the system in the *long after* phase saw an in-depth understanding of the process dynamics that determined the incident, but failed to remove some of the causes that Vaughan indicates as reasons for the normalization of the deviance. Among these, the hierarchical organization that made safety-related decisions became a management and not engineering concern. The *after* phase from the Challenger event appeared concentrated more on the technical aspects than on resolving the normalization of the deviance. This continued during the following *long before* phase of the Columbia event, with normal operations overlooking the foam shedding problem, and eventually made ineffective the predictive power of the *alert* in the *before* phase as threats such foam shedding were overlooked.

2) North Atlantic Air Traffic Collapse in April 2010: On 14th April, 2010, a mix of magma and meltwaters from the Eyjafjallajökull glacier generated an explosive eruption sending fine-grained ash the atmosphere. The jetstream quickly dispersed these over Europe. On the basis of previous encounters between airplanes and volcanic ashes, causing some jet engines to fail, the air traffic across most Europe was grounded for several days and intermittently in the following weeks [81]. It is estimated that, to the aviation industry alone, this costed 250 million per day [82]. It can be argued that the air traffic control showed some resilience by avoiding the risk of air disasters. However, this course of action was driven more by the uncertainty about the effects of volcanic ashes on jet engines, rather than the certainty that such a concentration of that specific compound could be fatal. Even accepting that the closure of the airspace was inevitable, the lack of preparation, alternative routing, or technological solutions to ensure a minimum continuity of service, were not in place. Analyzing the events, it appears how in the *before* phase, premonitory signs were advisable as the eruption culminated 18 years of intermittent volcanic activity [83]. The fact that immediate short-term eruption precursors may be subtle and difficult to detect highlights the gaps in science (in this case geophysics) that we advocate should support engineering. The fact that the *during* phase was dominated by uncertainty highlights the lack of knowledge across fields and the research gap on the specific effect on engineered systems [84]. Once achieved, this should not rest within the engineering of turbomachinery, but reach out to the air traffic regulations and operations. The same uncertainty dominated the *after* phase, when air traffic was intermittently restored. The *long after* and the *long before* phase lead up to the present days, with analysis that saw network science used in the attempt to explain why a pointwise threat became a continentwide problem [65]. Several voices are now calling for greater cooperation between scientists and aviation-sector service providers to provide support to decision-makers [85]. With the premonitory signs now being more clearly identifiable and with the research that is currently undergoing, the opportunity arises for better preparation to be made in the new *before* phase. This appeal is an example, limited to the problems of the aviation sector, of the general position expressed in this article. How this appeal will be received and how quickly we realize that the same can be extended to all CES domains will shape the resilience of our society through the systems on which it depends always more.

IV. Conclusion and Way Forward

The rush toward integrated, intelligent, and synchronized transportation, new energy sources, congestion-free urban environments, and their realization is associated, in many cases, to a matter of "just" engineering. This so far successful approach is revealing less capability to deliver resilient systems as the boundary of systems are trespassed by increasing interconnectivity where systems evolve in response to the evolving surrounding environment. We acknowledge that all engineering systems have some degree of complexity—from Roman aqueducts to Babbage difference engine, but the complexity of such systems was confined in time and space. Modern CES, those we are concerned with, evolve over time, bolting new onto old technologies and in space, interacting and changing the environment (natural, technological, social, urban, economic) in which they operate. Our analysis of the literature confirmed that engineering systems are perceived as complex but there is not a defined and self-standing research stream looking at their resilience as complex systems as opposed to specific, domain-bound systems. The most popular engineering resilience definitions, even within specific sectors, do not capture evolution and crossing boundaries, appearing often inadequate. In response to this, we argue that the understanding of a system is a proxy for its resilience. It is the key point in preventing, mitigating, adapting, and improving after failures. This understanding, which translates into learning around its failures, can only be captured using a complexity perspective. There are multiple possibilities through which this can be practically addressed. One can be summarized as investing in research to progress complex system modeling to integrate specific systems' and environment's features. The new models, while incorporating real system features, should keep the analytic tractability of abstract models, currently more popular in science than engineering. In this way, the new models can be useful to understand and predict complex system behavior by uncovering and leveraging their fundamental dynamics.

As engineering systems evolve and do so at an increasing pace, the design approach must evolve to incorporate the fundamentals of complexity science. This will push designers to look beyond strictly engineering to incorporate wider system aspects into their job, enabled in this by the analytic tools that complexity science can deliver. As Newtonian physics underpins our world from the engineering of road bridges to the principles of flight, so complexity science will underpin the understanding, at least partially, of why cities are central for economic and cultural prosperity, how the self-organization of the national grid allows for handling, within some limits, a variety of load profiles, and so on, up to deceptively simple phenomena such as the effects of roundabouts on the traffic flow. Having such understanding will allow learning across all phases of the resilience wheel before the following shock hits the system. Achieving this passes through research that bridges fundamental and abstract knowledge to actual system dynamics. There is the need to conjugate heterogeneous systems and be able to model their joint dynamics in a way that captures nonobvious interactions, including those which arise as a later result of the whole system's evolution. At the same time, resilience engineering needs to evolve to embrace complex features in understanding and designing of systems changing over time or presenting new features following a change in their environments. These ever-changing features of complex systems are nowadays instrumental to the object of resilience engineering.

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