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Disciplinary Convergence in Systems Engineering Research

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Editors
Azad M. Madni
Professor, Astronautics, Executive Director, Systems Architecting and Engineering Program
University of Southern California
Los Angeles, CA, USA

Barry Boehm
Professor, Computer Science, Director, Center for Systems and Software Engineering
University of Southern California
Los Angeles, CA, USA

Roger G. Ghanem
Professor, Aerospace & Mechanical Engineering
University of Southern California
Los Angeles, CA, USA

Daniel Erwin
Professor, Astronautics
University of Southern California
Los Angeles, CA, USA

Marilee J. Wheaton
Systems Engineering Fellow
The Aerospace Corporation
El Segundo, CA, USA

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Preface

Innovation growth in the twenty-first century is continuing to fuel the way we live, work, learn, and entertain. This era augurs well for societal well-being so long as we make the understanding and management of complexity a top priority. Specifically, the impact of innovation needs to be studied with regard to unintended consequences. The latter is a challenge for complex systems engineering and a fertile ground for conducting systems engineering research.

According to the World Economic Forum, we are in the early stages of the Fourth Industrial Revolution. Coming on the heels of the Third Industrial Revolution, which produced dramatic advances in electronics, computers, communications, and information technology, the Fourth Industrial Revolution is going to be an era of convergence. Increasingly, we are beginning to see the convergence of engineering with behavioral and social sciences, entertainment and cinematic arts, biology, and the physical sciences.

At the same time, systems in the twenty-first century are becoming increasingly hyper-connected and more complex. Recognizing that traditional systems engineering methods, processes, and tools no longer suffice, the research community supported by government, academia, and industry has begun working together to transform systems engineering. Central to this transformation is exploiting innovation and capitalizing on convergence to develop new approaches, methods, and tools. The emphasis is on reaching beyond traditional engineering to address problems that appear intractable when viewed solely through an engineering lens. Today disciplinary convergence is beginning to play a key role in this transformation.

> "....The central idea of disciplinary convergence is that of bringing concepts, thinking, and approaches from different disciplines in conjunction with technologies to solve problems that appear intractable when viewed through the lens of a single discipline." (Madni, A.M. Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyper-Connected World," Springer, 2017)

This vision inspired the central theme of 2017 Conference on Systems Engineering Research (CSER): *Disciplinary Convergence: Implications for Systems Engineering Research*. This volume is a collection of peer-reviewed research papers from university, government, and industry researchers who participated in 2017 CSER. To help the reader conveniently navigate this volume, the papers are organized into ten sections. Each section represents a key research area in systems engineering research today.

It is our hope that this volume will get you interested in systems engineering research that exploits disciplinary convergence and pursues cross-disciplinary approaches to solve complex scientific and societal problems.

Los Angeles, CA, USA

Azad M. Madni
Barry Boehm

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Chapter 1
Engineering Resilience for Complex Systems

Colin Small, Gregory Parnell, Ed Pohl, Simon Goerger, Bobby Cottam, Eric Specking, and Zephan Wade

Abstract In recent years there has been an increased need for resilience in complex military and civilian systems due to evolving adversarial and environmental threats. Engineered Resilient Systems (ERS) is a Department of Defense (DoD) program focusing on the effective and efficient design and development of complex engineered systems. These complex systems need to be resilient to threats throughout their life cycle. However, most current engineering resilience literature focuses on systems with a single function and a single measure. Today's systems are becoming more complex, with multiple functions and measures involving critical trade-offs during early life cycle stages. This paper develops criteria for a framework to incorporate resilience into DoD analysis of alternatives (AoA). Using the criteria, this paper creates a framework for defining and evaluating complex engineered systems that consider many missions, scenarios, uncertainties, functions, and measures. Lastly, using the criteria and the framework, the current literature is shown to have gaps for incorporating resilience into DoD AoAs.

Keywords Resilience • Engineering Resilient Systems • Resilience cycle • Systems engineering • DoD • Analysis of alternatives

1.1 Introduction

In recent years there has been an increased need for resilience in complex military and civilian systems due to evolving adversarial and environmental threats. As systems become increasingly interconnected and technology advances more quickly, it becomes harder for systems to resist threats. Often systems are used in unplanned missions or new scenarios with different threats. Therefore, systems

C. Small (✉) • G. Parnell • E. Pohl • B. Cottam • E. Specking • Z. Wade
University of Arkansas, Fayetteville, AR, USA
e-mail: cxs050@uark.edu; gparnell@uark.edu; epohl@uark.edu; bjcottam@uark.edu; especki@uark.edu; zwwade@uark.edu

S. Goerger
U.S. Army Engineer Research Development Center (ERDC), Vicksburg, MS, USA
e-mail: Simon.R.Goerger@erdc.dren.mil

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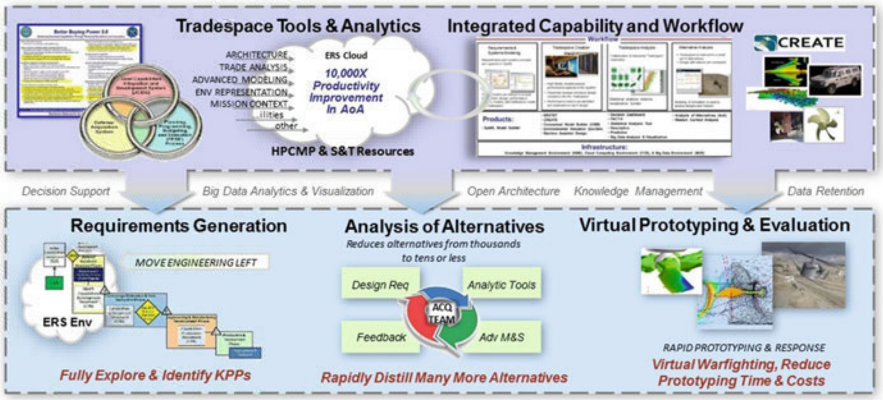

Fig. 1.1 ERS summary [1]

need to be resilient not only to planned threats and functions, but they also need to be resilient to uncertain threats and changing functionality. In the military and defense industries, current analysis of alternatives (AoA) using requirements analysis does not always plan for future threats, missions, or scenarios. However, systems cannot simply be designed for one mission; instead they need to withstand threats and have multiple functionalities. Therefore, complex systems should be engineered to be resilient to uncertain and evolving threats, missions, and scenarios.

As a response to the need for resilient systems, the Department of Defense (DoD) has created the Engineering Resilient Systems (ERS) program. ERS focuses on the effective and efficient design and development of complex resilient engineered systems throughout their life cycle. This research focuses on defining engineering resilience to enable key stakeholders such as planners, concept developers, system designers, system engineers, program managers, and system acquisition leaders to assess options to improve system resilience in the early life cycle stages. By considering resilience, the DoD strives to improve its AoA as shown in Fig. 1.1 [1]. Specifically, it seeks to improve its buying power by specifically addressing resilience early in the design cycle. In addition, it wants to add efficiency to the AoA process by using tradespace and analytics tools that use high-performance computing to explore the design space, efficiently sift through millions of designs, and quantify resilience and help analyze alternatives. Lastly, it wants to improve the design process by using Computational Research and Engineering Acquisition Tools and Environments (CREATE) that allow for virtual prototyping, design verification, and operational testing.

In order to engineer resilient systems, system designers and managers must contemplate design options considering various scenarios, missions, functions and their performance measures, threats including environmental conditions, adversary actions, detectable performance degradation, uncertain survivability, and measurable recovery over time. Resilient design options include means for flexible adaptability, which provide the ability to reconfigure and/or replace components during the system lifetime. The criteria to evaluate the design options must include the impact on performance, cost, and schedule. A tradespace analysis is critical to ensure senior decision-makers are able to determine the affordability of systems and their design options allowing for improved resilience.

With the aim of developing an appropriate framework for Engineering Resilient Systems, this paper first examines the existing academic literature. Using this literature along with stakeholder input, a set of criteria for Engineering Resilient Systems was created. To meet these criteria, a framework for incorporating resilience into AoAs was created. This framework will be used in future research to develop different methods of quantifying resilience. Lastly the literature was evaluated once again for gaps using the criteria and the framework.

1.2 Engineering Resilience Concepts and Definition

Recently our research team wrote a literature survey involving 47 papers [2]. In the research, the team found varying terms and definitions of resilience. In order to understand the literature and create a definition of resilience encompassing the varying uses and definitions of resilience, the team created the Venn diagram shown in Fig. 1.2. This Venn diagram shows the common themes and terms of resilience used in the literature search grouped into similar areas.

While designing this Venn diagram, our research led us to view resilience from two perspectives: platform and mission resilience. Platform resilience involves engineering changes and other features allowing a system platform to be flexible

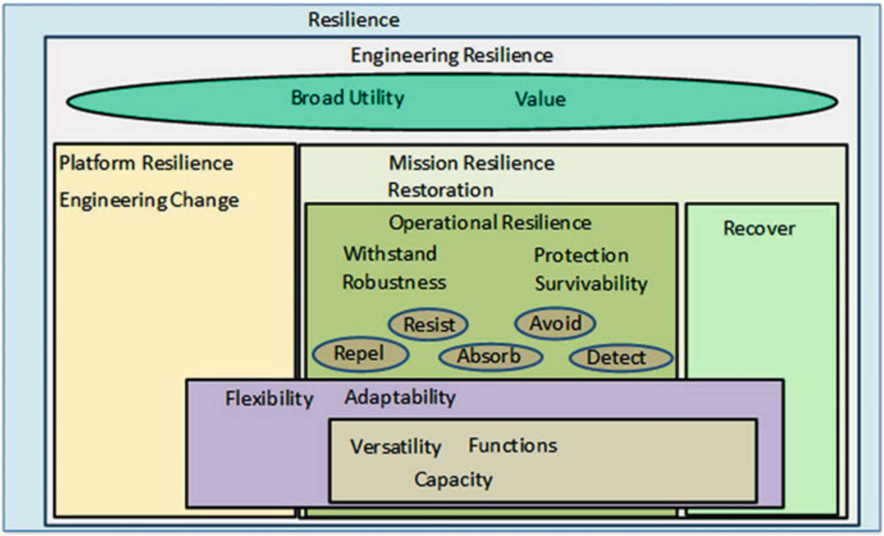

Fig. 1.2 Resilience Venn diagram [2]

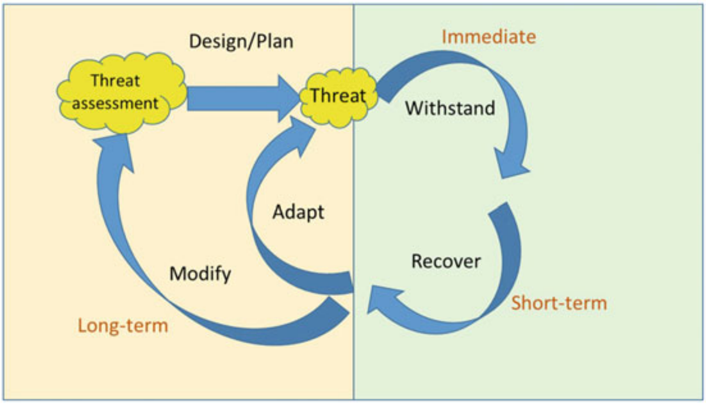

Fig. 1.3 Resilience cycle [2]

and adapt to new missions, scenarios, and threats. Mission resilience is the ability of a system to withstand and survive threats and disruptions and to recover from them quickly to achieve the mission. The majority of the literature was focused on mission resilience. Using this knowledge gained from the literature survey, the team created a broad definition of resilience:

> A resilient engineered system is able to successfully complete its planned mission(s) in the face of environmental and adversarial threats, and has capabilities allowing it to flexibly adapt to future missions with evolving threats.

Using this definition, the authors view resilience as the cycle shown in Fig. 1.3. In designing a resilient system, the process begins with a threat assessment. After this, systems are designed to face these threats. Once systems are operational and performing missions, the systems face evolving threats. Immediately they need to withstand the threats to accomplish the mission. If the system survives, it needs to recover from any damage or performance loss. After recovering, systems either return to face another threat or adapt to new threats by using platform resilience options incorporated in the original design decisions. If more significant changes are needed, the system may need to be modified. In this case, systems go through another redesign or modification process. After any redesigns, the systems face threats once more and cycle through the process until the systems are retired.

1.3 Criteria for Incorporating Resilience into Analysis of Alternatives

Using the results of the literature search, the team identified criteria a framework for incorporating resilience into AoAs. The eleven criteria are as follows: (1) use standard terms encompassing many engineering domains, (2) focus on early system definition, (3) consider multiple scenarios, (4) consider multiple threats, (5) consider short-term and long-term resilience, (6) expand the design space, (7) consider many system functions and performance measures, (8) incorporate the "Illities," (9) be independent of the modeling and simulation techniques, (10) allow for uncertainty analysis, and (11) support affordability analysis.

The framework should use common mission analysis terms from many engineering domains. A framework only using terms specific to one engineering domain cannot be easily applied elsewhere. Consequently, if it cannot be applied to other domains, it cannot be widely used or effective in general system design.

Engineering resilience must be considered early in the system life cycle. To be effective in creating resilient systems, the evaluation of engineering resilience must include the early system definition, including the "pre-Milestone A" decisions.

DoD systems are used in different missions and scenarios to perform multiple functions. Therefore, an effective framework needs to consider multiple missions and scenarios.

Numerous papers on engineering resilience focus on only one threat. Realistic DoD systems will face multiple uncertain threats throughout their life cycle. Therefore, any framework developed should allow for multiple threats rather than a single threat.

Time is a critical factor in engineering resilience. Systems face threats throughout their life cycle, and the threats may evolve or change dramatically. In addition, resilient systems not only respond and recover from threats in the short term, but they need to be able to take advantage of designed adaptability to be affordably modified to face new threats in the long term. Since resilience involves the system response to dynamic threats, a framework needs explicitly time, short-term resilience, and long-term resilience (Fig. 1.3).

The best practice is to avoid AoAs with a few point-based solutions. Point-based solutions do not provide sufficient insights about the design space. A goal of the ERS systems engineering process is to transform traditional point-based, requirements-driven design into set-based and data/analysis-driven design [3].

The majority of papers in the literature focus on one function and one performance measure. However, complex DoD systems perform several functions and have multiple performance measures.

The evaluation of resilience requires consideration of many "illities." These are terms such as availability, reliability, survivability, producibility, supportability, and others. These "illities" are a key consideration in the cost and value of systems. Hence, they need to be considered in a resilience framework.

Mission analyses and AoA use modeling and simulation techniques tailored to the system and the availability of data. Since modeling is the best way to estimate cost and value in early life cycle stages, the framework must be independent of the modeling and simulation techniques used in AoA.

Uncertainty is a reality in engineering resilience decisions. Many DoD systems have service lives lasting for decades. During this time, missions, scenarios, and threats change as new technology and adversaries arise. In addition, every situation is different and can have different outcomes leading to uncertain performance and cost. Therefore, the framework should explicitly consider uncertainty.

Affordability is an important consideration in system development. "Big A" affordability evaluates and assesses the value versus the costs at major milestones. "Little a" affordability refers to the continual evaluation of the value versus cost on all program decisions. Since the DoD and all decisions makers are concerned with cost and value, the framework must support affordability analysis.

In summary, these criteria together will allow for incorporating resilience into analysis of alternatives. However, as a list, these criteria mix both best practices and ERS requirements. To resolve this, Fig. 1.4 includes the criteria, the flow of time, and as a result the dependencies. In addition, it identifies the new steps to analysis of alternatives that ERS adds in red lettering. In addition, they do not show the sequence and dependencies involved in the criteria. The sequence and dependencies are shown in Fig. 1.5.

Analysis needs to begin with identifying missions, scenarios, and value gaps. Next, ERS adds a step to AoA requiring expanding the design space and providing resilience options. Then cost drivers, performance measures, and relevant illities need to be determined. To quantify the uncertainty in these, engineers need to perform modeling and simulation. Using these, the value tradespace and the costs need to be quantified. In addition, during this stage, another step is added in AoA to extend the service lifetime. Specifically, this will analyze the effects of platform resilience and responds to evolving threats and scenarios. Using the previous analysis, decision-makers can make resilience and affordability trade-offs. In

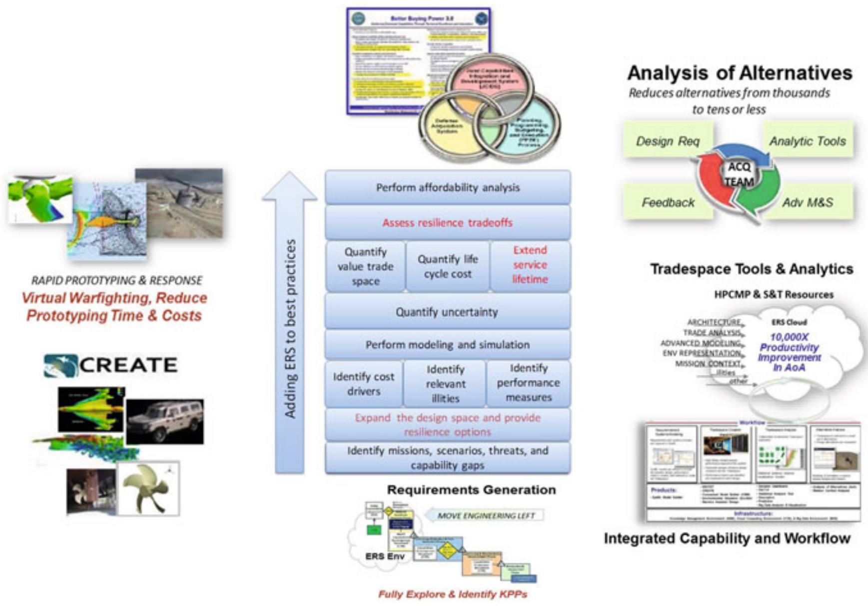

Fig. 1.4 Incorporating ERS into analysis of alternatives

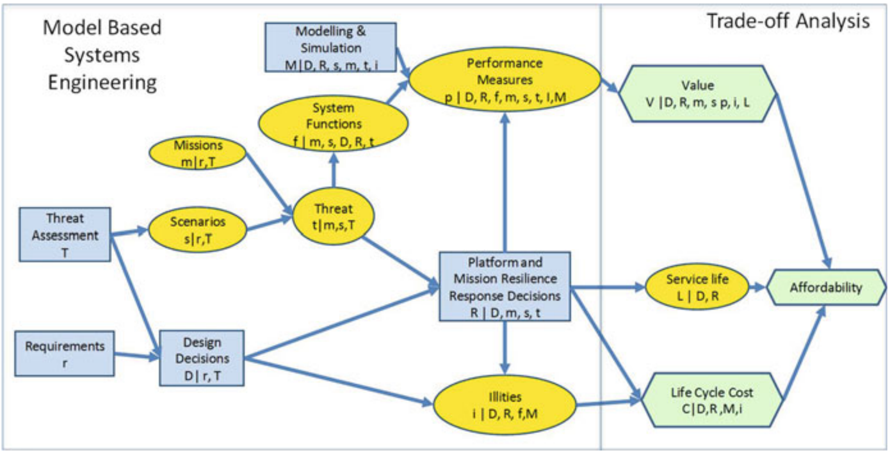

Fig. 1.5 Framework for incorporating ERS into analysis of alternatives

addition, these criteria incorporate the goals and objectives of ERS. The CREATE and tradespace tools will be used to expand the design space and modeling and simulation to provide detail required to better predict costs and values. Lastly, affordability analysis and resilience trade-offs in the AOA directly support the better buying directives of DoD.

1.4 Proposed Framework for Incorporating ERS into Analysis of Alternatives

In order to help make decisions during the early life stages of systems, the authors created a framework to incorporate the criteria into analysis of alternatives. Visually this framework is shown as an influence diagram in Fig. 1.5. An influence diagram is a concise representation of a decision problem or opportunity [4]. They identify the variables and their relationships but suppress the details. They use four nodes: decision nodes, uncertainty nodes, constant nodes, and value nodes. A decision node signifies the decision alternatives or options and is displayed by a rectangle. An uncertainty node represents the different outcomes of an uncertain event and is depicted as an oval. A constant node symbolizes a function or number that will not change and is depicted by a diamond shape. Lastly, an influence diagram has value nodes denoting the decision-makers' preferences for outcomes. Value nodes can have different types of values such as cost, performance measures, or an affordability based on cost, performance, and service life. A hexagon depicts a value node. In the diagrams, arrows are used to display influences. There are two types of influences: a probability relationship and the availability of information. The time sequence of the events is from left to right.

In Fig. 1.5 the nodes are:

- Threat assessment, T – a decision that identifies the anticipated threats the system will face.
- Requirements, r – a set of decisions determining the use of the system and required minimum performance.
- Design decisions, D – a set of decisions made with knowledge of the requirements and threat assessment. These can be point-based design decisions or set-based decisions. However, only set-based design decisions will meet the requirements to expand the design space.
- Modeling and simulation, M – the decisions made which methods and techniques used to model and what scenarios and missions to simulate the system in order to predict measures, illities, and costs.
- Platform and mission resilience response decisions, R – a decision node representing mission response decisions (short term) and platform response decisions (long term) informed by threats.
- Scenarios, s – a chance node representing an uncertain scenario, which may or may not be in the original threat assessment or requirements analysis.
- Missions, m – a chance node representing the missions the system is actually used on; this may or may not be included in the initial threat assessment or requirements analysis.
- Threat, t – a chance node representing the uncertain threat that depends on the mission. There can be different threats to different system functions. In this diagram, threat is the term used for any adverse event (environmental or adversary) that could degrade any capability of the system. This may or may not be in the original T.
- System functions, f – a chance node determining how the system is used; it is influenced by the missions and scenarios the system is used in.
- Performance measures, p – a chance node depending on the function, the illities, modeling and simulation, and resilience response decisions.
- Illities, i – a set of chances such as reliability, survivability, availability, and others affecting the performance and cost of the system.
- Service life, L – a chance node affected by the performance of the system, the illities, and the resilience response decisions.
- Value, V – a value node depending on the performance for the mission for all functions and several other variables.
- Life cycle cost, C – a value node depending on the design, the producibility, the supportability, and the platform and mission response decisions.
- Affordability, A – a value node comparing value versus life cycle cost.

In a defense design process, intelligence analysts first determine what threats new systems will face in the threat assessment. In addition, requirements for the system will be analyzed. The threat assessment and requirements analysis inform the design decisions. After the design decisions, the systems are employed in uncertain missions and scenarios. Next, even though there is an initial threat assessment, the threats the system faces are uncertain and based on the scenarios and missions the system is sent to perform. When facing these threats, users can make resilience response decisions based on uncertain threats. These options are based on what the design decisions allow the system to do and how they allow it to adapt. These decisions can be short term such as avoiding a threat. They can be a simple modification of the system like adding a new sensor. Or they can also be long-term decisions to significantly modify or adapt to the system to face new threats. For instance, a historical long-term decision was to add weapons to a C-130 to change the functionality of the C-130 from tactical airlift to a gunship. Depending on the threats, design decisions, and response decisions, the system can have different functions. From these functions, the illities, or set of characteristics including reliability, availability, producibility, survivability, etc., are determined. Next, the functions, threats, scenarios, missions, illities, design decisions, and the resilience response decisions influence the performance. The performance measures should be estimated using modeling and simulation. But, the choice of specific models and simulations is a decision because analysts need to decide which type of models and simulations to use for each system. From the performance, the value of the system is determined. Using the design decisions, the resilience response decisions, and the illities, the life cycle cost is evaluated. Then the service life is estimated from the response decisions, the design decisions, and the performance. Using the estimated values, costs, and life cycles, decision-makers make affordability decisions early in the life cycle.

Throughout this decision process, the uncertainties should be estimated using model-based systems engineering. Model-based systems engineering is a process of engineering systems using modeling throughout the AoA and decision process. Various types of models should be included. Specifically, the systems will each need at least a physics-based performance model and detailed cost model.

In addition, using the data from the right side of the framework, decision-makers need to perform trade-offs between value and cost. To balance the needs for high-performance systems and with the budget requirements, the decision-makers need data on the life cycle length, the life cycle costs, and the value of the system to allow them to assess the affordability of the system.

This framework for resilience was created to fit the criteria for incorporating resilience into AoAs. Although many of the terms are drawn from the defense industry, the framework as a whole can be applied to many different areas. In particular, the authors are currently applying the problem definition to two systems with application in the defense industry and in the public sector: unmanned aerial vehicles (UAVs) and autonomous vehicles. The analysis will focus on the early-stage decisions. It allows for set-based design. Both short-term and long-term resilience are considered in the platform and mission resilience response decisions. Multiple scenarios, threats, functions, and performance measures can be considered. The illities are incorporated. In addition, leaving the chance node as the broad term "illities" allows for inclusion of any illities a system might be concerned with. This framework accounts for uncertainty. And many different types of modeling and simulation can be used with this framework. Lastly, the framework enables affordability analysis.

1.5 Comparing the Literature to the Framework

Lastly multiple papers in the literature were analyzed using the criteria and the framework. In Fig. 1.6, the green boxes show papers fully meeting each criterion, red illustrates where papers fell short on each criterion, and the yellow displays where papers partially meet, but can be improved on each criterion. Lastly, the papers in the figure are organized from top to bottom based on first how many criteria they met and second how many they partially met.

Out of 13 papers:

- 5 papers consider resilience in general systems.
- 4 papers consider resilience in the early stages.
- 1 paper considered expanding the design space using set-based design.
- 8 papers considered both short- and long-term resilience.
- 1 paper considered multiple scenarios.
- 6 papers considered multiple threats.
- 5 papers considered multiple functions and performance measures.
- 10 papers considered the "illities."
- 5 papers used uncertainty analysis.
- 7 papers used modeling and simulation techniques.
- 3 papers supported affordability analysis.

Moreover, although meeting many of the criteria, no papers met all of the criteria required for the framework. Therefore, since many of the criteria are not considered by a large number of papers and no single paper met all of the criteria, there are gaps in the literature.

1.6 Future Work

The authors have five activities planned for future work. First, we will continue to present this work at various conferences. This allows feedback to improve the definition of engineering resilience, the engineering resilience cycle, and the framework for incorporating resilience into AoAs. Second, we will continue the literature search to identify possible solutions to the identified gaps and refine the framework. Third, we will validate the framework using illustrative engineering examples including autonomous systems (e.g., UAVs and autonomous vehicles). Fourth, the framework will be expanded to account for manned and cyber systems. Lastly, the team is researching different methods of resilience quantification to use with the framework.

Framework Criteria														
Criteria	Use terms encompassing many engineering domains	Focus on the early system definition	Expands Design Space	Consider short and long term resilience		Considers multiple scenarios	Considers multiple threats.	Considers system functions and performance measures		Incorporate the "Illities"	Allow for Uncertainty analysis	Be independent of the modeling and simulation techniques	Support affordability analysis	
Elements	*Engineering domain*	*Life cycle stage*	*Discusses Set Based Design or other design space expansion*	*Short Term*	*Long Term*	*# of scenarios explicity considered*	*Threats*	*Systems functions*	*System performance measures*	*Number of "Illities"*	*Techniques used*	*M & S techniques*	*Value-multiple/ single*	*Cost*
Sitterle et al. [5]	General DoD sytstems	Concept Stage	Discusses Set Based Design	Yes	Yes	0	Not explictiy discussed- Allows for consideration of multiple	Multiple	Multiple-Utility	Flexibility, chageability, adaptability, agility, versatility	Discusses	None	Multiple	Yes
Youn et al. [6]	General Engineered Systems	Early Stage	No	Yes	Yes	1	Internal threats- resilience a subset of reliability	Multiple	Single-Cost	Reliability, flexibility, adaptability, detectibility	Prognostics and Health Mangagent methods	Prognostics and Health Mangagent methods	None	Yes
Ross et al. [7]	Aerospace Systems	Design Stage	Design Vectors	Yes	No	0	Environmental Disturbances	Single Function	Multiple utility measures for one function	Adaptability, flexibility, changeability, survivabililty.	Monte Cartlo Simulations	Physics Based Models	Multiple Utility Meausres	Yes
Shafieezadeh and Burden. [8]	Seaport Operations	Existing systems	No	Yes	No	1	Seismic Disturbances	Multiple	Multiple	Fragility, vulnerability, reliability, flexibility, availability (of equipment)	Ground Motion Prediction Equations	Ground Motion Prediction Equations	Multiple	Yes
Kahan et al. [9, 10]	Infrustructure and Buildings	Early Stage	No	Yes	Yes	1	Terrorist Attacks	Multiple	Multiple	Flexibility, broad applicability, vulnerability, adaptability	Discusses	None	Single: resilience.	Yes
Henderson and Lancaster [11]	Technology Enterprise	Existing systems	No	Yes	Yes	Multiple but not identified	Multiple but not identified	Multiple	Multiple	recoverability, vulnerability, availability	Discusses	OODA control Loop	Multiple	Included in performance metrics
Jackson and Ferris [12]	Organizational, physical, procedural systems	No specific lifecycle stage	Resilience principles (ie Redundancy, etc)	Yes	Limite d	0	Terrorist attacks, Natural Disasters, Human and design errors.	Multiple	Multiple	Adaptability, vulnerability, survivablity, flexibility, reliability, repairability	Discusses	None	Principles of resilience not Value	No
Ettouney [13]	Communties and Civil Infrastructure	Existing systems	No	Yes	Yes	1	Man Made events Natural Events	Single: survive	Multiple to measure Resilience	Sustainability, vulnerability, reliability, availability (of workforce)	US-DHS pubically avaiblable tools- compute resilience for buildings, trasit stations and tunnels.	US-DHS pubically avaiblable tools- compute resilience for buildings, trasit stations and tunnels.	Single: Resilience	Yes
Madni and Jackson [14]	General Systems	Throughout Lifecycle	No	Yes	Yes	1 for each system	External: environmental, adversary; Systemic: Internal threats, human errors	Single: resilience- Framework designed to measure resilience	Multiple to measure Resilience	Adaptability, flexibility, reliability, survivability, changeability, predicability, inspectability	Discusses	None	Single currently, could be included in utility	Yes
Sheard et al. [15]	General Systems	Existing systems	Resilience principles (ie Redundancy, etc)	Yes	Yes	0	Failures, Accidents, Attacks, Pathogesn, Natural Hazards, Competetive Challenge	Single: survival	Single: resilience	Survivability, reliability, agility, flexibility, vulnerabilty	Discusses	None	None	None
National Academies [16]	Communties and Civil Infrastructure	Existing systems	No	Yes	Yes	Mulltiple	Natural Disasters and Man Made Disasters-i.e. Terrorism, financial crises, or social unrest	Single -Survive/ recover	Multiple to measure Resilience	Vulnerability, flexibility, recoverability,	None	San Fransisco Planning and Urban Resarch Association (SPUR) Method	Single: resilience	No
Franchin and Cavalieri [17]	Civil Infrastructure	Existing systems	No	Yes	No	1	Earthquakes	Single: survival	Multiple to measure Resilience	Vulnerability, reliability, availabillty (of tools), flexbility, adapability	Network of random variables	Using network models	Single: resilience.	No
Bruneau et al. [18]	Physical Communities	Existing systems	Resilience principles (ie Redundancy, etc)	Yes	No	1 for each type of system	Seismic Disturbances	Single: Survive	Multiple to measure Resilience	Sustainability, flexibility, reliability, fragility, vulnerability, availability, viability	Discusses	None	Single: resilience.	Limited

Fig. 1.6 Literature conceptual framework analysis

1.7 Conclusion

The authors propose a definition of resilience that is independent of the means to achieve resilience. Using this definition alongside the research from the literature search and knowledge from stakeholders, the team identified criteria for incorporating resilience into AoA. These efforts mix AoA best practices and ERS. Figure 1.4 identifies best practices and ERS in addition to showing how the criteria fit into ERS. Using this criterion, the team has created a framework to incorporate ERS into AoA and to quantify resilience (Fig. 1.5). This framework is represented as an influence diagram that can be used by many different modeling techniques. In addition, the framework fulfills the criteria identified. In the future, the framework will be revised and refined through peer reviews. In addition, the framework is currently beginning to be applied to two different autonomous applications. Using the framework, the team will continue its research and develop methods of quantifying resilience to fill the identified research gaps.

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Chapter 2
Early Life Cycle Cost Estimation: Fiscal Stewardship with Engineered Resilient Systems

Travis Moody, Robert Provine, Samantha Todd, Nicholas Tyler, Thomas R. Ryan, and Ricardo Valerdi

Abstract Organizations are constantly seeking to achieve earlier and more accurate cost estimates in order to make better trades space and design decisions, as well as minimize project cost and schedule overrun. These estimates facilitate decisions that are more informed – especially within the United States Department of Defense's engineered resilient systems (ERS) program. This paper will discuss the current methods used to achieve life cycle estimates, the role of estimation within ERS, and recommend a parametric life cycle cost estimation model that will support decision-making. In addition, this paper will focus solely on early life cycle engineering inputs that translate with Department of Defense's pre-Milestone A in order to create an early life cycle cost estimation model (ELCE). This model leverages the engineering inputs (design parameters) that are typically available early in the design process in the following five categories: hardware, software, systems engineering, project management, and integration. This paper will also highlight future research goals to determine values for factors of economies of scale, regression analysis with real data, limitations, and potential impacts of application.

Keywords Acquisition • DoD 5000.02 • Engineered resilient systems • Life cycle • Costing • Hardware estimation • Software estimation • Systems engineering estimation • Project management • Project management estimation • Integration • Integration estimation • COSYSMO • COCOMO II • Cost estimation relationships

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T. Moody (✉) • R. Provine • S. Todd • N. Tyler • T.R. Ryan
United States Military Academy, West Point, NY, USA
e-mail: travis.moody@usma.edu

R. Valerdi
University of Arizona, Tucson, AZ, USA
e-mail: rvalerdi@arizona.edu

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2.1 Introduction

Estimating the life cycle cost of a new system, in a stage early enough to procure funding, is a difficult proposition. The Department of Defense (DoD) is at the forefront of military costing, but the institution as a whole needs to produce estimates that are more effective. For example, when the F-35 Lightning II Program was proposed for funding in October 2001, the total program cost was estimated to be $224.77 billion dollars for 2866 units. As of August 2013 after 121 months behind schedule, the total program cost had soared to $332.32 billion dollars. This constitutes an increase of 47% while producing 409 less units and a 72% increase in per unit cost from the original estimates [9]. This is unacceptable and breaches the trust between the citizens of the United States, the government, and the DoD [4, 5].

Engineered resilient systems (ERS) is one such DoD program attempting to help reduce cost-associated problems by attaching life cycle estimates to decision alternatives. ERS is housed within the US Army Engineer Research and Development Center (ERDC) and aims to provide a data-driven approach to building resilient systems through trade space analysis tools [10]. Within the ERS suite of tools, there exists a need for an embedded cost estimation component that is provided as an output to ERS users during the early stages (pre-Milestone A) of a system life cycle, as shown in Fig. 2.1. As design parameters are entered into the ERS tradespace tool, a SysML-like architecture is created, which allows for the generation of life cycle cost estimates. These estimates will then be attached to different design alternatives to aid engineers in the decision-making process.

Established methods for determining the cost of a system are described as top-down, bottom-up, and parametric [1, 15]. This research is concerned

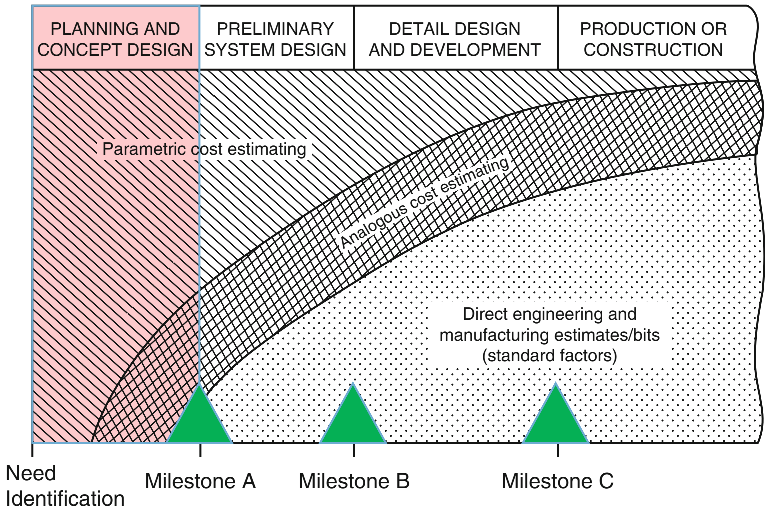

Fig. 2.1 DoD acquisition milestones overlaid on general cost estimating techniques by engineering phase. This depicts the three milestones of the DoD acquisitions process in relation to the systems phases. The *red* box outlines the boundary of the research in this paper [1, 6]