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Defining Resilience for Engineered Systems

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Abstract

This paper surveys the literature on resilience, provides several definitions of resilience, and proposes a new comprehensive definition for a resilient engineered system, which is: *a system that is able to successfully complete its planned mission(s) in the face of disruption(s) (environmental or adversarial), and has capabilities allowing it to successfully complete future missions with evolving threats.* This definition captures the subtle differences between resilience and a resilient engineered system. We further examine the terminology associated with resilience to understand the various resilient time-frames and use the terminology to propose a resilience cycle, which differentiates mission resilience (short term) and platform resilience (long term). We then provide insight into various resilience evaluation methodologies and discuss how understanding the full scope of resilience enable designers to better incorporate resilience into system design, decision makers to consider resilient trade-offs in their assessment, and operators to better manage their systems. A resilient engineered system can lead to improved performance, reduced life-cycle costs, increased value, and extended service life for engineered systems.

Keywords: adaptability, engineered systems, flexibility, recoverability, resilience

1 Introduction

In this paper we review existing resilience literature with a focus on engineered systems. We focus on engineered systems (systems designed, developed, and implemented by using a systematic engineering process) because engineered and natural systems work and respond differently. Our focus is on deployable engineered systems.

Resilience is not a new subject; it has been examined in a variety of fields for decades. Ecology and psychology have historically studied and made use of the term resilience most often. Resilience has recently become a research topic in man-made systems, primarily in the areas of networks and infrastructure. Engineered systems, which are systems created by and for people and are designed to satisfy key stakeholder's value propositions, are the most recent field to incorporate resilience concepts (Engineered Systems glossary 2018). Specifically, when designing large complex engineered system platforms, such as Department of Defense (DoD) weapon systems, the designers and decision makers are more interested in incorporating resilience into these systems. To perform better in today's increasingly connected world, this research topic is being extended to collections of individual systems called systems of systems (SoS).

Engineered systems benefit from clear definitions and methods of measurement. Currently, resilience is not defined for engineered systems in a way that incorporates the entire scope of resilience. Literature reviews substantiate that there has been no complete or agreed upon method for evaluating engineering resilience (Hosseini, Barker, & Ramirez-Marquez, 2016; Sheard & Mostashari, 2008; Reid & Botterill, 2013). Most discussions of resilience focus on design principles and methods for improving resilience.

This paper compiles the definitions from the existing literature and develops a definition for engineered systems resilience that does not include the means to attain resilience as part of the definition. The means to achieve resilience span a wide array of time frames from predesign until after the system has been deployed and completed many missions. Accordingly, we incorporated all the time frames over which resilience should be considered into our definition. To better understand the effect that time plays on engineered systems resilience, we partition these timeframes using the proposed Resilience Cycle into two segments: mission resilience and platform resilience.

This definition and the associated framework allow for a better discussion of resilience, which can aid in the design, development, operation, and evaluation of a complex system. By considering the entire resilience cycle we can improve analysis and evaluation of resilience in these engineered systems. This improved analysis allows for better product life cycle management, which is crucial for improving the performance of new product development (NPD) (Tai, 2017).

We start this paper by providing an explanation of the literature review process and a summary of the current state of the engineered system resilience literature in order to identify common trends. Next, we examine the various terminology related to resilience in order to understand their connection to resilience. We then review the existing definitions, explain the short-comings of these existing definitions, and propose a new definition for a resilient engineered system. Finally, we introduce the Resilience Cycle as a framework to better differentiate the multiple aspects of resilience and discuss the implications of resilience to the systems design and management process.

2 Engineering Resilience Literature Review

2.1 Resilience Literature Review Process

A structured literature search was performed to identify and evaluate the proposed qualitative and quantitative definitions of engineered systems resilience. The literature search included peer-reviewed journal papers, conference papers, technical reports, and International Organization of Standardization (ISO) standards. We focused on the linkage between qualitative and quantitative definitions of engineering resilience and the context of each definition. We also considered modeling approaches and evaluation metrics used to assess engineered resilience.

We conducted this literature survey in three parts. In the first part, the existing survey papers on resilience were reviewed to determine if a need existed to further explore engineered resilience or if it had been sufficiently explored. Eight survey papers were reviewed. While some specifically discussed engineering resilience, none of them focused on the engineering domain. These papers served as a starting point for the second part of the literature search, in which the citations from the survey papers were explored to find the most relevant papers for engineering resilience. This effort considered engineering journals, ISO standards, the Systems Engineering Body of Knowledge, and the International Council on Systems Engineering's (INCOSE) Systems Engineering journal. We also examined recent engineering conference proceedings. The International Organization of Standardization does not include resilience in the systems engineering standard. The only standard reference to resilience is in ISO/TC 292 – Security and Resilience, which was not pertinent to engineered systems as it focuses on community and organizational resilience (International Organization for Standards, 2016). The final source that we reviewed in this portion of the literature review was the Systems Engineering Body of Knowledge (SEBoK). In addition to the eight survey papers on resilience, this portion of the literature review found 38 papers that provided some definition of engineering resilience.

For the third part of the literature review we used a systematic literature review. Cronin et al. (2008) provide detail information on the systematic literature review process. Our searches included the Web of Science, ProQuest, and Google Scholar databases. A search was performed on the terms:

- Resilience
- Resilience 'and' Engineering
- Engineered Resilient Systems

For each of these search terms in each database we reviewed the 100 most relevant papers. The following criteria were used to determine which of these papers were relevant. The paper must:

- be a journal or conference proceeding
- discuss engineered resilience
- provide a definition of resilience

The first criterion ensures only peer-reviewed references are used. The second criterion excluded many papers that used resilience in reference to psychology, ecology, and socio-ecological systems. The final criterion ensured that a paper did not simply state that resilience was added, but actually defined resilience. Any papers that used another author's definition were excluded in favor of the original source of the definition. The first two criteria were able to be assessed by using the meta-data for the title and the abstract. This eliminated 856 paper, leaving 44 papers. For those 44 papers we checked for the third criterion and found eight papers that featured a new definitions of engineering resilience. This brought the total relevant paper count to 54 papers for inclusion in our analysis. Figure 1 shows the results from each stage of the literature search, while Figure 2 shows the process that was used for the structured literature review in the third stage.

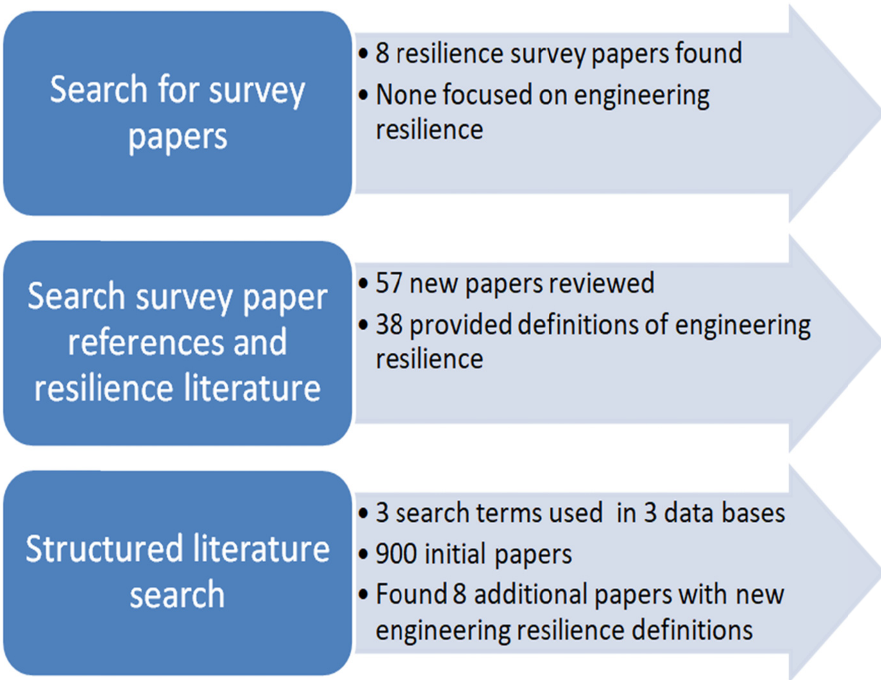

Figure 1. Literature survey results

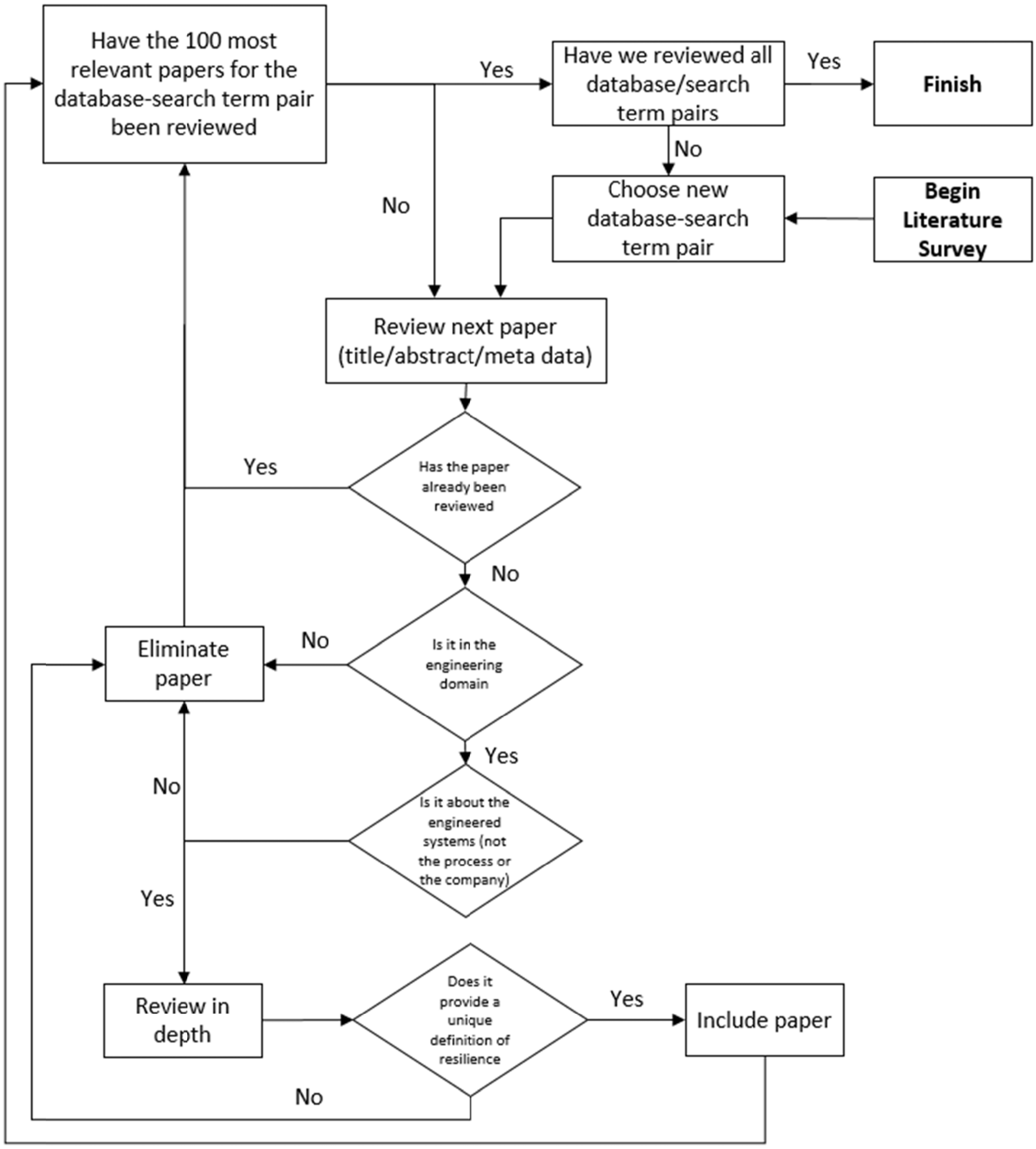

Figure 2. Structured literature review flow chart

Figure 3 shows the journal sources and their corresponding number of articles out of the 54 primary source papers reviewed. Figure 4 shows the date of publication for all of the primary sources reviewed. A majority of the sources were published from 2010 to 2015. While there has been a steady increase in publications on resilience, most of the articles being published in the last few years are using derivatives of existing definitions, which is why those years appear underrepresented in this literature search.

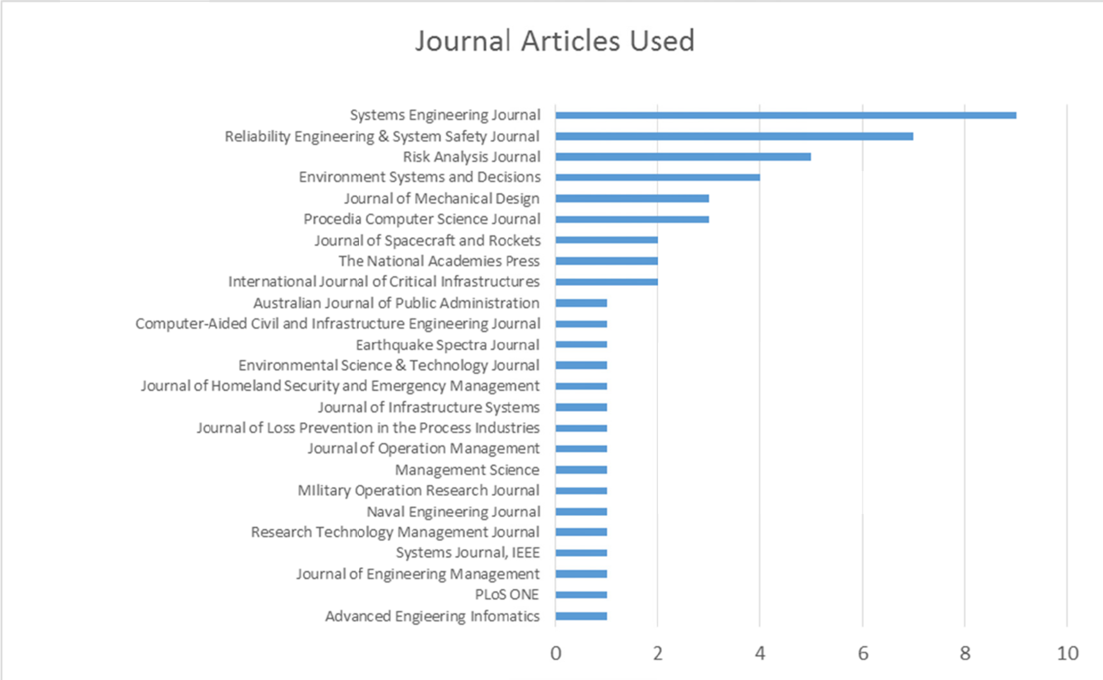

Figure 3. Number of engineering resilience articles by publication

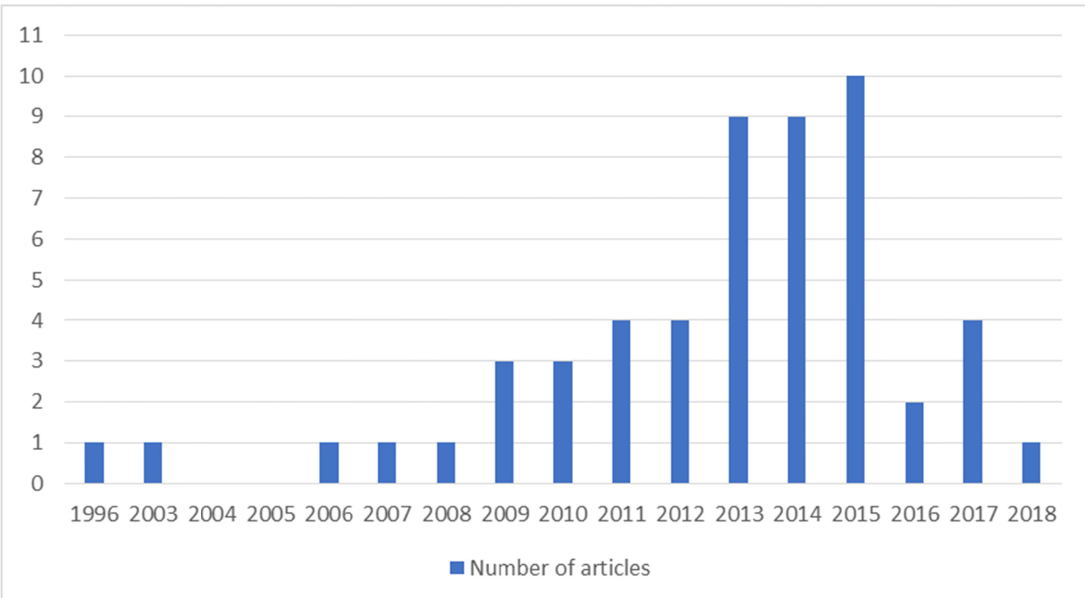

Figure 4. Number of engineering resilience articles by year published

2.2 Resilience Survey Papers

The survey papers on resilience clearly revealed that resilience is not a new topic. Resilience is defined qualitatively in various domains, but the research contained few papers that defined and quantified resilience in the engineering domain. Sheard and Mostashari (2008) presented a Framework for a Systems Resilience Discussion. The takeaway from their paper was a description of the aspects of resiliency: what is the system being discussed, what are the time frames considered, what are the events it is resilient to, what are the actions that are performed, and what qualities is the system trying to preserve through those actions? Erol, Henry and Sauser (2010) reviewed a range of disciplines that included materials science, ecology, organizational theory, economics, risk management, sociology, and psychology, but did not include engineered systems, such as infrastructure or mechanical systems. In 2013, Reid and Botterill identified multiple meanings of resilience (Reid & Botterill, 2013); however, only four papers considered engineering resilience. Ryan, Jacques, and Colombi (2013) noted the confusion of resilience terms that included flexibility, adaptability, and robustness. Later in 2015, Larkin et al. (2015) described how various United States governmental organizations defined and measured resilience and identified four resilience functions: plan, absorb, recover, and adapt. This resilience framework considered four different time frames: before a threat, during a threat, in the short term after a threat, and in the long term after a threat. Uday and Marais (2015) looked at resilience in more complex systems of systems (SoS). They noted that at a basic or component level, reliability and resilience are very similar, but begin to differ drastically with increasing complexity towards a SoS. They noted that they "were unable to find any published papers that provide a focused review of designing and operating resilient SoS" (p. 492). They outlined ten design principles that can be used to increase resilience but acknowledged there are currently no methods that satisfactorily evaluate resilience. A recent resilience literature survey reviewed the definitions and measures of system resilience and looked at 144 different sources, 12 of which were in the engineering domain (Hosseini, Barker, & Ramirez-Marquez, 2016).

Based on our initial analysis of the literature, we determined that there is a need to focus on a narrower definition of resilience that is specific to the engineering domain in order better define the term "engineered resilience." In addition to understanding the current literature on the definitions and measures of engineered resilience, this paper will clarify and organize several related terms in the literature

2.3 Attributes of Engineering Resilience Literature

In Table 1, the 44 papers with resilience definitions are classified using 9 categories (author, publication year, number of citations, definition, time, model, system type, methods of improvement, and application) to provide insights into the different attributes of each paper. The publication year and the number of times the work has been cited according to Google Scholar (Google, 2018) provides insight into the timeframe of the article and its impact on other scholarly work. Figure 5 summarizes the relative frequency of the information found in Table 1.

The definition category had three subcategories: qualitative, conceptual framework, and quantitative. Qualitative definitions describe resilience. A conceptual framework provides a more complete understanding of resilience. It describes how resilience factors into the systems operation throughout its life cycle and how it interacts with other characteristics of the system. Quantitative definitions are methods that mathematically evaluate resilience. The quantitative definitions included area-under-the-curve analysis, network performance, and several other calculations that viewed resilience to be an extension of an existing concept (e.g., safety or reliability). While at least one of these methods of defining resilience was a requirement to be included in our literature survey, 19 papers provided definitions that fit into two or more of these categories. Most papers contained either a qualitative or conceptual framework definition rather than a quantitative definition. Categorizing each paper revealed that most of the research on engineering resilient systems has focused on qualitative definitions (39 papers contained qualitative definitions or conceptual frameworks while only 19 contained quantitative definitions). Without understanding exactly what resilience is and how to measure it, there is no way for managers to assess its value in the design space.

The time category classifies each paper based on the resilient time frames. These time frames are before the disruption, during the disruption, short-term-after the disruption, and long-term-after the disruption. Before the disruption involves planning for and designing for disruptions the system might encounter. During the disruption involves any action while the disruption is occurring such as surviving, absorbing, resisting, avoiding, and repelling the threat. Short-term-after involves restoring the system after a disruption, including recovery, flexibility and adaptability. Long-term-after the disruption, includes flexibility, adaptability, engineering change, and modifying the system to better handle any new disruptions that arise. Most of the papers considered resilience during and in the short-term-after timeframes. This time categorization is a building block of our Resilience Cycle, discussed later in the paper.

Since a quantitative model is an end goal of defining engineering resilience, the 44 papers were classified by the type of model used. The model categories included single objective, multiple objective, cost, or value models. The most complete model used a multiple objective model that included cost and value (Sitterle, Curry, Freeman, & Ender, 2014). The quantitative definitions typically focused on a single objective and related cost models. This review demonstrated an opportunity to create a more complete quantitative evaluation method that includes multiple objectives, value and cost models, which can be tailored to an organization's preferences and goals.

The next category in the table is the system level presented in the paper, with options being component, subsystem, or system of systems (SoS). Every paper reviewed discussed the resilience of a system; however, many of these also considered how other levels of a system impacted, or were impacted by, the system's resilience. This category proved enlightening because the way resilience applies varies at each level of the system. Understanding these variations is useful during new product development. The resilience of a single car's engine is different than the resilience of the Humvee vehicle platform and those are both different than an onboard navigation system that is used across multiple vehicles and platforms. In general, the lower the level of the system, the easier it was to evaluate resilience. The resilience of individual components was stated to be the same as reliability (Shafieezadeh & Burden, 2014). Ayyub (2014) continued to evaluate resilience as an extension of reliability through to the system level. In his calculations, he showed each additional component reduces the resilience of the system as it increases the likelihood that any one component could fail. This does not consider the complete view of resilience which could incorporate redundancy and the specific impact of the component failure. Taking a limited view of resilience in the system design phase could cause significant delays during new product development or even worse yet, be released and provide poor functionality and reliability to the customer. The primary discussion of components and subsystems was how they impact the resilience of the system, through practices such as redundancy, flexibility, and modularity (Madni, 2012; Jin, Li, & Kang, 2017; Mitchell, 2007; Dinh, Pasman, Gao, & Mannan, 2012). Some authors believed that components viewed in isolation gave no information about resilience, and that one must evaluate the entire systems performance in order to make any useful claim about resilience (Park, Seager, Rao, Convertino, & Linkov, 2013; Alderson, Brown, & Carlyle, 2015).

System of Systems was the final level in the category. The majority of papers that discussed SoS were infrastructure related. A SoS must have two primary characteristics that distinguish it from a system and subsystems – managerial and operational independence (Maier, 1996). This means that not only can the system operate without the other systems, but that it is typically operated independent of the greater coordinated SoS. Many of the examples and demonstrations also focused on natural disasters, as seen in the application column of Table 1. SoS was not always the terminology used by the author to refer to this concept. Ettouney (2014) referred to systems as assets and a community was a collection of interdependent related assets, which aligns with the definition of a SoS. These SoS cases were the most difficult to evaluate resilience in, with only one paper that discussed SoS providing a quantitative definition of resilience (Guariniello & DeLaurentis, 2013).

The last two categories were methods of resilience improvement and application area. A paper was categorized as containing a method of improvement if it provided a means or suggestion on how to improve resilience, such as adding redundancy. Twenty-one of the papers discussed ways to improve resilience. While we have referred to these ways to improve resilience thus far as means, many of the authors refer to these as design principles. Once we fully define resilience and begin to quantitatively assess it, these means and principles can provide the basis for developing more resilient systems. These more resilient systems can contribute to better overall product designs. The application category was used to identify the application domain. The most frequent applications were for generic engineered systems and infrastructure.

While these are the common attributes we identified and discuss, it is important to note that the literature discusses other important resilience constructs. This includes operational resilience, proactive, and reactive resilience.

2.4 Literature Trends

Qualitative definitions of resilience were the most common as it is difficult to discuss a concept without providing at least a basic description of that concept. Many of these definitions were variations on the traditional (material-science) definition of resilience referencing how much energy could be absorbed and elastically released upon unloading to create no permanent deformation (Callister, 2017). This definition is only concerned with the during and short-term-after time periods, which are the most commonly discussed time frames, both appearing in over eighty percent of the papers. Only three papers discussed neither the during or short-term-after time frames. The remaining two time frame categories took a wider view of resilience noting that actions could be taken before a disruption ever occurs to impact resilience, and well after the disruption has been resolved but before the next disruption arrives. Generally, both of these timeframes can be thought of as planning. Nineteen papers recognized this need to include planning when considering resilience.

Just under half of the models had no consideration of cost. Only one paper used a cost model without a corresponding single or multiple objective value/performance model. Value was only modeled four times and three of those were in conjunction with a cost model. This cost and value pairing is a useful method to make design trade-offs and decisions for large complex systems.

Table 1. Analysis of engineering resilience literature

Author	Publication Information		Definition			Time				Model				Type of System				Application
	Year	Number of times cited in google scholar	Qualitative	Conceptual Framework	Quantitative	Before	During	Short Term	Long Term	Single Objective	Multiple Objective	Cost	Value	Component	Sub System	Systems of Systems	Methods of Improvement	
Richards	1996	3	●			●		●										Space Transportation System
Bruneau et al.	2003	1624		●		●	●	●								●		Infrastructure Systems: Seismic Resilience
Brizon et al.	2006	6	●			●	●	●									●	Systems
Mitchell et al.	2007	4			●		●			●				●				Material Resiliency
Kahan et al	2009	110	●	●		●	●	●	●							●	●	Homeland Security
Madni et al.	2009	256	●	●			●	●	●									Engineering general
Richards et al.	2009	56			●		●	●			●	●					●	Systems Engineering
Erol et al.	2010	4	●			●	●	●									●	Systems
Henry et al.	2010	1	●		●		●	●		●								Systems
Aven et al.	2011	192			●		●	●							●			Systems Engineering
Hollnagel et al.	2011	176	●				●											Systems
Vurgin et al.	2011	31	●		●		●	●		●		●						Infrastructure assessment
Youn et al	2011	57	●	●	●	●		●		●		●		●	●		●	Simplified Aircraft Control Actuator Design
Dinh et al.	2012	97	●				●	●			●							Flammable Materials
Mackenzie et al.	2012	16			●			●		●								Electric Power Outage
Madni et al.	2012	41	●				●	●						●	●			Platform Based Engineering
Urken	2012	19	●					●										Evolvable Systems
Alderson et al.	2013	24			●	●				●		●		●			●	Networks
Guarinello et al.	2013	19			●		●			●						●		System of Systems
Jackson et al.	2013	65	●	●		●	●	●	●					●		●	●	Systems
Linkov et al.	2013	74	●			●	●	●	●							●		Systems
Neches et al.	2013	62	●			●											●	Systems
Park et al.	2013	214	●			●	●	●	●					●			●	River Flooding Management
The National Academies	2013	79	●	●		●	●	●	●			●					●	Infrastructure to Natural Disasters
Ayyub	2014	136	●		●		●	●		●		●	●	●				Systems
Balchanos et al.	2014	3	●				●	●		●						●		UAV
Ettouney	2014	116	●	●		●	●	●		●		●	●		●	●	●	Infrastructure
Goerger et al	2014	53	●			●	●	●	●									Department of Defense
Han	2014	2	●		●		●	●		●		●				●		Naval Ship and Air Transportation
Ross et al.	2014	203	●		●		●	●			●	●			●		●	Systems Engineering
Shafieezadeh et al.	2014	31	●	●	●		●	●			●	●		●				Infrastructure: Seismic Resilience of Seaports
Tokgoz et al.	2014	2	●		●	●	●	●									●	Buildings During Hurricanes
Alderson et al.	2015	42	●			●	●	●	●		●	●		●				Infrastructure
Franchin et al.	2015	37	●	●			●	●		●				●	●			Infrastructure to Earthquakes
Henderson et al.	2015	1	●	●			●	●	●				●	●	●		●	Computer IT Enterprise Systems
Lundberg	2015	33		●		●	●	●	●							●	●	Systems: SyRes model
McDermott et al.	2015	0	●						●		●					●	●	Sociotechnical Systems
Sikula et al.	2015	15	●			●	●	●						●			●	Systems: Military Installation Resilience Assessment Model
Sitterle et al.	2015	10	●	●	●	●	●	●	●		●	●	●	●	●		●	Defense
Teodorescu et al.	2015	6	●		●	●		●		●								Large Scale Systems
Jackson	2016	1	●			●	●	●	●								●	Systems
Cai	2017	1	●		●		●	●		●				●				Power Grid
The National Acadamies	2017	3	●			●	●	●	●								●	National Electric System
Jin et al.	2017	1	●		●		●	●		●				●				Networks
Lewis	2017	0	●	●	●	●	●	●	●					●		●	●	Acquisition System and Mass Transit System
Baroud	2018	0	●				●	●		●				●				River Navigation System
TOTAL	**46**		**38**	**13**	**19**	**23**	**38**	**40**	**15**	**16**	**7**	**12**	**4**	**17**	**8**	**11**	**21**	

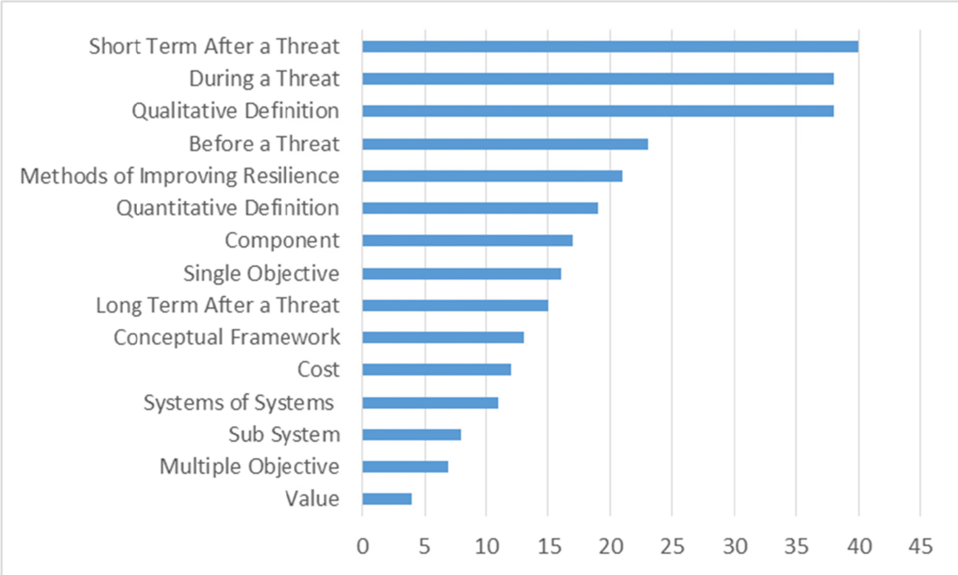

Figure 5. Summary of Research Analysis

3. Engineering Resilience Definitions

The engineered systems resilience literature produced widely varying definitions. Several of the resilience definitions were not applicable to all of engineering but limited to a particular domain or application (e.g., seismic resilience from Franchin and Cavalieri (2015). These definitions did not provide a complete view of resilience, but they did provide pieces to the resilience puzzle. One cannot say the leaves, branches, or roots are a tree. They are pieces, but they do not provide a complete understanding of a tree. By piecing together all of the descriptions and the associated terminology related to resilience in the literature, the full meaning of engineering resilience can be understood.

3.1 Related Terminology

Several of the terms used in the previous section, such as robustness, flexibility, and adaptability, are used synonymously with resilience (Neches & Madni, 2013). While not inaccurate, these synonyms do not capture the full complexity of engineered resilience. An understanding of how these terms connect to engineered resilience was needed to develop a complete view. Franchin & Cavalieri (2015) noted that the ability to adapt to post event circumstances is what distinguishes resilience from similar concepts such as vulnerability, reliability, and robustness.

Flexibility was one of the most frequent words used to describe resilience, but Dinh et al. (2012) described it as a principle of resilience. This was one example of how a term can be a part of resilience, but not resilience itself.

Restoration is described as a measure of "the ability of an engineered system to restore its capacity and performance by detecting, predicting, and mitigating or recovering from the system-wide effects of adverse events" (Youn et al., 2011). The authors later state that restoration can be viewed as adaptability. This connection between adaptability and restoration can be regarded as a response in order to recover performance.

Several other works list dimensions, requirements, or measures needed for a resilient system. Each of the principles defined one component of resilience, but did not completely define resilience. Shafieezadeh and Burden (2014) state that there are four dimensions of resilience: robustness, redundancy, resourcefulness, and rapidity. Capacity, flexibility, tolerance, and cohesion are four attributes that the SEBoK lists as requirements of a resilient system (SEBoK Authors, 2019). Henderson and Lancaster (2015) specify that robustness has multiple aspects including, being immune to a threat, having excess capacity, and absorbing damage in order to degrade gracefully.

The Venn diagram in Figure 6, connects the most common terms used to describe resilience to demonstrate the relationship of each term to resilience. It introduces two new concepts, mission resilience and platform resilience, which are discussed more in depth in the next section. The Venn diagram is structured so that each descending level is a component of the previous, higher level. For example, engineering resilience was shown as one domain of resilience. Engineering resilience consisted of three main areas: value created, mission resilience, and platform resilience. The value created was represented by the oval that encompasses value and broad utility, which are often used to represent the same concept when evaluating engineered resilience and determining if it is valuable and profitable to include in the product or system design. Platform resilience and engineering change reference the ability to alter a system between missions or required engineering changes needed to perform new missions (Sitterle, Freeman, Goerger, & Ender, 2015). Both platform resilience and engineering change refer to changes that are implemented for multiple instances of a system rather than on one particular instance of that system. On the other hand, mission resilience is typically referenced for the changes to a particular instance of the system. The concept of mission resilience is similar to restoration referred to by several other authors and it encompasses surviving and recovery (National Academies of Sciences & Medicine, 2017; Baroud, Ramirez-Marquez, Barker, & Rocco, 2014; J. Kahan, Allen, George, & Thompson, 2009). Surviving the threat, withstanding the threat, protecting against the threat, or being robust to the threat, are all means that the system uses to maintain its functionality and to prevent it from being destroyed (Richards, Ross, Hastings, & Rhodes, 2009; Han, 2014; Brtis, 2016; Mitchell, 2007; Vugrin & Camphouse, 2011; Ross, Rhodes, & Hastings, 2007; Jackson, 2016). In networks, this is referred to as operational resilience (Alderson et al., 2015; National Academies of Sciences & Medicine, 2017). Within the mission, the system can recover to increase its performance above the minimum survival level. When a system is versatile, it contains a large capacity or can perform many functions (Goerger, Madni, & Eslinger, 2014; Sitterle et al., 2015). Versatility and capacity overlap both operational resilience and recover since they contribute to the survivability or recovery rate of a system. The last box, flexibility and adaptability, are used most ambiguously. According to the literature, a system can adapt to survive a threat during a mission, to perform new functions, recover from a threat, or accomplish new missions (Ross et al., 2007; Madni, 2012; Jackson, 2016). Flexibility is similarly used and is the reason these terms span across all parts of mission and platform resilience (Ryan et al., 2013).

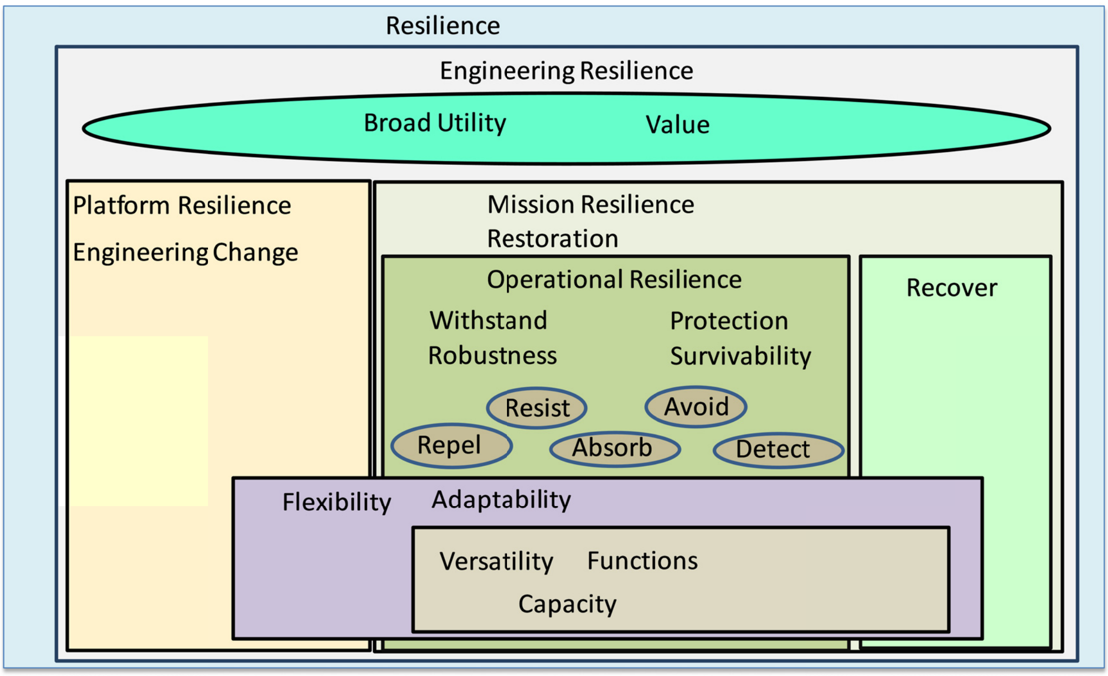

Figure 6. Engineering resilience terminology venn-diagram

3.2 Time Component and Means Objectives

When reviewing resilience definitions, it is important to consider the planning horizon of the definition. It is equally important to consider the ends versus the means. The resilience ends should be independent of the means in order to attain true system resilience.

While the time frames for resilience are rarely explicitly stated, the means for achieving resilience included in the definitions show what time frames were being considered. We categorize the actions and definitions discussed in the literature into four time frames: 1) before, 2) during, 3) short-term-after, and 4) long-term-after. Madni & Jackson (2009) used avoid, absorb, recover, and adapt. This definition provided an example of a means in both short-term-after and long-term-after time frames. Leveson et al. (2006) used prevent, adapt, and recover, an example of before, during, and short-term-after, while Youn, Hu, and Wang (2011) described resilience by using anticipate, reorganize, and learn, which were means that occur in the before, short-term-after, and long-term-after time periods. Another definition that focused on the during and short-term-after time frames is presented in a critical infrastructure resilience definition: "Critical infrastructure resilience is a concept that describes the ability of infrastructure systems to absorb, adapt, and recover from the effects of a disruptive event" (Vugrin & Camphouse, 2011). Respond, monitor, anticipate, and learn provided means that covers all of the time frames except during the threat (Hollnagel, 2011). Kahan, Allen and George (2009) defined a difference between soft and hard resilience. Hard resilience aligned closely with engineering resilience and referred to the qualities, capabilities, capacities, and functions of institutions and infrastructure. They believed that the objectives (or end states) of resilience were resistance, absorption, and restoration, however, we can see that these are in fact means to achieve resilience. These four time frames were perhaps most fully incorporated by the National Academy of Science in 2013 when they defined resiliency as the ability to plan and prepare for, absorb, recover from, and adapt to adverse events (National Academies, 2013).

A majority of the papers focused on describing specific means to accomplish resilience, such as anticipating, preparing, adapting, withstanding and recovering rapidly (Sikula, Mancillas, Linkov, & McDonagh, 2015). Others focused on the methods to improve resilience. Jackson detailed 14 sub-principles and how each contributed to the different resilience phases (Jackson & Ferris, 2013). Resilience was improved by adding redundancy and increasing flexibility (Youn et al., 2011). Dinh et al. (2012) improved resilience through controllability, flexibility, and capacity. They also discussed resilience strategies: minimize the probability to failure, minimize the consequences, and minimize the restoration and recovery time, early detection, flexibility, controllability, limitation of effects, administrative controls, and procedures. Prevention and learning were *long-term-after* means discussed for improving resilience, whereas protection and vigilance were the *during* means that contributed to resiliency (Brizon & Wybo, 2006). All of these are options for improving resilience and should be considered when looking to improve resilience during product developments or updates. A complete definition of resilience needs to be able to accommodate all of these means and many more.

To better understand the difference between objectives and means and the importance of specifying objectives rather than means, let us consider an example of a drone. When focusing on the means, we would claim that for a drone to be resilient it must be able to absorb the impact from a collision. The system performance and objective could be equally well served by withstanding the collision, avoiding the collision, or having a redundant capability to replace the function damaged in the collision. All of these are resilient options that operate across different time frames to accomplish similar results. Claiming that the system must absorb the impact would be the specifying the means rather than identifying the objective. Using a means-based definition limits the design solutions available to handle potential disruptions to an engineered system, which could likely result in higher cost, lower performance, or both. Several definitions from the literature are shown in Table 2 with the means underlined and objectives bolded to demonstrate this means-versus-ends concept. The ideal definition must be written in such a way that it can be widely accepted in order to create a standard definition. Engineering definitions should not include the means. For example, reliability is "the probability of a system or system element performing its intended function under stated conditions without failure for a given period of time" (SEBoK Authors, 2019). The definition does not include the possible means to make a system reliable.

Table 2 presents a range of definitions to demonstrate the difference between means, which are underlined and are not desirable in an engineering definition and objectives, which are bolded and should compose the definition of a technical term such as resilience.

Table 2. Engineering resilience definitions: means vs. objectives

Source	Definition
Kahan et al. 2009	"The objectives (or end states) of resilience that underpin our approach are <u>resistance</u>, <u>absorption</u>, and <u>restoration</u>."
	"a basic tenet of our approach to resilience is to maintain the key functions of critical systems, both human and technical, pending restoration."
Madni et al. 2009	"In our view, resilience is a multi-faceted capability of a complex system that encompasses <u>avoiding</u>, <u>absorbing</u>, <u>adapting</u> to, and <u>recovering</u> from disruptions"

Neches 2011	"A resilient system is trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function."
Neches et al. 2013	"the ability of a system to adapt affordably and perform effectively across a wide range of operational contexts"
Linkov et al. 2013	Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.
Alderson et al. 2015	"the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

3.3 Proposed Definition

At the beginning of the literature review, we presented several apparently conflicting definitions of resilience. Further examination reveals that the definitions were not conflicting, but rather contained overlapping terminology as discussed in the previous section. This conflict was caused not by the definitions themselves, but rather by the scope of the definitions. Several of the definitions focused on a specific application area or used means instead of providing a broad translatable definition. Our proposed definition refined from (Anonymous) focuses on the objectives of resilience rather than the means and can be applied to any engineered system. It also includes current and future uses.

An engineered resilient system is a system that is able to successfully complete its planned mission(s) in the face of disruption(s) (environmental or adversarial), and has capabilities allowing it to successfully complete future missions with evolving threats.

This definition spans all of the definitions surveyed in this literature search. A mission is a generic term used for whatever the system needs to accomplish. For a running watch, that mission could be tracking time on a run, while a future mission could be tracking time during a swim. While the watch that one consumer purchased may not be able to adapt to the new mission, the watch platform as a whole could be improved to handle it. This new mission also has the added threat to the system of operating under water. A military system could have been designed to repel small arms fire in the jungle but is later retasked to a dessert environment where IEDs are a new threat that the platform would need to handle.

The means to complete a mission may be to repel, resist, or absorb (or any other means discussed in the literature) the threat to prevent the deterioration of any mission critical functions. Be it activity tracking in the watch, or mobility and safety in the military vehicle.

In the face of a disruption, the system or its operators/users will respond in some way; it may be an active response such as avoiding the disruption (e.g., going around a storm) or a passive response of simply absorbing or resisting the disruption (e.g., a system that is waterproof will be unharmed by the rain). If the threat does cause a deterioration of the function, there needs to be a means of recovering those functions to the required minimum levels. Here again the design decision to include distributed capacity, redundancy, flexibility, or any other method will affect the resilient responses. After the specific disruption has ended and the mission is complete, the system should then be able to adapt and be modified to improve its response to similar threats in the future. This extends its lifecycle instead of requiring an entirely new system to handle the disruption. While keeping these concepts in mind, it is important to plan and prepare for threats and responses in advance during the system design phase because as noted by Dinh et al. (2012) how fast and effective this response is will depend not only on recovery plans, but also on the system design itself. Kahan, Allen, and George (2009) also stated that resilience needs to be planned in advance—before systems are damaged and undesired consequences occur. This "in advance" time period can occur at a variety of times throughout the system's life cycle since there are many threats that the system will likely encounter.

It is important to note that this is not a new definition for resilience. Standard dictionaries and international organizations already define resilience. For example, the SEBoK defines resilience as the "ability to maintain capability in the face of adversity (SEBoK Authors, 2019)." Our proposed definition builds upon this idea and provides more clarity for engineered systems. The proposed definition more clearly defines what the resilient engineered system should achieve and under what system specific conditions.

4. Resilience Cycle

Park et al. (2013) proposed that resiliency can be modeled as a cycle by including "at least four components that are often missing from the use phase of many engineering projects: (1) sensing, (2) anticipation, (3) adaptation, and (4) learning." According to Madni (2012), adaptable platform based engineering is an enabler of resilience. Planning occurs during the initial design before the first time the product is ever used. After the initial design, the system will be employed on a variety of missions and situations by the users and customers During the first use, the system has to accomplish its intended function in spite of any disruptions that it encounters or be able to recover its functionality. If any problems are found during a given mission, the platform can be modified as needed to correct them. These could be bug fixes, recalls, or upgrades. This process allows for multiple design modifications for each platform, making it better for specific missions or disruptions that are encountered as well as addressing any weaknesses that are discovered. After the system begins to be used there may be changes that would be beneficial for its continued future use. These engineering changes, be they modifications to the design or adaptations to the existing systems must be planned. This means that planning exists both at the end of one mission and before the start of another. This creates the cyclical nature of resilience. At any stage, the platform can be modified (including redesigned) to accommodate new challenges, disruptions, or missions. Figure 7 shows this cyclical process and the transitions between mission and platform resilience. This cycle differentiates between adaptation, which is making changes to an existing system (post-production), and modifying the design for a new version of the systems (pre-production). Both are long term engineering changes that do not occur during the mission.

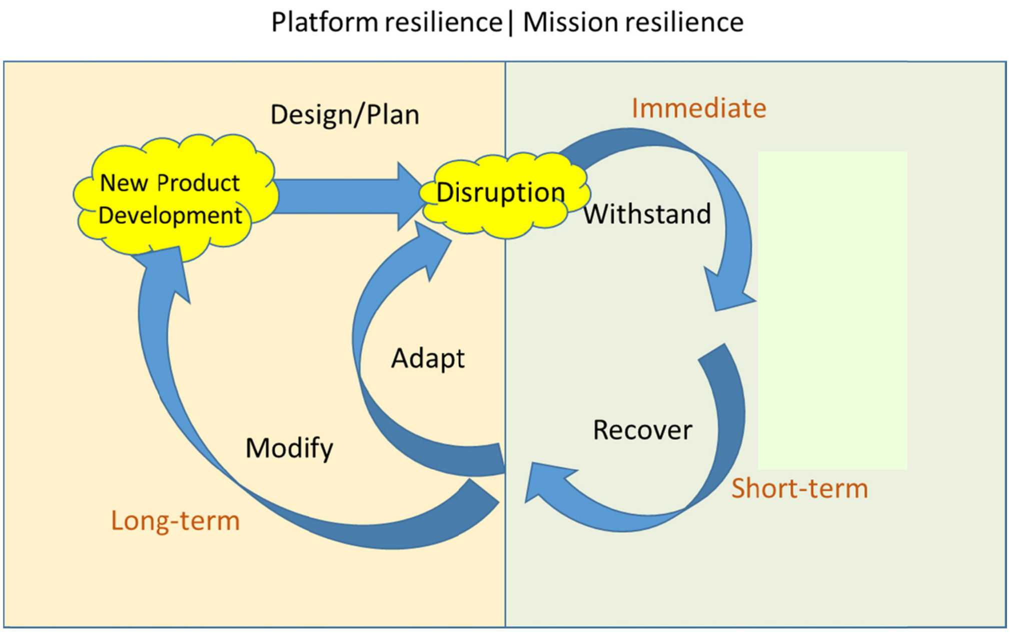

Figure 7. Engineering resilience cycle

This cyclical concept has been presented to the Department of Defense's (DoD) Engineered Resilient Systems (ERS) program, and they envisioned how it might be applied across the entire life of a platform by mapping capability over time to specific resilience events. This is shown in Figure 8. This figure demonstrates many of the intricacies inherent in the resilience cycle and the difference between mission and platform resilience. It illustrates how multiple missions can occur without any platform resilience actions, as well as what some of the changes affecting the platform resilience might be in practice. It also shows that within a given platform (e.g., the C-130 aircraft) individual systems (e.g., a specific C-130 aircraft) could be on multiple missions at the same time with each performing different mission resilience actions. Additionally, each mission may be at a different capability, as the capability of a system is relative to the goals of that mission. A similar process could be applied to consumer products updating a product to a new generation to incorporate disruptive technologies, or new functions that had not been originally envisioned during the original product design. Learning how to better manage technology, market disruptions, and adapt to the changing environment, is critical for companies to survive and maintain a competitive advantage (Badawy, 2009)

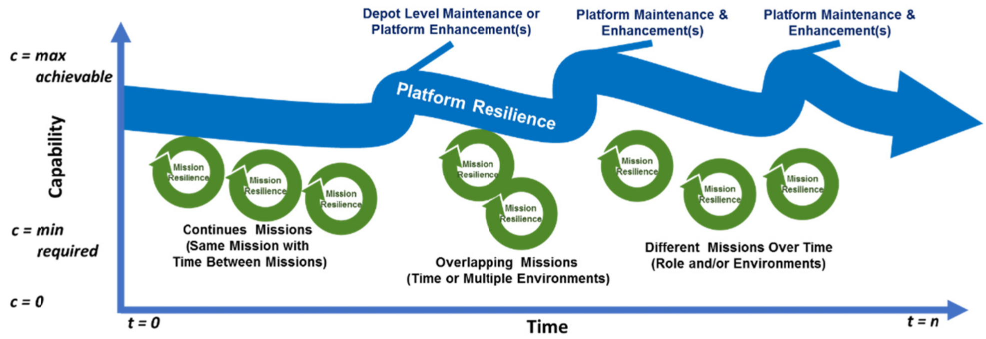

Figure 8. Engineering resilience life cycle

5. Engineering Resilience Evaluation Methods

There are several papers that evaluate resilience. We divided these methods into qualitative and quantitative methods. The qualitative evaluations methods lack mathematical methods to evaluate resilience. For example, evaluating resilience by using checklists would be categorized as qualitative. The quantitative methods provide at least some basic mathematical framework for evaluating resilience. These methods were either extensions of existing mathematical concepts or graphical methods that show the loss of performance over time, which can be mathematically interpreted. A reoccurring concept when measuring resilience is the notion that the system must be resilient to something (i.e. resilience is measured relative to specific disruption(s)). Alderson, Brown, Carlyle, and Cox Jr (2013) using only a single performance metric, point out that it is possible for System A to be more resilient to small disruptions, while System B may be more resilient to large disruptions. This demonstrates the need for a modeling to account for the uncertainty of disruptions and the value of adding resilience to a system. Uncertainty is considered in risk analysis, but not typically used in the evaluation of resilience or vulnerability, which creates an inherent conflict when discussing the way in which resilience relates to risk (Aven, 2011). An added difficulty is that system resilience is primarily an emergent property which means it “cannot be understood by analyzing the components of the system in isolation” (Dalziell & McManus, 2004). This provides an impetus to view resilience from a systems engineering perspective. This is a view that is becoming more important for today’s engineering managers.

It is also worth noting that there is a large body of literature that explicitly evaluates specific components of resilience, even if it does not directly refer to it as resilience. For example, planning for an emergency response to a hurricane in a transportation system and determining how to evaluate those responses, as seen in Anonymous (2012), evaluates components that are part of system resilience. In this case, the process involves timeframes of before and short-term-after.

5.1 Qualitative Evaluation Methods

The resilience evaluation methods vary due to differences between systems and systems’ complexity, which make evaluation methods more difficult to develop. Several organizations inside the Department of Homeland Security (DHS) are evaluating resilience by creating a checklist that allocates a point to every method that adds to resilience (National Academies, 2013). Similarly, the Environmental Protection Agency (EPA) proposes that characteristics of resilience (diversity, adaptability, cohesion, latitude, and resistance) could be evaluated to assess resilience (Larkin et al., 2015). This is consistent with the SEBoK, which considers resilience to be an emergent property (SEBoK Authors, 2019). It further discusses a method to evaluate resilience as an extension of safety and risk by using a modified System-Theoretic Accident Model and Processes (STAMP). The OpenSEAT program attempts to develop a model that can take into account qualitative as well as quantitative measures specifically for dealing with complex adaptive sociotechnical systems (McDermott, Folds, Ender, & Bollweg, 2015).

5.2 Quantitative Evaluation Methods

There are a variety of quantitative approaches that have been used to evaluate engineered resilience; however, they do not evaluate the entire scope of the definition that has been presented in this paper. This presents an opportunity within the resilience research domain. Often the quantitative analysis that is performed is merely an extension of already existing mathematical evaluations. Resilience has been computed as an extension of safety and reliability (Leveson et al., 2006; Richards et al., 2009). Resilience has also been evaluated as an extension of risk analysis, by adding in conditional probability for recovery within some expected time (Teodorescu, 2015). This is only explicitly considering the recovery phase of resilience, and only on a pass-fail level, assessing whether a system returns to level X in time Y. There is no credit given for faster recovery or recovery to a higher level. It also requires the prediction of all threats that may occur, which is problematic as one of the common themes of resilience is being able to handle unknown disruptions. A similarly simplistic metric was to only consider the level of recovery, full recovery back to 100 percent or some fraction of its performance that was recovered. In this case, there is no benefit given based on the amount of time or the amount of degradation being recovered from. A system that goes from 100% to 45% and back to 100% would be considered equally as resilient as a system that declines to 90% before recovering fully (Henry & Ramirez-Marquez, 2010). This coarse metric would provide little benefit in understanding the value of resilience. Alternatively, MacKenzie and Barker (2012) focused on the planning stage and considered known threats. By reviewing all of the known impacts from a certain disruption (e.g., a power outage) based on previous occurrences, they evaluate the degree of resilience that a system has based on the likelihood of the impacts and associated disruption occurring and the ability of the system to cope with them.

A fairly common, though limited method for determining resilience is through calculating the area under a performance curve. This method is limited because it only considers one measure of performance and does not account for uncertainty, which is one of the key factors of performance. Figure 9 illustrates a version of this method (Barker, Rocco, & Ramirez-Marquez, 2013). There are other methods that added complexity by considering the system not returning to the initial performance level as well as including a time component for the threat and the performance degradation. These methods consider resilience inversely proportional to the size of the area lost when comparing the degraded performance curve to the initial performance curve (Uday & Marais, 2015).

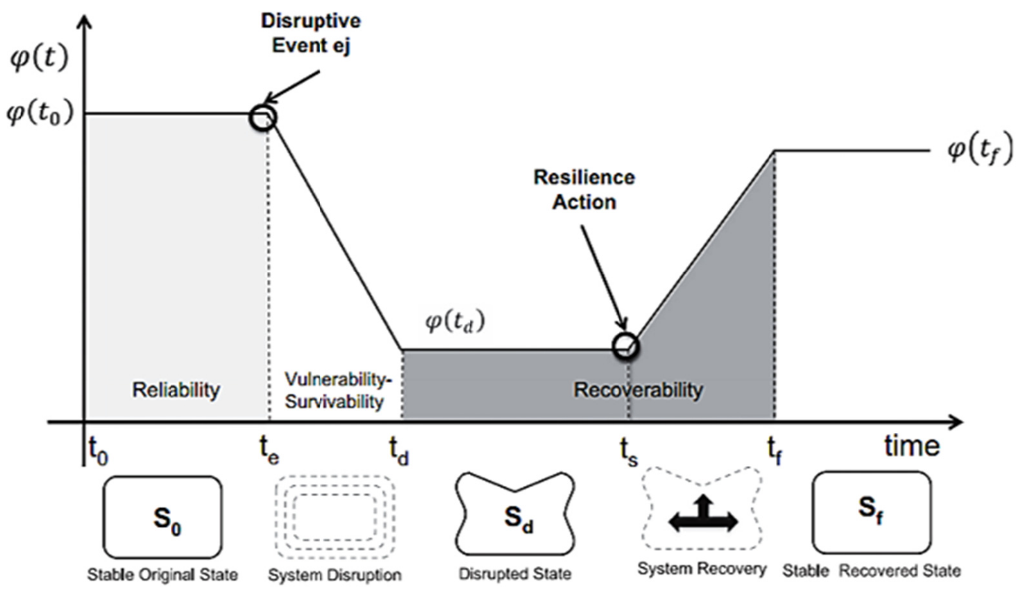

Figure 9. Area under a performance curve: resilience evaluation methodology (Barker, Rocco, & Ramirez-Marquez, 2013)

In order for any of these methods to be useful from a system design and decision standpoint, they need to be able to provide a tangible return on investment (ROI). Without an ROI, a decision maker will not be able to compare design alternatives that are created to improve resilience (Kahan Allen & George, 2009).

While the graph in Figure 9 only displays a single metric, it is useful to demonstrate the different dimensions of mission resilience. Equally important is understanding how engineering change, enabled through platform resilience decisions, can affect this graph. If the vulnerability to a disruption was reduced, then the drop from $\varphi(t_0)$ to $\varphi(t_d)$ would be decreased. An adjustment could be made to the platform so that the recovery action would bring back the system's performance more rapidly, reducing the time between t_s and t_f, which would increase the slope in the system recovery stage. This attribute is sometimes referred to as the systems rapidity (Bruneau et al., 2003). A third adjustment would be a change to the system that would allow it to reduce the disrupted time, by reducing the amount of time between when the disruptive event has finished (t_d) and when the recovery begins (t_s). A platform resilience change could also be made to increase the final value of $\varphi(t_t)$, allowing it to better recover from a disruption. A platform resilience change could also be made that would increase the initial performance $\varphi(t_0)$. This would allow the system to better complete its mission and deal with additional disruptions, thus increasing the performance at every step along the resilience curve. It is worth noting that this is a simplified figure. Any system could have numerous performance measures each with its own unique curve. Furthermore, none of the sections need be made of simple line segments. They may be curved or made of multiple segments. Lastly, the system performance does not always begin or end at optimal performance.

In relation to the multiple performance curves, the effect of stresses and disruptions on one part of the system can affect the ability of other systems to withstand stresses (Mitchell, 2007). This emphasizes the need for high-quality modeling and simulation that captures the complete interactions between components, and systems in a SoS context.

6. Implications

In order to effectively incorporate resilience into a system design, engineering managers need to understand resilience and what can be done to improve resilience throughout the systems life cycle. Disruptions and system failures are inevitable for any engineering system. Copper states "A key challenge faced by new product development is how to acquire and manage sources of uncertainty in order to reduce the risk of failure of either the project or the resulting product" (Cooper, 2003) Resilience provides a way to deal with those disruptions and uncertainty in the most effective way. Robustness and resilience could be considered insurance policies against risk and uncertainty in long-term-after plans and designs, especially where technological, budget or even focus shifts are likely (Richards, 1996). Resilient engineered systems have the ability to extend the service life of a system or a platform and significantly increase the value provided over the life of the system. Thought of another way, the impact that research and development and manufacturing costs have on the total cost of the system is reduced as the service life extends. Resilience is quickly becoming an important consideration due to the increasing complexity of engineered systems, rapidly developing technology, and an ever-increasing set of possible disruptions from the environment, technological malfunctions, human error, and malicious activity. As complexity of systems has increased, so too have cost overruns; engineering more resilient systems is a way to combat this trend (Roberts, Mazzuchi, & Sarkani, 2016). The definition and framework provided in this paper will help retain the focus of the value of resilience. It also demonstrates the various points in a systems life cycle that resilience can be incorporated and that it is not just an upfront investment, but can continually be improved with intelligent design and careful planning.

7. Summary and Future Work

In this paper we reviewed the engineered systems resilience literature. We found no standard definition of resilience and the definitions found included a variety of means in their definitions of resilience while not including the objectives over the full life cycle. This paper provides a new definition of a resilient engineered systems that includes the objectives of resilience without dictating the means to achieve them - *An resilient engineered system is a system that is able to successfully complete its planned mission(s) in the face of disruption(s) (environmental or adversarial), and has capabilities allowing it to successfully complete future missions with evolving threats*. This definition is useful because it encompasses the totality of what resilience means and enables more meaningful conversations about how to improve the system resilience during new product/system development. We also developed the resilience cycle which separates mission resilience (short term) and platform resilience (long term). An understanding of engineered systems resilience can help engineering managers, designers, and other engineered system stakeholders evaluate resilient options to improve the affordability and value provided to the customer over the product/system life cycle.

Much of the current work on quantifying resilience is focused on mission resilience. Future work should build upon the definition presented in this paper to incorporate platform resilience as well. There is also a need for more in-depth and comprehensive modeling efforts for effectively incorporating resilience in tradespace analysis, improving the evaluation of the usefulness of various system resilience options, and assessing platform resilience, as seen in the literature search results. The lack of value models, specifically using multiple performance measures, in the literature make it difficult to develop tradespace analysis methods. Additionally, the literature search demonstrates resilience research opportunities in the development of techniques, principles, and etc. during the long-term time frame of resilience. A more in-depth analysis of resilience terminology will help improve resilience research. This includes categorizing resilience terminology by proactive and reactive.

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