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Broad Utility: Architecting Flexible and Robust Systems for a Complex Operational Environment

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Abstract

The current and future Operational Environment (OE) for the United States (U.S.) military is becoming increasingly complex. This complexity requires Systems Engineers and Architects to develop new approaches for evaluating the variability inherent in the OEs of today and tomorrow. In response to this growing capability gap, the U.S. Department of Defense (DoD) established the Engineered Resilient Systems (ERS) program. A core property of ERS is Broad Utility—the ability of a system to, "**perform effectively in a wide range of operations across multiple futures despite experiencing disruptions.**" [1] This paper discusses on-going research intended to provide system designers with an approach to architecting systems for Broad Utility. Specifically, this research seeks to accomplish three objectives: **(1)** Identify gaps in current U.S. DoD doctrine impacting the ability to architect for Broad Utility; **(2)** Develop an integrated network model of the Operational Environment that highlights how OE variables can impact system effectiveness; and **(3)** Propose an approach for ensuring that system architectures exhibit Broad Utility, through a process of mapping system Flexibility and Robustness to the variables of the OE. By employing this approach early in the Systems Engineering process, system designers can increase the likelihood that the resulting system responds appropriately to a changing environment.

Keywords: Engineered Resilient Systems; Broad Utility; Operational Environment; Ilities; Flexibility; Robustness; System Architecture

1. Introduction and Motivation

The Engineered Resilient Systems (ERS) program seeks, "to develop engineering concepts, science, and design tools to protect against malicious compromise of weapon systems and to greatly enhance the manufacturability of trusted and assured defense systems across the acquisition life cycle," [3] as well as enhance the DoD acquisition

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process. [2, p. 5] The adoption of these methods should result in systems developed faster and cheaper, with increased effectiveness in the evolving OE. Previous research conducted by members of the U.S. Army Engineer Research and Development Center (ERDC) and the University of Southern California defined the four properties of ERS as (1) Broad Utility, (2) Repel, Resist, or Absorb, (3) Adapt, and (4) Recover. [1, p. 868]

The motivation for this research focuses on understanding the disruptions that technical systems face in the OE and to develop an approach for architecting those systems to exhibit Broad Utility: the ability of a system to, "perform effectively in a wide range of operations across multiple futures despite experiencing disruptions." [1, p. 867] Notwithstanding the validity and importance of the three remaining properties, the scope of this research is limited to that of Broad Utility.

2. A Complex Operational Environment

According to current U.S. Joint doctrine, the Operational Environment (OE) is, "the composite of the conditions, circumstances, and influences that affect employment of capabilities and bear on the decisions of the commander/ It encompasses physical areas of the air, land, maritime, and space domains; the information environment (which includes cyberspace); the [Electromagnetic Spectrum] EMS; and other factors." [4, pp. IV-1] In the environment, understanding the ability of near-peer adversaries to achieve technological and tactical over-match against the U.S is of great importance to ensuring U.S. military superiority on the battlefield. [5, p. 1] In order to make sense of the OE, many frameworks exist to assist military leaders in describing the environment, at the tactical, operational, and strategic levels. Common frameworks, and those employed in this research, include DIME (Diplomatic, Information, Military, and Economic) at the strategic level, PMESII-PT (Political, Military, Economic, Social, Infrastructure, Information, Physical Environment, and Time) at the operational level, and METT-TC (Mission, Enemy, Terrain, Troops Available, Time, and Civilian Considerations) at the tactical level. Each framework seeks to describe the external variables which impact the conduct of U.S. Army missions. By extension, these variables can directly and indirectly impact the effectiveness of technical systems Soldier employ. As a result, it is critical to understand how these variables can impact a system's Broad Utility.

The *Strategic Operating Environment (SOE)*, "is the global environment in which the U.S. President employs all the elements of national power (diplomatic, informational, military, and economic)." [6, p. 11] In this sense, these variables—Diplomatic, Informational, Military, and Economic—represent options available to the President of the United States in the conduct of his or her duties and advancement of national interests. However, these variables also impact every human and organization on Earth, including U.S. Army leaders. From a system design perspective, government and commercial system designers should also consider these variables because they have direct effect on the effectiveness of the systems they develop. Accounting for these variables in the conduct of operations, as well as in the architecting and development of technical systems used by Soldiers, is critical.

The *Operational Operating Environment (OOE)* can be described by using one of the most common tools for understanding the OE: the PMESII-PT framework. Found in a number of doctrinal publications, [4] [7] [8] [9] the variables described in this framework are applied by Army forces, "to the specific OE in which they are conducting or plan to conduct operations…[and aid in] decision making at any level, in any situation." [6, p. 54] The Political, Military, Economic, Social, Information, Infrastructure, Physical Environment, and Time variables have the potential to serve as significant drivers of change within the OE. As such, they play a critical role in defining the scope of the Operational Operating Environment and merit consideration during system design.

To describe the *Tactical Operating Environment (TOE)*, the Army uses a framework consisting of six first-level variables. Specifically, these variables are defined as Mission, Enemy, Terrain, Troops Available, Time, and Civilian Considerations (METT-TC). [9, pp. A-3] Terrain and Weather decomposes into Observation, Avenue of Approach, Key Terrain, Obstacles, Cover and Concealment (OAKOC), Visibility, Wind, Precipitation, Cloud Cover, Temperature, and Humidity. Civilian Considerations decomposes into Areas, Structures, Capabilities, Organizations, People, and Events (ASCOPE). Traditionally, the METT-TC variables are used for mission analysis and not explicitly for describing the OE; however, these variables represent critical factors that influence the execution of Army operations in real-time. Thus, the influence of these factors should also be considered when architecting systems because they help shape the OE.

Fig. 1 depicts the level of granularity at which each variable should be considered when architecting systems for Broad Utility. While some variables inevitably decompose further, they are beyond the scope of this research.

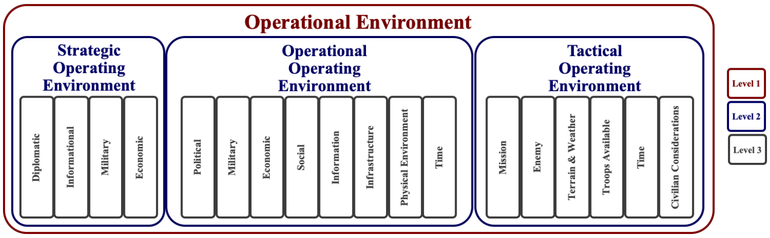

Fig. 1. Operational Environment Variable Decomposition

Based on a cursory examination of these frameworks, there clearly exists overlapping variables between each of the levels. Coupled with the prevailing sentiment in current U.S. DoD Joint doctrine [4, pp. IV-3], the model illustrates the dependency and interconnectedness between the OEs, as well as their associated variables. These frameworks establish the foundation for the proposed integrated network model of the OE.

In its current form, doctrine does well in describing these environments in isolation; however, three notable gaps exist in their application to architecting for Broad Utility. These deficiencies are of particular importance not only for understanding the OE and the conduct of U.S. Army operations, but also for the design and development of the systems that support these operations. In order to architect a system for Broad Utility, it is critical to understand the environment in which the system will operate and how the variables of the OE can impact the system's effectiveness.

3. Doctrinal Gaps in Architecting for Broad Utility

The previously discussed frameworks for describing the OE are widely used and assist Soldiers and leaders at all levels of the U.S. Army to better understand their environment. In their application to operational planning and mission analysis, lower echelons typically wait for their higher headquarters to bound the OE before completing their level of analysis. However, in a world of constant change, these frameworks must be re-evaluated and updated to reflect the realities of today's combined, multi-layered operating environments. By themselves, these frameworks do very well in describing the various operating environments; however, it is necessary to use a more integrated approach to reduce the likelihood (or risk) of adversaries exploiting gaps between echelons. In doing so, architecting for Broad Utility becomes a more manageable task.

Following the analysis of each doctrinal framework, three distinct gaps in current U.S. DoD doctrine were identified. These gaps must be addressed in order to effectively architect systems for Broad Utility. These gaps include: (1) integrating the Strategic, Operational, and Tactical Operating Environments together, (2) including the Soldier, their equipment (Engineered Resilient Systems), and their assigned tasks within the OE. [10, p. 45], and (3) specifying the exchanges between the variables of the OE. In order to address these gaps, the use of Systems Engineering tools and methods is required.

4. Operational Environment Exchange Network: An Integrated Network Model of the Operational Environment

The Joint Concept for Human Aspects of Military Operations (JC-HAMO), illustrates, "how the Joint Force will enhance operations by impacting the will and influencing the decision making of relevant actors in the environment, shaping their behavior, both active and passive, in a manner that is consistent with U.S. objectives." [12, p. 1] As a member of the Joint Force, this concept applies to the U.S. Army, at every echelon, down to the individual Soldier. Systems Engineers and Architects who design and develop systems to accomplish these objectives must consider this concept, as well. The execution of a task by Soldiers with their equipment can have far-reaching implications at the strategic level. The necessity of this concept is born from the idea that, "recent failure to translate military gains into strategic successes reflects, to some extent, the Joint Force's tendency to focus primarily on affecting the material capabilities—including hardware and personnel—of adversaries and friends, rather than their will to develop and employ those capabilities." [12, p. 1] This addresses the realization that Soldiers and their equipment are employed to achieve more than tangible physical ends. The elements that shape human behavior [12, p. 5], according to the JC-HAMO, include:

Social: "focuses on how a society, its institutions, and key relationship influence people…distinguished by the competing influence of groups and institutions, each seeking to impose its own priorities and perspective." [12, p. 6]

Cultural: "considers the way a society's beliefs (including religious and spiritual principles), customs, and way of life affect the many in which people behave." [12, p. 7]

Physical: "includes environmental aspects that shape the choices, outlook, values, and behavior of groups and individuals." [12, p. 7] As an important addition, for the purposes of this thesis, the physical element will also include the physical effects systems can have on Soldiers (visual, auditory, haptic, and olfactory), as well as their existence and operation in the OE. This addition is consistent with the JC-HAMO, which states "…the material capability and capacity of friendly, neutral, and adversary actors in the environment are also part of the physical element." [12, p. 7]

Informational: "centers on the sources, availability, and uses of data." [12, p. 7]

Psychological: "…influences how people perceive, process, and act upon information." [12, p. 7]

While the JC-HAMO is useful for understanding how and why humans behave in particular ways, it may also be used to guide and constrain the mechanical and electromechanical System Architect's design decisions about how the system will be employed by Soldiers. These elements influence not only Soldier behavior and effectiveness, but also the conduct of a tactical task and the effectiveness of the systems operated the Soldier.

To accomplish the second research objective—the development of a more comprehensive visual model of the OE—the exchanges between the variables of the OE must be specified. The Operational Environment Exchange Network (OEEN), illustrated in Fig. 2 is a visual tool based on the Stakeholder Value Network (SVN) described by Crawley, Cameron, and Selva [11]. It informs Systems Engineers and Architects of the ways in which the variables of the OE can impact a system's Broad Utility and rectifies the previously mentioned gaps. This is done through the specification of the exchanges between all variables within the OE, using the JC-HAMO elements.

The development of this integrated network model requires the exploration of the following question, as it pertains to the Soldier, their Equipment, their Task, and the Tactical, Operational, and Strategic environments: "Can a state change in one OE variable have a(n) Social, Cultural, Physical, Informational, or Psychological effect on, or cause a state change, in another OE variable?"

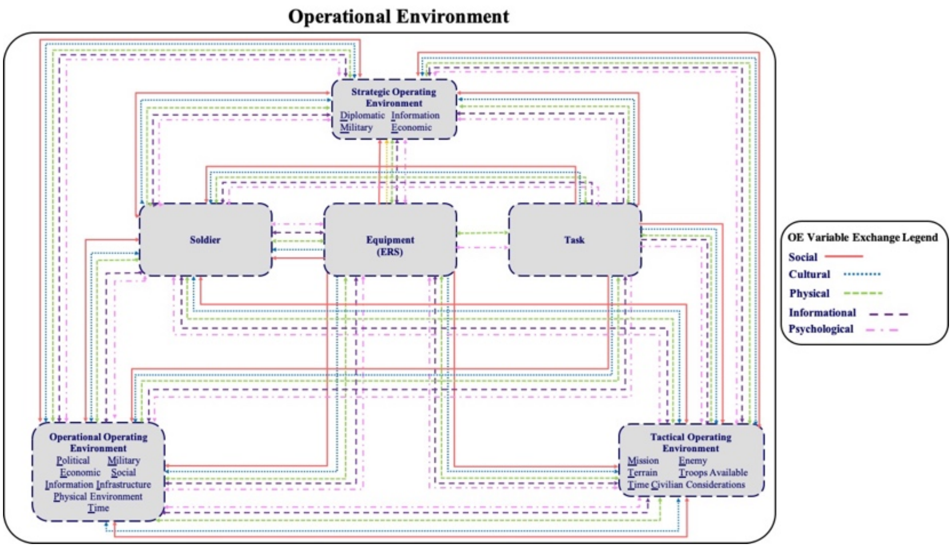

Fig. 2. Operational Environment Exchange Network (OEEN)

For each potential link (colored arrow), if the answer is 'yes', a direction arrow is assigned from the originating variable to the affected variable. Conversely, if the answer is 'no', an arrow is not attributed. If no linkage exists, a connection is not depicted. It is important to note that some relationships are 'one-way'. This question is central to the development of the OEEN because it allows for the comprehensive exploration of how the variables of the OE can affect one another, going beyond the mere recognition that a link exists.

Given the complexities illustrated in the OEEN, the challenge of architecting systems that can operate despite changes in any one of the numerous OE variables arises. The approach for doing so requires a focus on System Lifecycle Properties (Ilities), not measures of the system's performance. Changing OE conditions may not always affect the performance of the system, but will inevitably impact the system's effectiveness.

5. Ilities: Measures of Effectiveness in the Operational Environment

The challenge of architecting systems for Broad Utility is difficult, given a complex OE. With the near-infinite number of combinations and changes of this environment, it is impossible to architect a system that simultaneously addresses all OE variables solely from a performance perspective. However, by considering certain Ilities, system designers can begin to develop systems that may be more likely to perform effectively despite changing external conditions. As Measures of Effectiveness, Ilities go beyond satisfying discrete Measures of Performance (maximum speed, maximum effective range, projectile velocity, etc.) by ensuring that the system satisfies the operational needs of specified stakeholders. According to de Weck et al., "there is an increasing realization that much of the value that systems generate depends on the degree to which they possess certain lifecycle properties, a.k.a. 'Ilities'". [13, p. 3] By focusing on Ilities, system designers can adopt a process that instills greater confidence in the validity of the system's effectiveness, enabling the proposed Broad Utility Architectural Decisions to maintain a greater applicability because they are not system-specific, formal design requirements.

Previous research [13, p. 5] indicates that Ilities are somehow related; however, additional insight can be gained through the development of a Means-Ends Hierarchy. A Means-Ends Hierarchy is one that represents the relationships between Ilities in terms of using one Ility as a "means" for accomplishing another Ility ("ends")." [13, p. 6] As an extension of the research on Ility co-occurrence and to determine what, if any, means-ends relationships existed between Ilities, de Weck, Ross, and Rhodes conducted a multi-round exercise using twelve (12) individuals, broken up into two to four-person teams, with a range of one to ten years of experience researching and applying Ilities. [13, pp. 6-7] Each team then developed their own hierarchy without external input. After analyzing the four hierarchies, the following insights were derived:

(1) Value Robustness—"the ability of a system to maintain value delivery in spite of changes in needs or context." [13, p. 6]—is the ultimate 'end' goal for a system. The definition of Value Robustness can be closely linked to that of an ERS, which must "…serve effectively in a variety of missions with multiple alternative futures through rapid reconfiguration or timely replacement despite uncertainties about individual component performance." [1, p. 870]. Specific to Broad Utility, there are distinct similarities in its definition and that of Value Robustness.

(2) Robustness is consistently viewed as one of the main second-level Ilities to achieve Value Robustness. This lends further support to the idea that Robustness is an important component of Broad Utility.

(3) Changeability—"the ability of a system to alter its operations or form, and consequently possibly its function, at an acceptable level of resources" [13, p. 6]—is considered a second and third-level Ility two times respectively. As a second-level Ility, it links directly to Value Robustness.

(4) In all but one hierarchy, Changeability decomposes into Flexibility and Adaptability, and in some cases, other Ilities. This is of particular interest given the importance regarding the location of Change Agents. Change Agents, including the Soldier, their task, and each operating environment, are external to the system and imply a Flexibility-type change. This insight provides additional support to the idea that the variables in the OE act as Flexibility Change Agents.

While these insights represent the individual interpretations of each of the participants and groups, it suggests that Ilities are inextricably linked and, by extension, some lead to the realization of others. [13, p. 10] Given the consensus between the groups regarding Robustness' link to Value Robustness, it seems appropriate to consider Robustness as an important Ility of Broad Utility. Changeability, albeit less unanimous, is also linked to Value Robustness. As noted above, Changeability decomposes in several ways; however, as it pertains to systems in the OE, focusing on Flexibility is appropriate. While this analysis further supports the idea that Flexibility plays a critical role in a system's Value Robustness, or Broad Utility, it is not meant to imply a lack of importance regarding Adaptability. Within the scope of this research, Change Agents internal to systems are not explored, but do exist; however, given the focus on external system variables, Flexibility merits further examination. Despite strong evidence of Ility relationships, there does not appear to be a unanimous consensus regarding how they are related. In order to remain within proper research scope, this research subscribes to the hierarchy that illustrates Changeability, specifically Flexibility, and Robustness are two critical Ilities leading to Value Robustness, which can be another way of expressing a system's Broad Utility. This Means-Ends Hierarchy provides strong qualitative evidence regarding the importance of Flexibility and Robustness as a means for achieving Broad Utility; however, a lack of quantitative evidence exists to support this assertion.

In order to validate this theory, data gathered by the ERDC's Adaptive Red Teaming/Technical Support and Operational Analysis (ART/TSOA) program was utilized. Under this program, technical systems employed by Soldiers are tested in various environments and evaluated by Subject Matter Experts on their ability to perform effectively. These tests evaluated, reported, and analyzed 16 quantitative factors scored on a zero (0) to ten (10) scale, six (6) of which measured the system's Flexibility, Robustness, and Broad Utility. Previous research has explored the concept of system effectiveness; however, the data gathered by the ART/TSOA program allows for the employment of quantitative measures validated and utilized by an established DoD research program and serve as a useful means for representing the specified Ilities and Broad Utility. In total, 186 unique systems were evaluated, generating 533 assessments, enabling a quantitative examination of the relationship between Flexibility and Broad Utility, as well as Robustness and Broad Utility. These relationships were analyzed using Pearson's Correlation Coefficient, R_p, Spearman's Rank-Order Correlation Coefficient, R_s, and Box and Whisker Plots. R_p measures the degree to which a linear relationship between the variables exists, while R_s measures the strength of the monotonic relationship between the variables. The resulting hypothesis is systems that display greater Flexibility and/or Robustness will have a higher Observed Performance (OP), or Broad Utility (see Fig. 3a). This means that both coefficients should be closer to one (1), indicating a strong, positive relationship. This relationship is explored by first analyzing all system observations, then, using Box and Whisker Plots, analyzing the Mean Trendline. In the first test, a linear relationship between the chosen factors and OP is determined, without regard for the variability that results from different assessors having a wide range of experiences, knowledge, and biases. In the second, analyzing the Mean Trendline averages out this variability and determines the strength of each relationship.

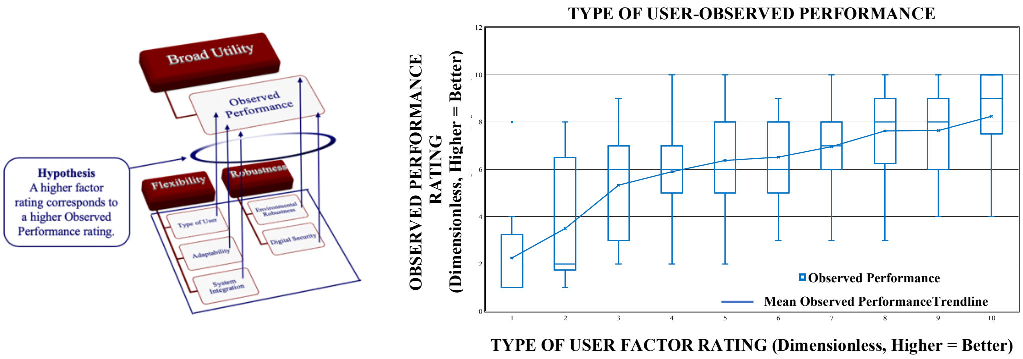

Fig. 3. (a) Hypothesis; (b) Type of User-Observed Performance Box and Whisker Plot

As an example, Fig. 3b displays the Box and Whisker Plot generated for the first factor, Type of User, and its relationship to OP. Using this plot of all 533 assessments, it can be visually confirmed that systems which scored higher on this measure of Flexibility typically scored higher in terms of OP (Broad Utility); however, this relationship must be confirmed. Regarding the variability in the assessments, it is readily apparent (see Fig. 3b, Type of User rating '2') that consensus between assessors varies greatly. By exploring both relationships, the validity of the hypothesis can be confirmed or denied with higher certainty.

As illustrated in Fig. 4, each factor representing Flexibility and Robustness exhibits positive linear and monotonic relationships to OP, with varying degrees of strength. In the first test (All System Observations), the linear relationship between the factors representing Flexibility/Robustness and Broad Utility is positive, albeit not very strong. While this provides support for the hypothesis, it does not do so convincingly. By conducting the second test (Mean Trendline), using Box and Whisker Plots, the data can be better visualized and the factors analyzed according to their monotonicity and linearity. By averaging out the variability associated with the judgements of different assessors, there are clear linear and monotonic relationships.

		Data Analysis Evaluation Criteria							
		All System Observations (w/ Assessor Variability)		Mean Trendline (Averaging Out Assessor Variability)				Inter-Quartile Range (IQR)	
Ility	Factor	Rp Value	Linear Relationship	Rp Value	Linear Relationship	Rs Value	Monotonic Relationship	Minimum (Rating(s))	Maximum (Rating(s))
Flexibility	Type of User	0.46	Low Positive	0.94	Very High Positive	1.00	Very High Positive	2.00 (4)	4.75 (2)
	Adaptability	0.63	Moderate Positive	0.99	Very High Positive	0.98	Very High Positive	1.00 (4,9)	4.50 (1)
	System Integration	0.48	Low Positive	0.96	Very High Positive	0.95	Very High Positive	2.00 (4,8,9)	4.75 (3)
Robustness	Environmental Robustness	0.56	Moderate Positive	0.98	Very High Positive	0.99	Very High Positive	1.50 (10)	5.00 (1)
	Digital Security	0.52	Moderate Positive	0.95	Very High Positive	0.96	Very High Positive	1.00 (4)	4.50 (3)

Fig. 4. Data Analysis Summary

Systems that scored lower in terms of Flexibility and Robustness generally performed less effectively. Conversely, systems that scored higher in terms of the Flexibility and Robustness achieved a higher OP (Broad Utility) rating. Despite these results, limitations surrounding these results exist, including the fact that they are not statistically conclusive and that the factors chosen to represent Flexibility, Robustness, and Broad Utility are not exhaustive. Regardless, the analysis provides compelling evidence supporting the inclusion of Flexibility and Robustness as means for achieving Broad Utility. While this is significant, these Ilities, depending on the intended function of the system, can manifest themselves in a multitude of different ways. Therefore, these results, in and of themselves, do not provide system designers with a method for architecting for Broad Utility. In order to remedy this deficiency, and accomplish the third objective of this research, the variables of the OE, exogenous to the system, are mapped to Flexibility and Robustness, yielding a set of Architectural Decisions available to system designers at the beginning of the Systems Engineering process.

6. Broad Utility Architectural Decisions

Having specified three critical gaps in current U.S. DoD doctrine impacting the ability to architect systems for Broad Utility and developed the OEEN as a means for understanding how the variables of the OE can impact system effectiveness, an approach to architecting systems for Broad Utility is proposed. The following Architectural Decisions, which include the most impactful decisions from which all future requirements stem [11, p. 197], map the variables of the OE to the qualitatively and quantitatively-validated Ilities of Flexibility and Robustness.

These Broad Utility Architectural Decisions provide system designers with a collective set of options that must be considered early in the system design process in order to ensure the system is capable of operating effectively in a wide range of operational contexts, despite experiencing disruptions (see Table 1).

Table 1. Broad Utility Architectural Decision Definitions.

Flexibility	Robustness
Soldier Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *Soldier* variable.	**Soldier Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *Soldier* variable.
Task Flexibility: the ability of the system to be *physically and/or psychologically* changed by the *task* variable.	**Task Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical and/or psychological* changes in the *Task* variable.
Tactical Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *mission, enemy, terrain, troops available, time, and/or civilian considerations* variable(s) in the *Tactical Operating Environment*.	**Tactical Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *mission, enemy, terrain, troops available, time, and/or civilian considerations* variable(s) in the *Tactical Operating Environment*.
Operational Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *political, military, economic, social, information, infrastructure, physical environment, and/or time* variable(s) in the *Operational Operating Environment*.	**Operational Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *political, military, economic, social, information, infrastructure, physical environment, and/or time* variable(s) in the *Operational Operating Environment*.
Strategic Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *diplomatic, information, military, and/or economic* variable(s) in the *Strategic Operating Environment*.	**Strategic Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *diplomatic, information, military, and/or economic* variable(s) in the *Strategic Operating Environment*.

Inevitably, each of the options is further decomposed to develop specific requirements for the system. Depending on the intended function of the system, each decision will manifest in a variety of ways; however, as the basis for the future design of the system, these Architectural Decisions should provide a means for earlier validation of the system's effectiveness in the OE.

7. Conclusions and Future Research

Through the conduct of this research, several key contributions are realized. First, three gaps in current U.S. DoD doctrine were identified and analyzed, in terms of their impact on the ability of system designers to architect technical systems for Broad Utility. In order to address these doctrinal gaps, the Operational Environment Exchange Network (OEEN) was developed and proposed. This network model provides a more holistic means for understanding how the variables of the OE impact one another. As a result of these interdependencies, changes in one part of the OE can propagate to others, leading to a more complex environment. This dynamic, complex environment requires systems to maintain their effectiveness in the face of changing conditions, necessitating a focus on key System Lifecycle Properties, or Ilities. Through the unique analysis of coupling qualitatively-developed Ility Hierarchies with the quantitative data analysis described, Flexibility and Robustness were validated as key means for achieving Broad Utility. Having accomplished the first two research objectives, a set of Broad Utility Architectural Decisions were defined and proposed, which mapped Flexibility and Robustness to the variables of the OE exogenous to the system itself. As high-level system requirements, these decisions serve as the source from which future formal and technical requirements are derived. Through these decisions, system designers are armed with a method that may increase the likelihood that the systems they develop have been architected to account for the environment that is known today and that which will evolve over time. Future research work will consist of applying the proposed Architectural Decisions to the conceptual design of a Position, Navigation, and Timing (PNT) system for the U.S. Army.

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