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Enhancing Set-Based Design To Engineer Resilience For Long-Lived Systems

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ENHANCING SET-BASED DESIGN TO ENGINEER RESILIENCE FOR LONG-LIVED SYSTEMS

by

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DEDICATION

To Mary.

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1.1. BACKGROUND OF THE PROBLEM

The Problem Itself

"I don't foresee a grand slam on the first pitch where we're going to deliver a fixed capability for the life of the vehicle. We've got to be knowledgeable enough to recognize that the environments change, threats change, new technology starts to come to pass, and we want to make sure this design will allow for that growth in the future. I think we're at a point in time where you really want deep thinking, good ideas that can help influence design, requirements, trade and cost at a stage in the program where it can make a difference".

Dr. J. Burrow, Executive Director, Marine Corps Systems Command, USMC ACV Team, *Inside the Navy*, March 25, 2013.

Increasing numbers of U.S. military systems, including ground vehicles and aircraft, are undergoing multiple rebuilds and capability upgrades throughout their design service life. Design service life is the summation of the engineering-based original design life plus any Service Life Extension Programs, System Enhancement Programs, or rebuild actions (modifications that result in additional miles or hours). Requirements typically specify design lives of 20 years for aircraft, 30 years for ground systems, and 30-50 years for ships. As illustrated in Figure 1, many aircraft and ground vehicles have *extended* service lives, driving the need for upgrades that were not planned (and could not be planned) when the systems were fielded. The primary cause of this phenomenon is requirement changes driven by threat variations, technology opportunities, and mission evolution, much of which could not be forecasted at the original design time. This drives the need for designing in resiliency, by way of "changeability," that enables unplanned easy and rapid replacement or upgrade of obsolete technologies. Examples of long-lived major systems that have undergone multiple unplanned capability upgrades are described in Appendix A. The problem to be addressed by this research is that of systems with design service lives well beyond the ability to forecast the specific requirements for the system over the entire life, necessitating multiple iterations of capability upgrades to remain relevant and meet the requirement change needs. Accordingly, there is need for planned and systematic insertion of new technologies and capabilities to: i) keep a system relevant, ii) maintain a level of customer value and satisfaction, and iii) meet or overcome evolving threat (Kerr *et al.* 2008).

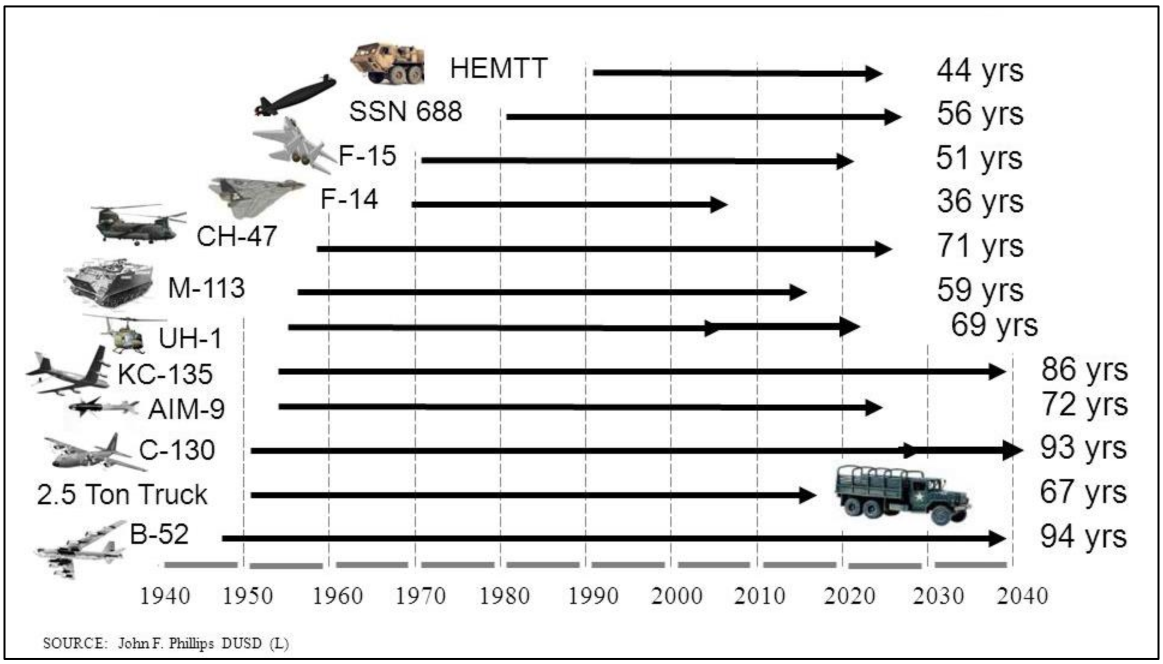

FIGURE 1. SYSTEMS EXCEEDING DESIGN SERVICE LIFE

Requirements for military systems typically include growth margin—also referred to as "reserve capacity" (RC) and design margin—for crucial functions and limitations (e.g., volume, power, and computing). Changeability, by way of flexibility and agility, is enabled through RC (Chalupnik *et al.* 2013). The Oliver Hazard Perry-class Guided-Missile Frigate (FFG-7) of the U.S. Navy provides an excellent example of the consequences of not achieving RC requirements

(Appendix B). The challenge is in valuing RC for future potential benefits against current costs and other burdens (e.g., weight). The future mission capability need and cost are not fully known, making the valuing of future potential enabled by current design a formidable task (Deshmukh 2012).

Set-Based Design Background

Set-Based Design (SBD) is a promising capability supporting engineering resiliency and requirement changes during a system's service life. SBD is an iterative process in which design and requirements evolve in parallel, and in which stakeholders restrict and relax requirements with feedback regarding feasible solutions in design space given the requirements (Singer 2009). It is a concurrent engineering process that helps stakeholders understand the interdependencies among the requirements and impact on design as they work to develop the performance specification and preliminary design (Rapp 2017).

A practical way of looking at SBD is that it shifts the focus from the typical point-based design strategy of selecting the most-promising concept early in the development phase, to that of eliminating the inferior ones only when it is determined that they do not meet relevant requirements (Malak *et al.* 2008), carrying forward the remaining potential solutions at each stage. Figure 2 shows the general conceptual difference between point-based design and SBD (Miller 1993). To capitalize on the advantage provided by SBD for promoting product resilience, program investment needs to be front-loaded to thoroughly explore alternative[1] solutions while the design tradespace is most open.

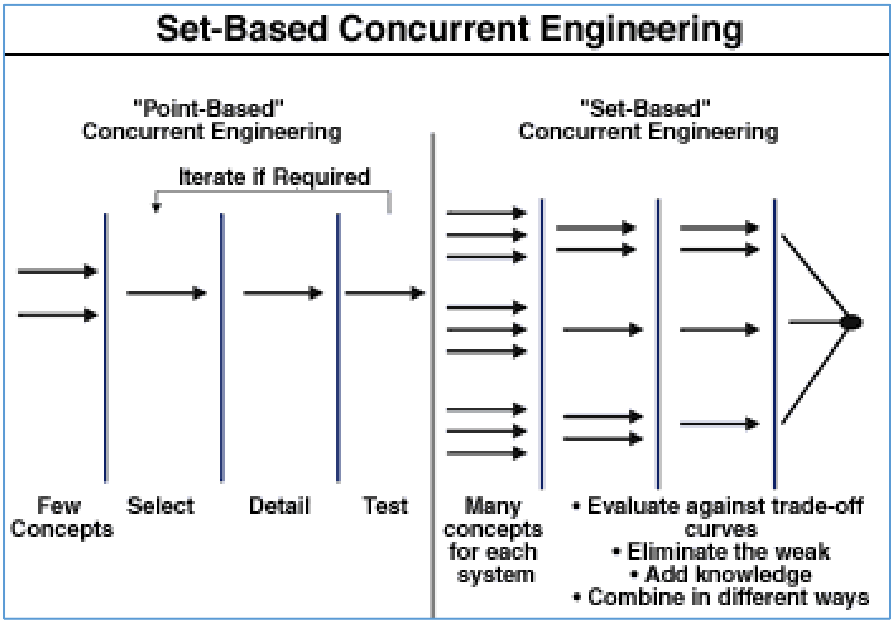

FIGURE 2. POINT-DESIGN VS. SET-BASED DESIGN CONCEPTS

1.2. STATEMENT OF THE PROBLEM

The principal question that this research set out to address is “How can set-based design be enhanced and applied to the engineering of resilient systems?” One aspect of SBD is about deferring decisions during the design process until the information necessary to make those decisions is known. The information could pertain to performance, such as RC, or burdens. In essence, a decision to eliminate a subsystem option is not made until it is reasonably certain that it will not

[1] The term “alternative” denotes a choice at the system level, whereas the term “option” denotes a choice at the capability or subsystem level.

meet its associated requirements. Extended, therefore enhanced, SBD is about the capability to defer decisions beyond the design process until after it is fielded, when additional or better information is obtained (Figure 3). The system-set is a set of capability option decisions carried through the system's service life.

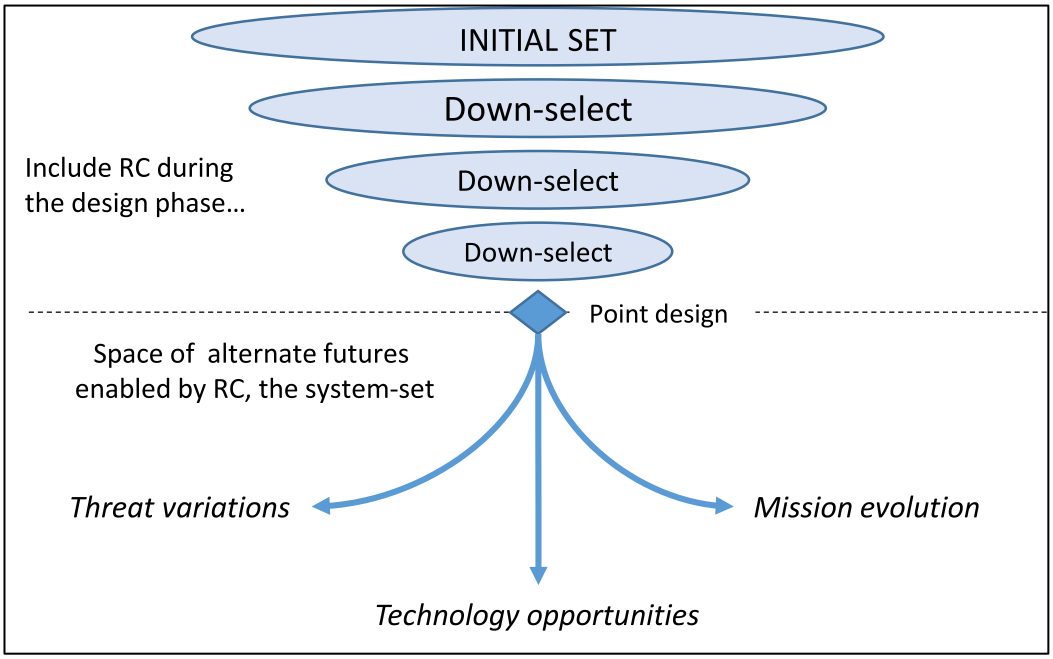

FIGURE 3. RC & SYSTEM-SET EXPAND THE ALTERNATE FUTURES SPACE

With respect to resiliency, this research focuses specifically on the second characteristic of resilient systems (Holland 2012)—systems adapted and/or extended to achieve higher levels of performance, perform new functions, and/or operate in a wider range of conditions.

Consider how RC intersects with SBD in two ways.

1. RC should be considered up-front in the system design process, in order to make an informed choice on the initial fielded point-solution. While it is generally appreciated that incorporating RC is a cost-effective objective to pursue, the shortage of supportive empirical evidence may be deterring decision-makers from pursuing necessary

up-front funding. However, analytical methods for determining a warranted amount of RC appear to be lacking.

2. More fundamentally, designing in RC is equivalent to designing in a future set of vehicles. What is a point design at fielding expands out into a set of potential futures through upgrades, to be decided in the future.

1.3. PURPOSE OF THE STUDY

The purpose of this research is to develop a framework that enhances SBD to produce engineered resilient systems with cost-effective post-production growth capability by means of flexibility and agility, achieved through appropriate types and amounts of RC. The framework will provide decision makers (DMs) and stakeholders with enhanced insight and understanding of the trade-space to promote smarter acquisition decisions. This research aims at enhancing SBD by establishing a quantitative capability within an analytical framework that allows DMs and stakeholders to adjudicate each system alternative as an single-point design *in combination with* a set of future upgrades, defined as a "system-set." The framework will facilitate the comparison of all feasible system-set alternatives based on the expected cost of future capability versus associated utility.

The framework is developed in two steps. First, for *Research Objective 1 (RO1),* an analytic framework is established to evaluate existing systems and capability need technology to identify system-set alternatives that meet critical requirements. This framework addresses the amount of RC necessary for a resilient system with cost-effective capability growth to accommodate associated upgrades loosely scheduled against an inexact timetable. Next, for *Research Objective 2 (RO2),* the RO1 framework is expanded for new system development to engineer resilient systems that will facilitate flexible, agile, and cost-effective capability growth in response to uncertain future needs. The production design is evaluated in combination with its affordable set of future upgrade options within the SBD paradigm, keeping the potential for future options open by focusing on RC and balancing average unit production cost against change and upgrade costs.

CHAPTER 2: REVIEW OF THE LITERATURE

The Literature Review identifies the current knowledge state of the following four categories: Set-Based Design, system resiliency, changeability, and adversarial risk.

2.1. Set-Based Design

The basic premise of SBD is that it can be advantageous for DMs to delay commitment to a particular design or sub-system option in favor of gathering knowledge about the problem (Singer *et al*. 2009). A key limitation of current SBD approaches is that they lack a general means for incorporating preference information, particularly to evaluate multi-attribute trade-offs. A more general approach is needed to allow DMs to express their preferences for trade-offs across multiple attributes. Additionally, current SBD uses are primarily qualitative in nature; consequently, more research is needed to create a functioning quantitative SBD trade-space framework and facilitating toolset (Malak *et al*. 2008).

Capability exists with current system design optimization models, but actual set-based resiliency is lacking since analytical mathematical tools, even if combinatorial based, provide only "point" solutions. The constricted point solutions eventually create design issues and unplanned changes as the design uncertainty diminishes over time (Rapp 2017). The U.S. Government Accounting Office (GAO) has recognized the need for a greater diversity of design concepts earlier to lower risk and design problems later (Martin 2012). When coupled with high-speed accurate optimization, SBD holds great promise to identify a robust, less failure-prone design set to accomplish smarter and less costly changes to a system throughout its service life (Rapp 2017).

2.2. System Resiliency

Holland (2012) characterized a resilient system as follows: 1) it is robust and reliable, i.e., it has predictable and reliable performance over a wide range of conditions, and can perform a wide range of missions and functions, 2) it can be adapted and/or extended to achieve higher levels of performance, perform new functions, and/or operate in a wider range of conditions, and 3) upon suffering damage, it has predictable and incremental loss of performance and function.

Goerger *et al*. (2014) assert that "resilient DoD (Department of Defense) systems need to be able to leverage new technologies and techniques as they appear, meet changing requirements, conform to new environments, and successfully meet the challenges of an adaptive foe. But, these systems also need to be manufacturable, deployable, sustainable, modifiable, and cost effective to be viable for inclusion in the force structure. Thus, the DoD *must design its weapons systems to be resilient at the outset*." They identify the four properties of a resilient DoD system as: Repel/Resist/Absorb, Recover, Adapt, and Broad Utility; and recognize the Boeing B-52 aircraft, M113 armored personnel carrier, M2 Bradley Fighting Vehicle, and High-Mobility Multipurpose Wheeled Vehicle (HMMWV) as examples of systems meeting the DoD definition of resiliency. Spero *et al*. (2014) examine Engineering Resilient Systems (ERS), the DoD effort to design and build resiliency into its systems, to evaluate the current state of trade-space exploration (TSE) processes and tools currently utilized in support of ERS. They identify the goals of ERS as to provide to engineering, warfighting, and acquisition DMs the needed capability to manage TSE activities with full and consistent information throughout the life of the systems by: i) producing more complete and robust requirements early in the engineering design process, ii) making the engineering design process much more efficient and effective, iii) considering the manufacturability of a proposed design explicitly, and iv) establishing baseline resiliency of current capabilities. One of their recommendations for future work is the development of value measures for attributes and functions to enable a more formal value-focused thinking approach for TSE.

Resilience is also defined as a system's ability to anticipate, perceive, and respond to surprise and failure (Hollnagel *et al*. 2006), its capability to survive large perturbations (Fiksel 2003), and further defined as a combination of changeability and dependability (Boehm 2016).

2.3. CHANGEABILITY

The need for changeability, specifically growth margins, was recognized for computer hardware and processing performance as early as 1975. In practice, unless provisions for adaptation to change are designed into a system, the consequences are often serious (Kossiakoff 1975). Changeability is described as having four key aspects: flexibility and agility (easy and rapid change), adaptability (a system's ability to adapt itself to change within its environment), and robustness (a system's insensitivity to change within its environment) (Fricke and Schulz 2005). These definitions align with the ontological framework for flexibility-related terminology developed by Ryan *et al*. (2012). Furthermore, scalability—defined as the ability to change the level of a parameter—is identified as an extending principle for flexibility and agility. The need for quantifying and measuring changeability, and by extension flexibility, agility, adaptability and robustness, is emphasized (Ross *et al*. 2008, Olewnik *et al*. 2004); however, Olewnik *et al*. (2004) claim that while there are several metrics for robustness, none exist for adaptability or flexibility in general.

RC is recognized as a significant enabler for changeability (Chalupnik *et al*. 2013). For the research framework, it is defined as designed-in spare capacity to accommodate additional volume, weight, power, cooling, and computing. These items are usually traded between each other and between subsystems (Bahill and Botta 2008). Literature on RC and design margin in military systems is particularly narrow. RC is examined mainly in applications for health and medicine, road and transportation networks, and energy systems.[2] Similarly, existing literature on design margin focuses on electronics and computer/information technology.[3]

2.4. Adversarial Risk

Meeting or overcoming the evolving threat, or adversary, is a driving need for planned and systematic insertion of new technologies and capabilities (Kerr *et al.* 2008). Daase and Kessler (2007) identify four kinds of danger that stem from the known/unknown matrix based on the methodological and empirical knowledge. Threat is known-knowns; risk is known-unknowns; ignorance is unknown-knowns; and disaster is unknown-unknowns. Furthermore, two definitions of probability are presented—relative frequency and degree of belief - based on definitive notions of non-knowledge and uncertainty. Paté-Cornell (1996) differentiates between epistemic (knowledge) uncertainty and aleatory or stochastic uncertainty (randomness) and describes probabilistic, i.e., probabilistic risk analysis (PRA), and deterministic methods for addressing risk and uncertainty. While PRA has been practiced for more than 30 years, its application aimed at terrorism risk is less mature (Ezell *et al*. 2010). Adversarial risk analysis (ARA) deals with the risk analysis of situations in which risks stem from the deliberate actions of intelligent adversaries (Rios and Insua 2012). The more common tools used in ARA include logic trees, which are further

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[2] Of the first 50 returns for a Google Scholar search on "reserve capacity," 40 addressed health/medical applications, four addressed road and transportation network applications, and three addressed energy applications. None of the returns addressed military systems or ground vehicles.

[3] Of the first 50 returns for a Google Scholar search on "design margin," 29 returns addressed electronics and computer science/information technology applications, six addressed nuclear science applications, and three each for chemistry/chemical engineering and optical science applications. None of the returns addressed military systems or ground vehicles.

divided into fault, attack and success trees, and probability, event and decision trees; influence diagrams; Bayesian network analysis; and game theoretical modeling (Ezell *et al*. 2010; Insua *et al*. 2009; Merrick and Parnell 2011). Merrick and Parnell (2011) compared these methods in two example decisions and expanded the application of decision and event trees to examine a given scenario from both the defender's and attacker's perspective. More recently, it's been recognized that the intelligent and *adaptive* nature of today's adversary sometimes requires a more dynamic approach. This requirement has resulted in an extension of statistical risk analysis and game theory to conduct intelligent ARA (Merrick and Parnell 2011), and has been an argument against the use of expert-elicited probabilities for ARA since these probabilities are not static (Ezell *et al*. 2010).

A significant gap in the realm of ARA knowledge is the shortage of examples addressing tactical scenarios. The preponderance of articles focus on the strategic or infrastructure level, such as weapons of mass destruction, e.g., bioterrorism targeting mass transit systems or high-population events, and the power grid, including dams, nuclear reactors, and non-nuclear power stations.

2.5. LITERATURE REVIEW SYNOPSIS

The Literature Review identified a need for enhancing SBD to i) allow for an expanded trade-space, ii) enable preference or value-based assessment, and iii) extend decision flexibility to align with the length of the system's service life. Also identified was the need for an improved capability for engineering system resiliency through designing for changeability, by means of flexibility and agility, and in turn, reserve capacity. This need includes the ability to measure levels of these attributes from a value-based perspective. In response to these needs just identified, this research addresses creation of a framework to enable resilient system design that will extend decision flexibility for complex long-lived systems.

Also identified was the need for a more tactical focus per ARA to better identify future capability need for tactical systems. Note that it is not within the scope of this research to actually estimate adversarial risk, but rather to understand its association with capability need.

CHAPTER 3: METHODOLOGY

3.1. THEORETICAL FRAMEWORK

Consider a system consisting of a finite number of capability need subsystems. A base system (vehicle platform) set is designated $V = \{V_1, V_2, ..., V_m\}$, and a technology capability subsystem set $T = \{T_1, T_2, ..., T_n\}$. Furthermore, portfolios of technology capabilities are designated as P, where each portfolio consists of a subset of T, including Ø (null). With 2^n elements, P constitutes all partial states of having every capability. Each V_i launches with an element from P, a technology capability *base* set, labeled $V_i = P_{Bi}$. Likewise for each V_i there is a P, labeled $V_i(\mathrm{P})$, that consists of all T that the vehicle platform can support, based on its RC. Thus, for each V_i the associated P decomposes into P_B and P_O, i.e., base and option elements. The methodology model consists of start states, intermediate states, end states, allowable moves (called *actions* from here on out), and cost and utility functions. A *system-set* is a sequence of actions, or path, through the available states. The objective is to select a system-set that is superior with respect to some system-level metric, such as "lowest cost."

Without loss of generality, the rest of this manuscript focuses on *vehicle* systems, though the methodology holds merit for designing other types of systems as well. The method begins with a vehicle from V, and for each action, either a P is added, subject to the constraints of the current vehicle, or there is a change of vehicle. Assuming that ultimately every capability will be implemented (P_∞), the expectation is to finish with at least one vehicle platform for which $P_\infty \in V_i(P)$. Another way to think about it is that each action results in reaching a state from the space S that is the *tuple* of P and V, so $S = P \times V$. Each element of S consists of a vehicle platform V_i and portfolio P_k. An example is to have $\{V_3, P_{1,3,4}\}$ as an element in S, where $P_{1,3,4} = \{T_1, T_3, T_4\}$; $P_Ø$

indicates that the vehicle platform has not received any capability option. Next, the cost function is the total cost of a system-set, defined as the initial vehicle platform cost plus the cost associated with each subsequent action. To realistically estimate action costs, points in time (*epochs*, *E*) are identified to designate when those actions are projected to occur. Lastly, the utility function reflects the total utility of a system-set, which is the sum of the utilities associated with each element in its respective S. Cost and utility details are addressed later in this section.

Figure 4 depicts a notional methodology model for $m = n = 2$, where $\mathrm{V} = \{V_1, V_2\}$, $\mathrm{T} = \{T_1, T_2\}$, and $P_\infty = \{\varnothing, T_1, T_2, T_1T_2\}$. For each state (oval), the symbols listed from top to bottom represent the vehicle platform V_i, base technology capabilities P_{Bi}, and technology capability options P_{Oi}, (epochs not designated). For example, the initial state for vehicle platform V_2 indicates that it starts with capability T_1. The arcs connecting the states distinguish an initial set of actions, where $\mathrm{S} = \{V_1, V_1T_1, V_1T_2, V_1T_1T_2, V_2T_1, V_2T_1T_2\}$. Two decision rules are declared: i) V_1 can be changed to V_2, however, changing from V_2 to V_1 is not feasible; and ii) capabilities can only be added. These rules prohibit the red dashed arcs. Furthermore, the order of capability upgrades is restricted to T_1, T_2, resulting in the black lines being the only action choices. For this example, three system-sets for which $P_\infty \in V_i(P)$ are identified (indicated by the bold black lines in Figure 4). Calculations of cost and utility are then necessary to help select the preferred system-set.

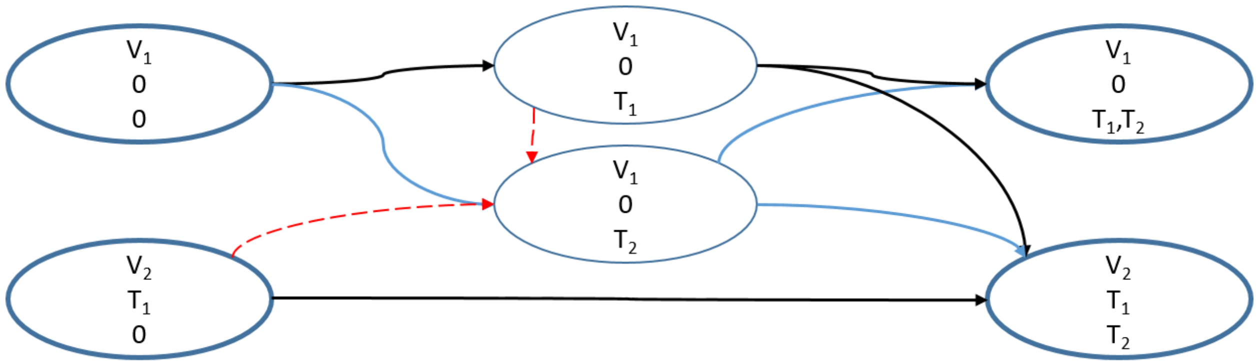

FIGURE 4. SAMPLE ILLUSTRATION OF METHODOLOGY FOR THE CASE OF *m* = *n* = *2*

This research compares the respective costs of system-set alternatives that meet or exceed an identical set of requirements, but are set apart by different levels of RC. Procurement cost is defined as the cost to procure a vehicle platform, or a subsystem associated with a capability upgrade; change cost is defined as the cost required to increase the infrastructure (e.g. volume, power) of the system to the level necessary to receive an associated capability upgrade; and upgrade cost is defined as the cost associated with installing a capability upgrade. Costs reflect the value at the time they are expected to be incurred.

The relationship between costs, achieved capability, and RC is stated in the following formula:

$$C_{TY} = Cost\ to\ achieve\ Capability\ (T), given\ RC\ (Y) \tag{1}$$

where $T = \{1, 2, ..., n\}$ and refers to technology capability upgrades, and $Y = \{A, B\}$ and refers to initial RC. Figure 5 illustrates equation (1) for a notional case where $n = 3$, and emphasizes the difference between change costs and upgrade costs. Since system RC-A has limited RC, it requires an increase to its infrastructure (power, suspension) in order to receive a capability upgrade, and hence, change costs without any capability increase; system RC-B does not require change costs since it has sufficient RC to receive the upgrades. It is conceivable that system RC-A may have adequate RC for the initial upgrade, resulting in change costs later at $n=2$. For this illustration, it is assumed that the upgrade cost for a given capability upgrade is the same for both systems. Once the costs are established, the DM can determine which system-set is preferable.

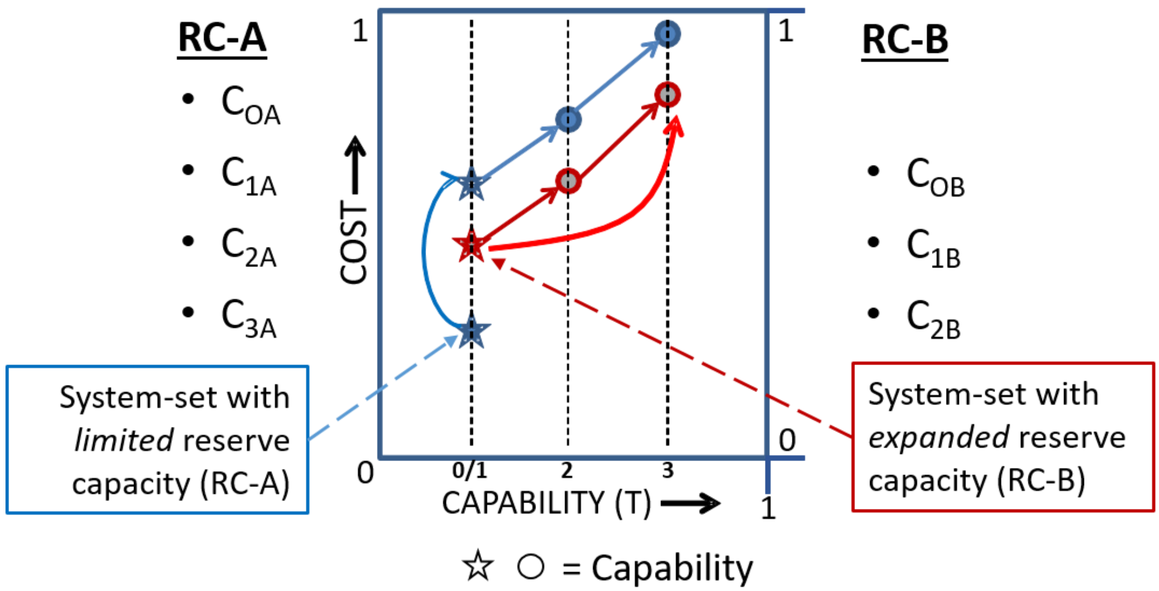

FIGURE 5. COSTS VS CAPABILITY FOR DIFFERENT LEVELS OF RESERVE CAPACITY

Though the decision-driven change schedule specifies epochs for capability upgrades E_n, E_{n+1}, they are for analysis and planning purposes and are not permanently set. The framework will allow new or updated information, such as performance and burden data of capability options, to be inserted into the models at any time to determine if changes to the change schedule are warranted.

Utilizing initial costs, change schedule, and escalation factor, expected costs of the vehicle platforms and capability upgrades are calculated at the 5th through 95th percentiles, as well as the minimum, maximum and mean. For RO1 problems, our framework employs a decision tree[4] to identify an optimal solution-set by using 95th percentile[5] expected costs, along with 0-100 percentages representing the effectiveness of each capability upgrade and dollar values representing consequence if the capability upgrade is not effective. Sensitivity analyses can also be conducted on the effectiveness and consequence variables to determine if variable uncertainty may alter the optimal solution-set. This is identified in Figure 6 (Rhodes and Ross 2014) as "Performance vs Burdens Analysis," essentially filtering out the less desirable system-sets based on cost-effective performance.

For RO2 problems, the framework generates system-set alternatives using a combinatorial system trade-off[6] model (CSTM) to assess multiple subsystems. CSTM is a multi-criteria integer linear programming tool used to optimize the configuration of a whole system by selecting among multiple subsystem options. This tool has validated capability of evaluating an expansive trade-space far exceeding billions of potential system alternatives and producing a Pareto-set in a matter of minutes, so in no way will this research test its limits. Each subsystem has an associated relative importance weight (RIW), performance score, cost and physical weight (burden). CSTM evaluates system configuration alternatives based on a set of competing measures: *maximizing performance* criteria and *minimizing burden* criteria. The output is a Pareto set of feasible and non-dominated system alternatives; a two-dimensional example is provided in Figure 6, and Figure 7

[4] See Ezell *et al.* (2010) for an explanation and examples of a decision tree.

[5] Although the mean or any percentile can be used, 95th was chosen to better ensure that worst-case cost estimates are included so as to minimize surprises for the customer.

[6] See Ahuja *et al*. (2007), and Collette and Siarry (2013) for combinatorial trade information and examples.

displays the same example in a three-dimensional view. In Figure 6, “ovals” mark the “knee-bends” where high-potential solutions can be found; for this example, solutions to the right of the ovals show comparable *performance*, but with increased *cost*. CSTM is identified in Figure 8 as the “Performance vs Burdens Model.”

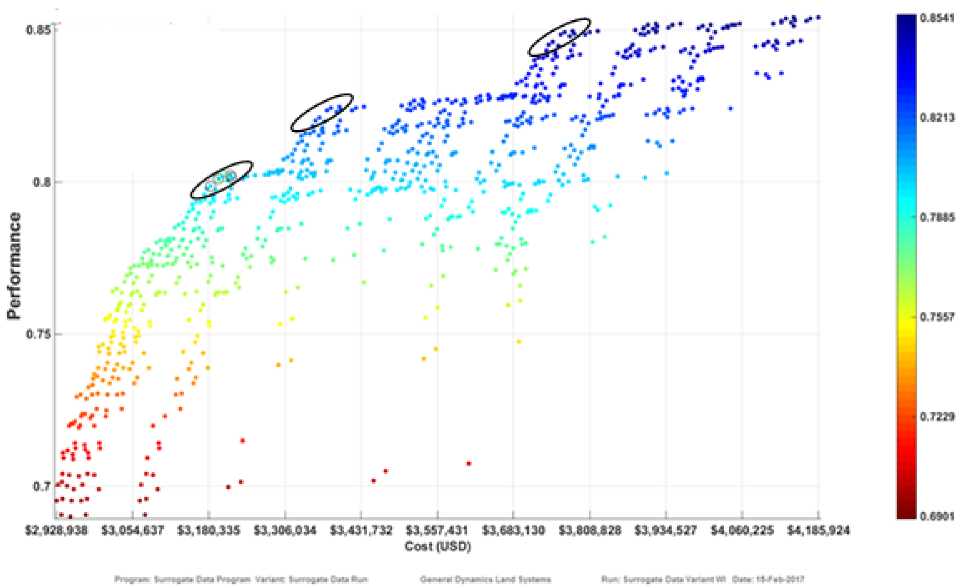

FIGURE 6. 2-D EXAMPLE OF PARETO SOLUTION SET PRODUCED BY THE CSTM

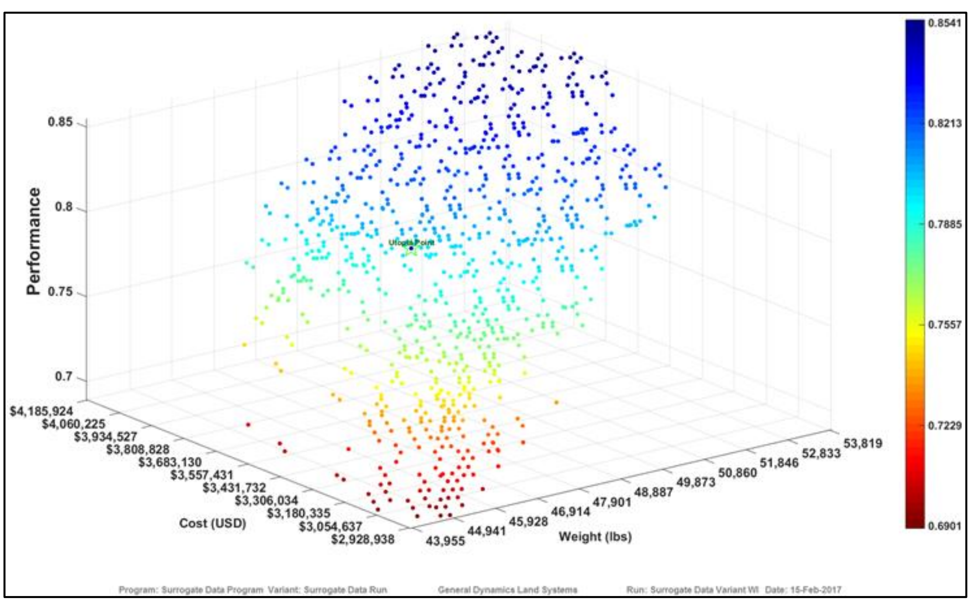

FIGURE 7. 3-D EXAMPLE OF PARETO SOLUTION SET PRODUCED BY THE CSTM

After taking into consideration all completed analyses, an appropriate number of system-set alternatives are selected for system-level analysis. A multi-attribute utility (MAU)[7] trade-off model, Logical Decisions® for Windows (LDW®), is used to identify the alternatives with the most utility from the decision-maker's perspective. LDW® is a decision support software for evaluating choices by way of quantifying preferences. This is identified in Figure 8 as the "MAU model." Each evaluation criterion has a RIW, and each alternative is assessed against every criterion (labeled a "measure" in LDW®), resulting in a total utility for each system-set alternative. Sensitivity analysis is performed on RIW to determine if any change to a criterion's importance weighting results in a change to the overall alternative ranking. Additionally, the MAU model allows direct comparison between any two alternatives to identify strengths and weakness; sometimes this capability can be used to generate hybrid alternatives based on existing strengths.

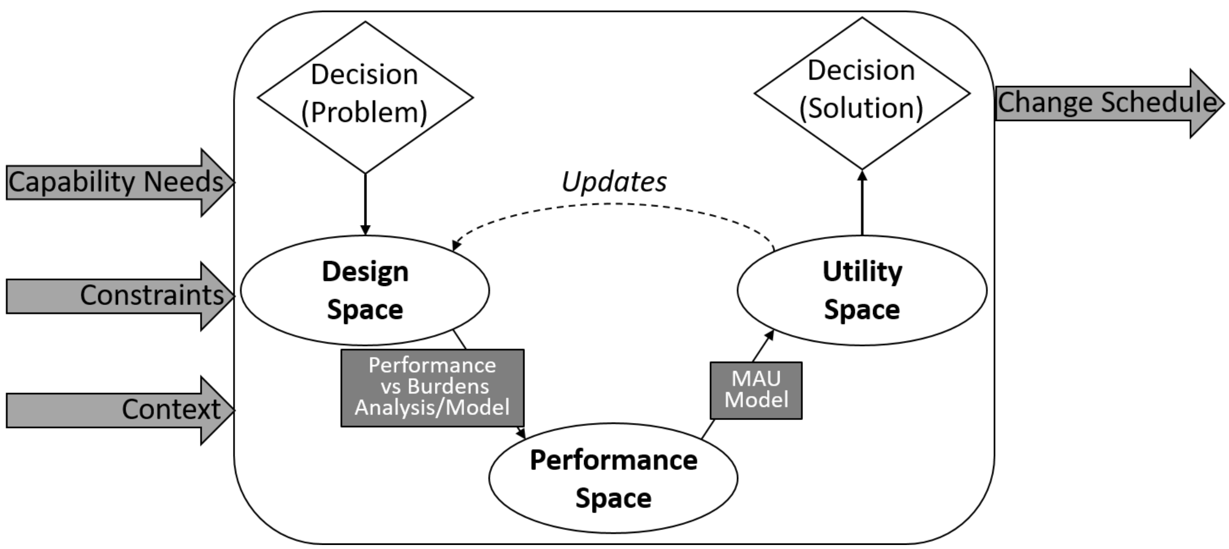

FIGURE 8. FRAMEWORK DECISION LOOP

[7] See Forman & Gass (2009) for an explanation of multi-attribute utility theory.

3.2. RESEARCH QUESTIONS

The principal question that this research set out to address is "How can set-based design be enhanced and applied to the engineering of resilient systems?" This question has two main elements: in what ways can SBD be improved, and how can each way be applied to the engineering of resilient systems? There are three avenues for improving SBD that this research will address: enhancement, expansion, and extension.

One avenue to address is how establishing a practical quantitative trade-space framework can *enhance* SBD. This includes quantification that will enable DMs to express preferences across multiple attributes. Will a preference or value-based approach produce different results compared to an approach based strictly on performance versus cost?

A second avenue is how *expansion* of the trade-space can improve SBD. Will a greater number of potential capability options provide more or better opportunities for engineering resilient systems? Also, can *expansion* be supported with a practical quantitative trade-space framework?

Lastly, can SBD be improved by *extending* its capability, to defer decisions beyond the design process until after a system is fielded, to explicitly carry a set of possible solutions past the point of the initial fielding of the system? Furthermore, what is a realistic expectation for how long system resiliency can effectively enable easy and rapid capability upgrades in response to requirement changes? 30 years? 50 years? Also, can *extension* be supported with a practical quantitative trade-space framework?

3.3. *Research Approach*

In this research the case system is defined as a ground combat vehicle platform with three capabilities/subsystems: protection, lethality, and mobility; mobility is a support capability necessary for propelling the vehicle platform with increased protection and lethality. Fielded capabilities influence the probability distribution of the adversary situations expected to be encountered. Adversary response is expected to exploit limitations and avoid strengths. In Figure 9, the perimeter notionally defines the capability limits of the vehicle platform for a given mission with respect to lethality and protection; if additional capability is required for a given mission, then a more capable system—one with increased lethality and/or protection—would be employed instead. Mobility could be considered in a third dimension to understand the relationship amongst the three parameters, e.g. increased weight from upgraded lethality or protection will degrade mobility. The performance envelope, representing current capabilities, displays two potential extremes of strength versus limitation, and how the adversary is expected to respond to each one. The adversarial risk value (ARV), a product of associated ARA, is a function of the performance envelope relative to the capability limits. In an abstract sense, ARV represents the portion of the capability limits not met with the current capabilities; capability need is the additional capability necessary to diminish ARV. As previously noted in Literature Review, it is not within the scope of this research to actually estimate ARV, but rather to merely understand its association with capability need.

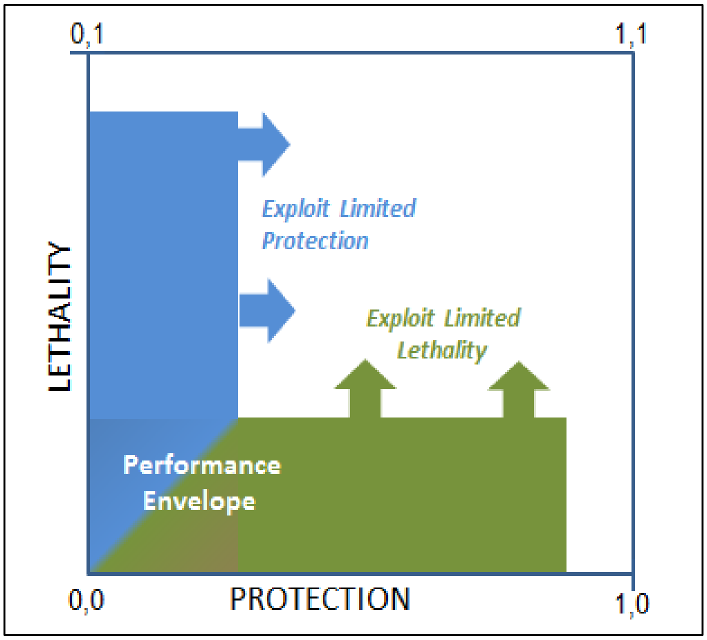

FIGURE 9. SYSTEM PERFORMANCE ENVELOPE VS EXPECTED ADVERSARY RESPONSE

For both the RO1 and RO2 design versions of the framework, two levels of armor protection {7.62mm (T_1) and 12.7mm (T_3)} and one level of lethality {7.62mm (T_2)} are identified as the capability needs. Mobility options, based on levels of horsepower (HP) suitable for supporting each vehicle platform and all T that it can support (V_i(P)), have been identified. Furthermore, times between E_n and E_{n+1} are based on triangular distributions. Though other distribution types could be used to estimate when necessary capability upgrades are to occur, triangular distributions—early case, most likely case, late case—are used due to their familiarity with most customers. Table 1 displays the designated triangular distributions.

TABLE 1. TRIANGULAR DISTRIBUTIONS

Units in Years	$E_0 \rightarrow E_1$ AP 7.62mm (T_1)	$E_1 \rightarrow E_2$ Lethality 7.62mm (T_2)	$E_2 \rightarrow E_3$ AP 12.7mm (T_3)
Early Case	1.7	4.0	8.1
Most Likely	2.4	4.9	9.3
Late Case	2.9	5.5	10.1

Evaluation criteria assess cost and performance: performance criteria includes physical-data metrics for mobility and payload, while agility and flexibility are constructed metrics, defined respectively as follows:

Agility

- High = requires no more than 72 hours to perform all upgrades.
- Med-High = requires at least 72 hours, but no more than 96 hours, to perform all upgrades.
- Med = requires at least 96 hours, but no more than 144 hours, to perform all upgrades.
- Med-Low = requires at least 144 hours, but no more than 168 hours, to perform all upgrades.
- Low = requires more than 168 hours to perform all upgrades.

Flexibility

- High = requires no more than 2 people to perform all upgrades at unit location.
- Med-High = requires up to 3 people to perform all upgrades at unit location.
- Med = requires more than 3 people to perform all upgrades at unit location.
- Med-Low = requires up to 2 people to perform all upgrades at multiple locations.
- Low = requires more than 2 people to perform all upgrades at multiple locations.

For brevity, no lifecycle costs other than those defined in Section 3.1 are included. All evaluated technologies are assumed to have achieved a technology readiness level (TRL)[8] of at least seven (Katz *et al.* 2014), to eliminate technology development costs as well as the associated risk. In estimating cost parameters, data available from multiple open sources was used. While these cost parameters are expected to accurately reflect actual costs, for the purpose of the study their validity was verified with subject matter experts. Furthermore, the scoring for alternatives and options with respect to decision criteria are estimates and, though considered realistic, should be regarded to serve the demonstrative purpose of the developed framework.

3.4. Analysis Vehicle

The High-Mobility Multi-purpose Wheeled Vehicle (HMMWV), commonly referred to as the Humvee, was originally designed and built by AM General in 1985 as a personnel and light cargo transport, replacing multiple vehicles such as the M151 Military Utility Tactical Truck (MUTT), M561 Gama Goat, and M274 Mechanical Mule (Green 2005). The baseline HMMWV (M998A0) had no armor protection and no lethality other than personal weapons carried by its passengers. During the next 10 years, the HMMWV was pressed into service in multiple new missions, with emphasis on urban combat roles, for which it was not originally intended. As weapons and an armored cupola were added, it raised the center of gravity and increased the propensity to roll-over, a very serious problem and cause of loss of life. There was no performance envelope for changes in the center of gravity (CG), no requirement for how much the CG could

[8] Technology Readiness Levels is a nine-level ordinal scale for measuring the technology maturity of system and subsystems (Katz *et al.* 2014).

shift without causing roll-over in the reference conditions. Similarly, when protection was necessarily increased, mobility was critically degraded because the mobility package (powertrain, suspension and steering) did not have adequate RC to handle the increased weight and angular inertia of additional armor (Boehm 2016). Although the greatly improved M998A2, fielded in 1995, had an additional 10 horsepower (160 vs 150, via turbocharger) and 1,950 pounds payload over the baseline model, its durability and reliability suffered significantly. That same year, AM General also began producing the M1113 expanded capacity variant; it offered 190hp and additional payload of 650 pounds compared to the M998A2, allowing the required lethality and armor protection while maintaining adequate mobility (Green 2005).

The HMMWV has been criticized in recent years for its inability to repel all adversary attacks. However, for its basic purpose as a four-wheel drive, cargo carrier, it has been quite versatile at performing its original mission in nearly every operational environment and weather condition encountered by U.S. forces since 1985 (Goerger *et al*. 2014).

CHAPTER 4: RESEARCH OBJECTIVE 1

For the first of two objectives, an analytic framework is established to evaluate *existing* systems and capability need technology to identify system-set alternatives that meet critical requirements. The framework addresses the amount of RC necessary for a resilient system with cost-effective capability growth to accommodate associated upgrades loosely scheduled against an inexact timetable.

4.1. RO1 SETUP

Three existing vehicle platforms, designated $\mathrm{V} = \{V_1, V_2, V_3\}$, are identified as the options. V_3 has integral 7.62mm AP and weapon capabilities, so $\{V_3, P_{1,2}\}$; therefore, there are no associated E_1, E_2 upgrade costs. Also, three decision rules are declared: i) the order of vehicle platform upgrades must be V_1, V_2, V_3; ii) capability options can only be added; and iii) the order of capability upgrades must be T_1, T_2, T_3. Figure 10 displays the RO1 model, where $m = n = 2$, $P_\infty = \{\varnothing, T_1, T_1T_2, T_1T_2T_3\}$, and $\mathrm{S} = \{V_1, V_1T_1, V_1T_1T_2, V_2, V_2T_1, V_2T_1T_2, V_2T_1T_2T_3, V_3T_1T_2, V_3T_1T_2T_3\}$. There are 14 solution-sets that achieve all requirements; $\{V_1, P_{1,2,3}\}$ is infeasible as V_1 lacks sufficient RC to receive T_3, and $\{V_3, P_{1,2}\}$ does not change until E_3, thus the dashed arcs between E_0 and E_2. Table 2 lists the data defining the necessary characteristics of the vehicle platforms and required capabilities.

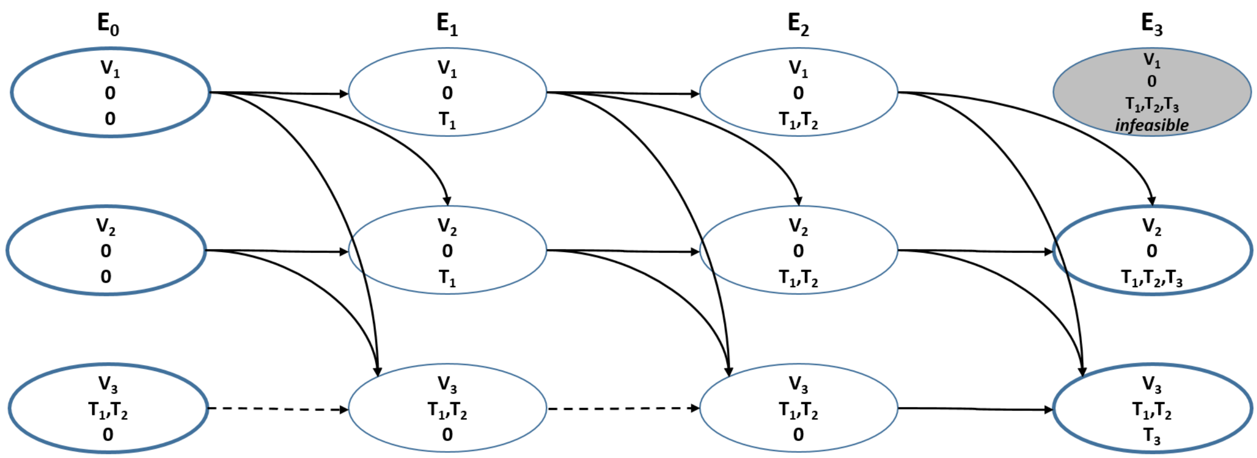

FIGURE 10. RO1 SOLUTION-SETS THAT ACHIEVE ALL REQUIREMENTS

TABLE 2. RO1 VEHICLE PLATFORMS / CAPABILITIES CHARACTERIZATION DATA

Vehicles	Initial Cost	Weight (lbs)	Payload (lbs)	HP
$V_1, P_{\varnothing}$	(\$48,000)	5,900	4,450	160
$V_2, P_{\varnothing}$	(\$102,000)	6,400	5,100	190
V_2, P_1	(\$121,300)	8,500	3,000	190
$V_2, P_{1,2}$	(\$156,400)	8,935	2,565	190
$V_2, P_{1,2,3}$	(\$194,300)	10,835	665	190
$V_3, P_{1,2}$	(\$433,500)	16,000	4,000	325
$V_3, P_{1,2,3}$	(\$476,100)	18,700	1,300	325
Capability Options	**Initial Cost**	**Weight (lbs)**		
$T_1\ (V_1)$	(\$17,800)	2,000		
$T_1\ (V_2)$	(\$19,300)	2,100		
$T_2\ (V_1)$	(\$33,400)	400		
$T_2\ (V_2)$	(\$35,100)	435		
$T_3\ (V_2)$	(\$37,900)	1,900		
$T_3\ (V_3)$	(\$42,600)	2,700		

4.2. RO1 Results

Based on initial (E_0) costs alone (from Table 2, with no escalation factor), the total costs of all 14 system-sets are displayed in ranked order (least to most) in Table 3 (Total Cost equals sum of $E_0 \rightarrow E_3$ costs per system-set). This represents the hypothetical case where all vehicle platform / capability upgrades are procured at E_0.

Table 3. Ranking of RO1 System-Sets Based on E0 Total Cost

	U = Upgrade; R = Replacement; X = No Change											TOTAL COST
System-Set #	E_0	Cost	E_1	To	Cost	E_2	To	Cost	E_3	To	Cost	
10	V_2	$102,000	U	T_1	$19,300	U	T_2	$35,100	U	T_3	$37,900	$194,300
6	V_1	$48,000	R	V_2	$121,300	U	T_2	$35,100	U	T_3	$37,900	$242,300
3	V_1	$48,000	U	T_1	$17,800	R	V_2	$156,400	U	T_3	$37,900	$260,100
1	V_1	$48,000	U	T_1	$17,800	U	T_2	$33,400	R	V_2	$194,300	$293,500
14	V_3	$433,500	X	V_3	$0	X	V_3	$0	U	T_3	$42,600	$476,100
9	V_1	$48,000	R	V_3	$433,500	X	V_3	$0	U	T_3	$42,600	$524,100
5	V_1	$48,000	U	T_1	$17,800	R	V_3	$433,500	U	T_3	$42,600	$541,900
2	V_1	$48,000	U	T_1	$17,800	U	T_2	$33,400	R	V_3	$476,100	$575,300
13	V_2	$102,000	R	V_3	$433,500	X	V_3	$0	U	T_3	$42,600	$578,100
12	V_2	$102,000	U	T_1	$19,300	R	V_3	$433,500	U	T_3	$42,600	$597,400
11	V_2	$102,000	U	T_1	$19,300	U	T_2	$35,100	R	V_3	$476,100	$632,500
8	V_1	$48,000	R	V_2	$121,300	R	V_3	$433,500	U	T_3	$42,600	$645,400
7	V_1	$48,000	R	V_2	$121,300	U	T_2	$35,100	R	V_3	$476,100	$680,500
4	V_1	$48,000	U	T_1	$17,800	R	V_2	$156,400	R	V_3	$476,100	$698,300

Using the "most likely" values from Table 1 (2.4, 4.9 and 9.3 years) for E_1, E_2, E_3, and an escalation factor to reflect the time-value of costs, the system-set total costs were recalculated. At 0% escalation, the revised system-set ranking matched the Table 3 ranking. Sensitivity analysis was conducted on the escalation factor, ranging from 0% to 20%, to determine if any increase would impact the ranking. Figure 11 illustrates the escalation factor sensitivity of all 14 system-sets for the "most likely" epoch scenario. No changes to the top six ranked (lowest cost) system-sets were observed until the escalation factor reached 8.2% for the "most likely" epoch scenario, where system-sets #1 and #14 exchanges positions. For the remaining system-sets, several rank changes occur prior to the escalation factor reaching 5%.

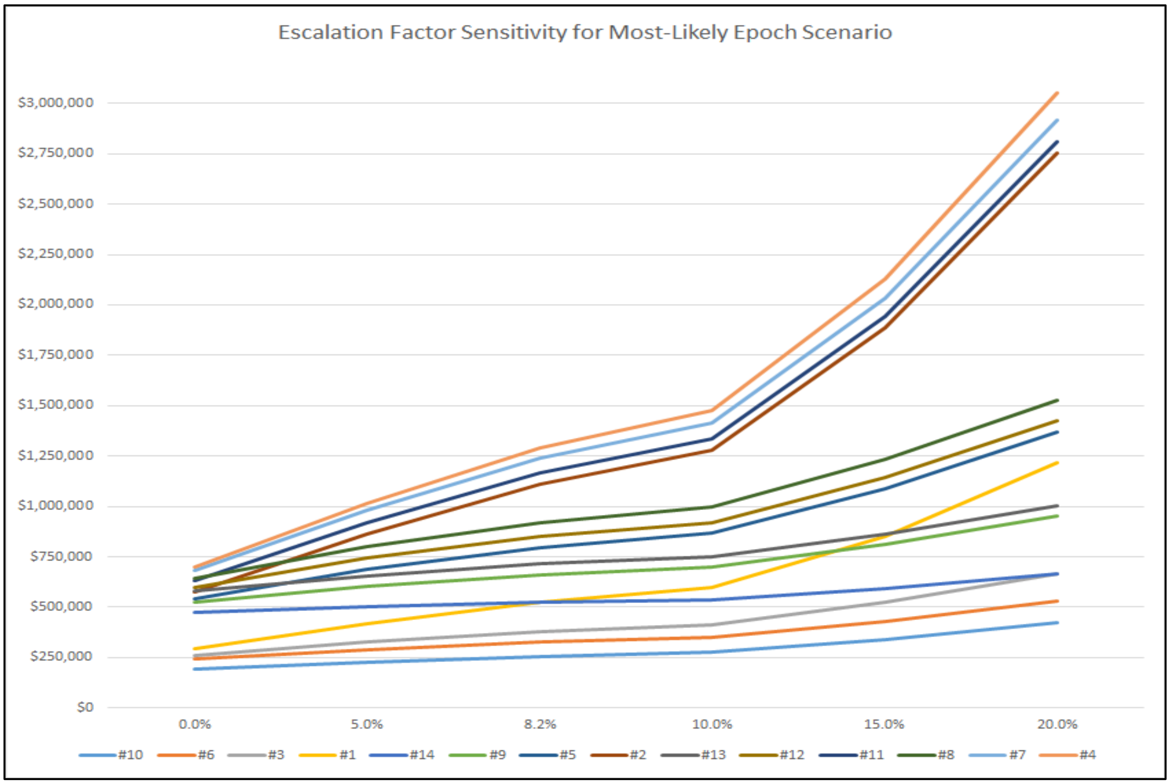

FIGURE 11. RO1 ESCALATION FACTOR SENSITIVITY FOR MOST LIKELY EPOCH SCENARIO

Quick examination of Figure 11 reveals that system-sets #2, #4, #7 and #11 have the steepest incline in total cost. Table 3 reveals that each of those system-sets call for the most costly action, replacing V_1 or V_2 with V_3, at E_3, the most costly time. System-set #1 exhibits the second-most steepest incline in total cost, with its most costly action, replacing V_1 with V_2, also at E_3, the most costly time. In contrast, #14 requires its most costly action, the initial procurement of V_3, at E_0 when the escalation factor has no impact, therefore explaining its relatively flat cost slope. Figure 12 provides a closer look, along with cost values for the eight lowest-cost system sets, at the same sensitivity graph to better examine the crossover points.

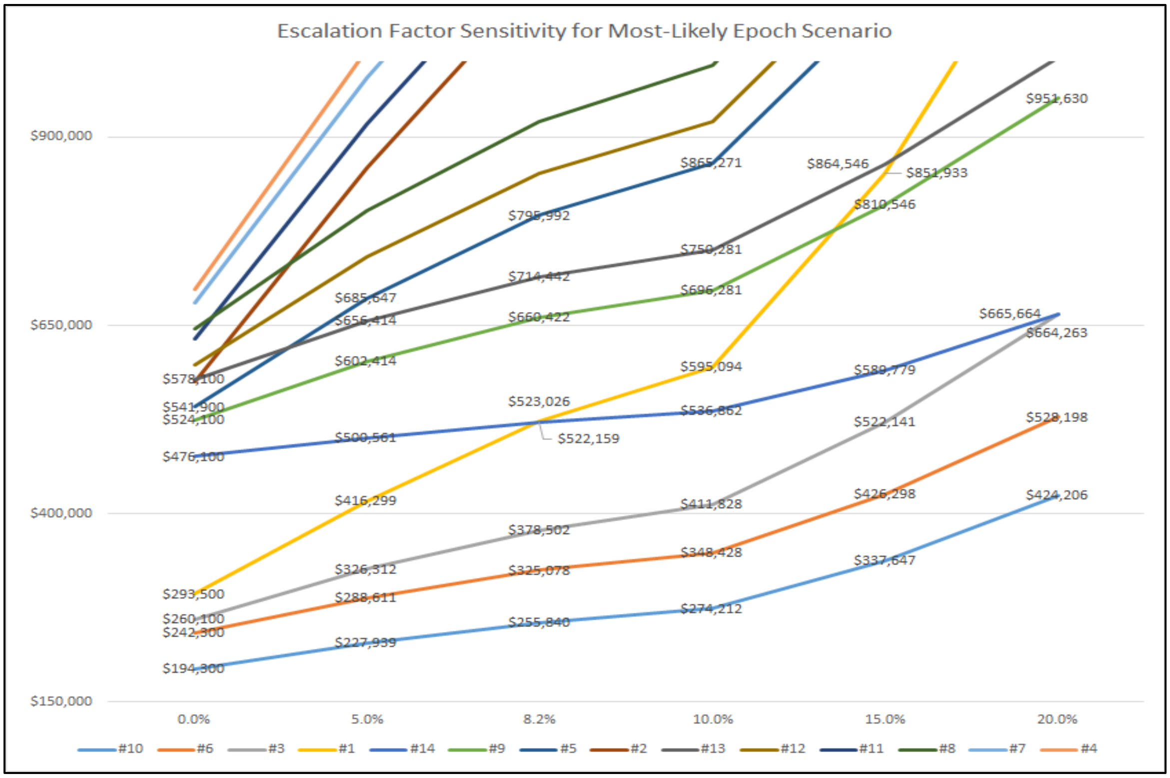

FIGURE 12. RO1 ESCALATION SENSITIVITY FOR MOST LIKELY EPOCH SCENARIO (CLOSE-IN)

Escalation sensitivity was also performed using the "early" case and "late" case epoch scenario values (triangular distributions) from Table 1. No changes to the top six ranked system-sets were observed until the escalation factor reached 9.6% for the "early" case, and 7.5% for the "late" case. As with the "most likely" case, the 4th and 5th-ranked system-sets (#1 and #14, respectively) exchanged positions.

At this point, Monte-Carlo simulation was used to generate expected cost distributions based on initial (E_0) costs, the "most likely" epoch scenario for capability upgrades, and an escalation factor (*nominal*) triangular distribution of 0% (best case), 8% (most likely), and 20% (worst case). Table 4 displays the system-set ranking based on associated 95% total expected cost. The correlation coefficient (Spearman's rho) between this ranking and the Table 3 ranking is 0.921, indicating strong positive correlation.

TABLE 4. SYSTEM-SET RANKING BASED ON FIRST CALCULATION OF 95% ETC

Name	95% ETC	Rank	Category
System-Set #10	\$361,035.90	1	$V_2 \rightarrow V_2$
System-Set #6	\$454,224.00	2	$V_1 \rightarrow V_2$
System-Set #3	\$561,344.60	3	$V_1 \rightarrow V_2$
System-Set #14	\$609,937.30	4	$V_3 \rightarrow V_3$
System-Set #9	\$849,986.60	5	$V_1 \rightarrow V_3$
System-Set #13	\$903,986.60	6	$V_2 \rightarrow V_3$
System-Set #1	\$949,042.10	7	$V_1 \rightarrow V_2$
System-Set #5	\$1,166,703.00	8	$V_1 \rightarrow V_3$
System-Set #12	\$1,222,868.00	9	$V_2 \rightarrow V_3$
System-Set #8	\$1,316,056.00	10	$V_1 \rightarrow V_3$
System-Set #2	\$2,116,179.00	11	$V_1 \rightarrow V_3$
System-Set #11	\$2,175,938.00	12	$V_2 \rightarrow V_3$
System-Set #7	\$2,269,126.00	13	$V_1 \rightarrow V_3$
System-Set #4	\$2,376,247.00	14	$V_1 \rightarrow V_3$

Additionally, Monte-Carlo simulation was used to generate expected cost distributions based on initial (E_0) costs, *all triangular distributions* for capability upgrades (Table 1), and the same escalation factor triangular distribution used previously. Table 5 displays the system-set ranking based on associated 95% total expected cost, which is identical to the Table 4 ranking, or a correlation coefficient of 1.0.

TABLE 5. SYSTEM-SET RANKING BASED ON SECOND CALCULATION OF 95% ETC

Name	95% ETC	Rank	Category
System-Set #10	$358,436.90	1	$V_2 \rightarrow V_2$
System-Set #6	$446,396.60	2	$V_1 \rightarrow V_2$
System-Set #3	$552,398.20	3	$V_1 \rightarrow V_2$
System-Set #14	$609,859.60	4	$V_3 \rightarrow V_3$
System-Set #9	$842,066.50	5	$V_1 \rightarrow V_3$
System-Set #13	$896,066.50	6	$V_2 \rightarrow V_3$
System-Set #1	$947,633.90	7	$V_1 \rightarrow V_2$
System-Set #5	$1,148,588.00	8	$V_1 \rightarrow V_3$
System-Set #12	$1,204,784.00	9	$V_2 \rightarrow V_3$
System-Set #8	$1,298,499.00	10	$V_1 \rightarrow V_3$
System-Set #2	$2,114,257.00	11	$V_1 \rightarrow V_3$
System-Set #11	$2,173,920.00	12	$V_2 \rightarrow V_3$
System-Set #7	$2,260,142.00	13	$V_1 \rightarrow V_3$
System-Set #4	$2,371,440.00	14	$V_1 \rightarrow V_3$

Based on expected total cost, system-set #10 consistently is the top-ranked alternative. Decision tree analysis also identified system-set #10 as the optimal choice; sensitivity analyses resulted in no change. Based on the performed analyses, the lowest-cost system-set for each of five categories, beginning with V_1, V_2 or V_3 and finishing with V_2 or V_3, was chosen for system-level analysis; those five selected system-sets are #6, #9, #10, #13, and #14. Additionally, system-sets #1 and #3 were selected since they always ranked in the top seven overall. Although all 14 system-sets could move forward into system-level analysis, seven were selected to make it easier to focus on a smaller alternative set.

For the system-set analysis, Figure 13 displays the Goals Hierarchy from the MAU model, listing each criterion along with its respective RWI. The input data for the MAU model, along with the RIW for each criterion, are provided in Table 6. Cost data are entered as three-point distributions using respective 5%, 50% and 95% values derived from the earlier second Monte

Carlo simulation; the mean values are shown in Table 6. Agility and Flexibility are estimated from the constructed scale defined in paragraph 3.3. Mobility and Payload data are derived from Table 2 (Mobility = HP/(Weight/2000); Payload reflects a weight RC by measuring how much payload is available for additional cargo.

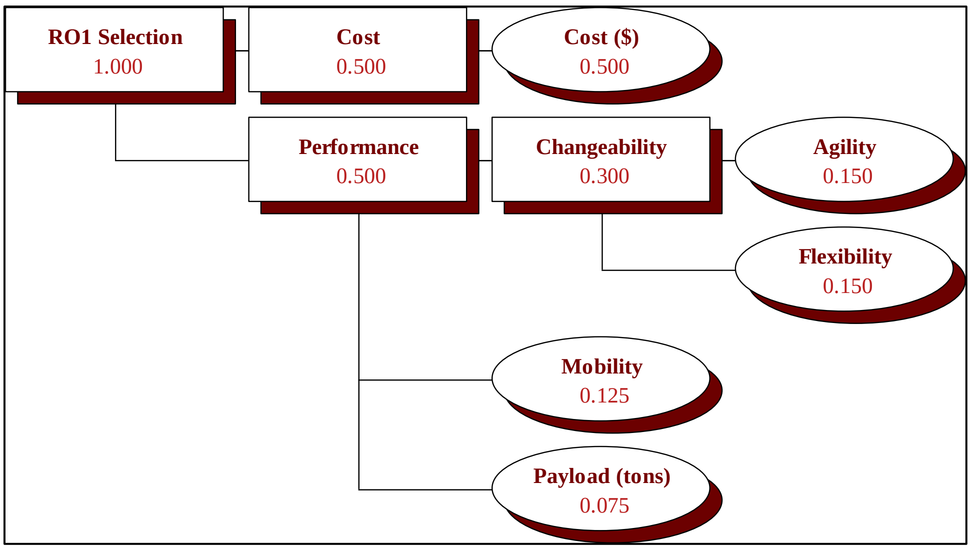

FIGURE 13. RO1 GOALS HIERARCHY FROM THE MAU MODEL

TABLE 6. INPUT DATA FOR RO1 SYSTEM-SET ANALYSIS

Criterion	Cost ($)	Agility	Flexibility	Mobility	Payload (tons)
RIW	0.5	0.15	0.15	0.125	0.075
Alternative					
System-Set #01	588460	Med-Low	Med-Low	35.1	0.33
System-Set #03	403281	Med-Low	Med-Low	35.1	0.33
System-Set #06	342188	Med-Low	Med-Low	35.1	0.33
System-Set #09	683420	Medium	Medium	34.8	0.65
System-Set #10	271211	Medium	Med-High	35.1	0.33
System-Set #13	737420	Medium	Medium	34.8	0.65
System-Set #14	535735	High	Med-High	34.8	0.65

Stacked-bar rankings of the system-sets, based on total utility, are displayed in Figure 13. Each colored segment of a stacked-bar represents the utility associated with the same-colored criterion for the respective alternative (the longer the segment, the greater the utility). Uncertainty markings at the right end of each stacked-bar reflect the cost distribution. RIW sensitivity analysis reveals a moderately robust model; see Figures 23-27 in Appendix C for a sensitivity graph for each criterion (labeled "measure" in LDW®). Cost, Agility, and Payload are the only criteria that exhibit any sensitivity, and the sensitivity for each is judged to be *moderate* (delta of 7–11 percentage points). In order to produce a change in ranking, the Cost RIW would have to be decreased from 50% to 39.8%, *or* the Agility RIW would have to be increased from 15% to 24.8%, *or* the Payload RIW would have to be increased from 7.5% to 14.7%. In each situation, the top- ranked system-set 10 and 2nd-ranked system-set 14 would switch positions. For this problem, regardless of any modification to the RIWs, the preferred alternatives are the two system-sets that do not require a change of vehicle platform for any capability upgrade (#10 and #14).

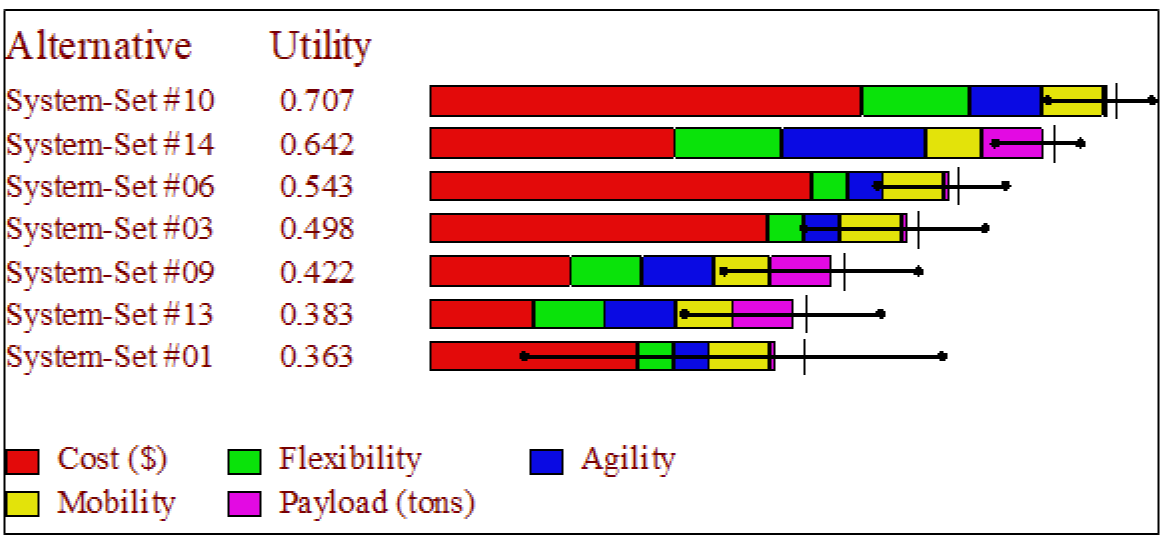

FIGURE 14. RANKING OF RO1 SYSTEM-SETS BASED ON TOTAL UTILITY

Additionally, Figure 15 illustrates the direct comparison of strengths and weaknesses between the two top-ranked alternatives: top-ranked #10 is superior with respect to (wrt) Cost and Mobility, while second-ranked #14 is superior wrt Agility and Payload, but to a lesser degree than

#10's Cost dominance. See Figures 28-29 in Appendix C for additional comparisons of the three top-ranked alternatives.

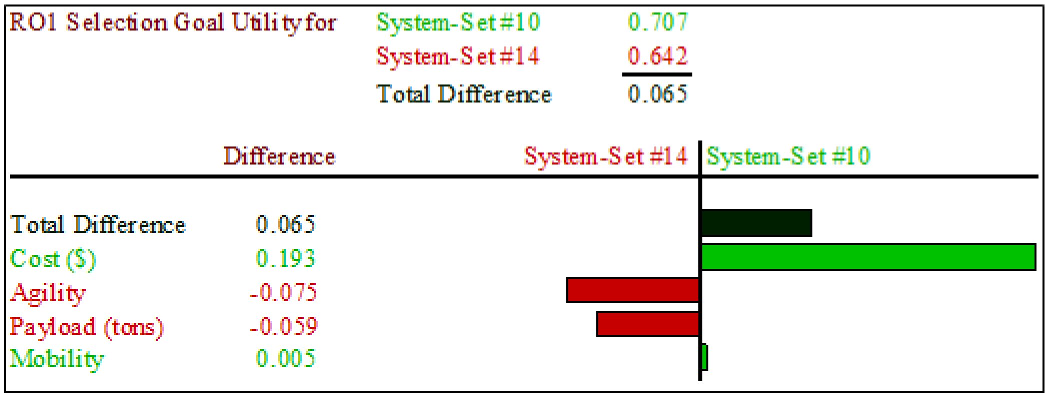

FIGURE 15. COMPARISON BETWEEN RO1 #1 AND #2 RANKED SOLUTION-SETS

Another way to directly compare multiple alternatives is with the MAU tool's scatter diagram capability. In Figure 16, all seven system-sets are compared wrt Cost vs Mobility vs Payload criteria, though any three criteria can be selected. By referring to Table 3, it can be determined that system-sets #1, #3, #6 and #10, represented by the small circles, all finish with vehicle platform V_2. Likewise, it can be determined that the three system-sets represented by the large circles, all finish with vehicle platform V_3. From this chart, it can be concluded that in order to increase Payload in the top-ranked system-set alternative (#10), with minimal Mobility degradation, #14 would have to be the selected system-set, with the associated cost increase. As previously stated, increasing the RIW for the Payload criterion from 7.5% to 14.7% would also result in #14 becoming the top-ranked system-set.

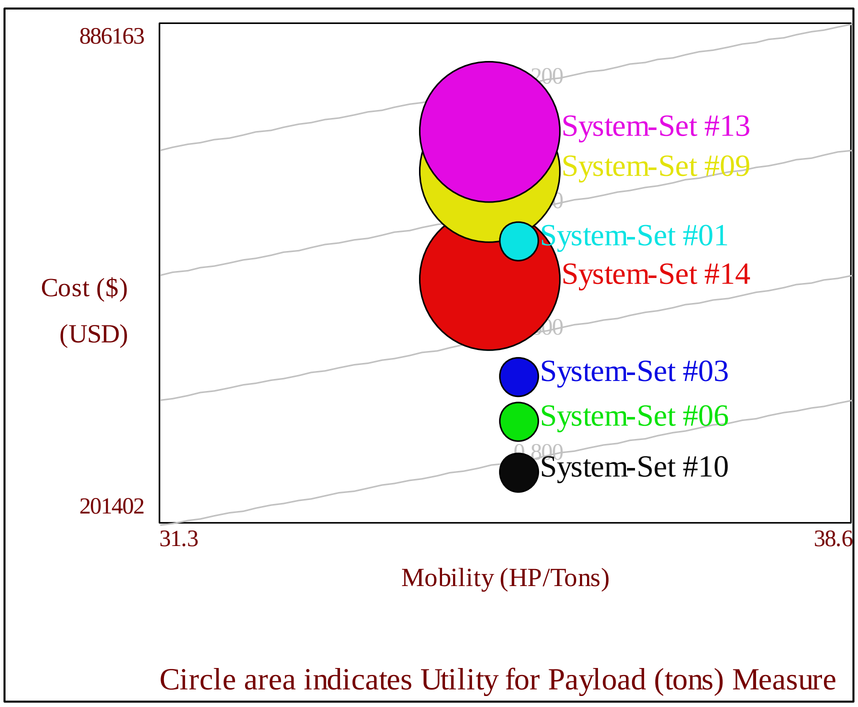

FIGURE 16. SCATTER DIAGRAM COMPARING ALL RO1 SOLUTION-SETS

CHAPTER 5: RESEARCH OBJECTIVE 2

For the second research objective, the RO1 framework is expanded to *new system development* for engineering resilient systems that will facilitate flexible, agile, and cost-effective capability growth in response to uncertain future needs. The production design is evaluated in combination with its affordable set of future upgrade options within the SBD paradigm, keeping the potential for future options open by focusing on RC and balancing average unit production cost against change and upgrade costs.

5.1. RO2 SETUP

Instead of designated *vehicle platforms*, there are now four *hull configuration* options $\mathrm{H} = \{H_1, H_2, H_3, H_4\}$, and five *mobility* options $\mathrm{M} = \{M_1, M_2, M_3, M_4, M_5\}$; the capability needs remain the same as earlier defined $\{T_1, T_2, T_3\}$. Table 7 displays the input data for the RO2 combinatorial trade-study model. It includes the subsystem options considered for this problem, along with respective RIWs and performance scores, physical weights, and costs. RIWs are usually agreed upon by stakeholders, but for this research they are set equally for all subsystems. Performance scores generally reflect how well the option meets its associated requirements; for this research the scores are simply estimates based on 0.50 meeting a minimum requirement and 1.00 meeting a maximum requirement. For other than hull configuration, the subsystem options are identified by full nomenclature so they can be quickly recognized.

The hull configuration includes all other subsystems in the vehicle platform not listed in Table 7. H_1 has minimum volume necessary to accommodate those subsystems not listed; options $H_1(E_1)$, $H_1(E_2)$, and $H_1(E_3)$ represent option H_1 extended to a size equivalent with option H_2.

TABLE 7. INPUT DATA FOR RO2 PERFORMANCE VS BURDENS MODEL

Subsystems/ Options	Performance Score and RIW	Burden Max Weight (lbs)	Burden Expected Cost (USD)	Subsystems/ Options	Performance Score and RIW	Burden Max Weight (lbs)	Burden Expected Cost (USD)
Hull Configuration	**20.0%**			**Protection-1**	**20.0%**		
H1	0.50	3,644	$82,500	7.62mm H1 (E0)	1.00	2,000	$18,381
H1(E1)	0.80	4,505	$154,272	7.62mm H1 (E1)	1.00	2,000	$24,341
H1(E2)	0.80	4,505	$201,808	7.62mm H1 (E2)	1.00	2,000	$31,841
H1(E3)	0.80	4,505	$375,845	7.62mm H1 (E3)	1.00	2,000	$59,300
H2	0.80	4,505	$102,000	7.62mm H2 (E0)	1.00	2,100	$19,300
H3	0.90	6,750	$143,575	7.62mm H2 (E1)	1.00	2,100	$25,558
H4	1.00	8,850	$187,272	7.62mm H2 (E2)	1.00	2,100	$33,433
Mobility	**20.0%**			7.62mm H2 (E3)	1.00	2,100	$62,264
M160 (E0)	0.25	2,856	$23,700	7.62mm H3H4	1.00	0	$0
M160-210 (E1)	0.50	2,931	$40,257	**Protection-2**	**20.0%**		
M160-210 (E2)	0.50	2,931	$52,661	12.7mm H1 (E0)	0.75	1,435	$28,624
M160-210 (E3)	0.50	2,931	$98,074	12.7mm H1 (E1)	0.75	1,435	$37,905
M210 (E0)	0.50	4,320	$29,276	12.7mm H1 (E2)	0.75	1,435	$49,584
M210-230 (E1)	0.65	4,395	$48,038	12.7mm H1 (E3)	0.75	1,435	$92,345
M210-230 (E2)	0.65	4,395	$62,840	12.7mm H2 (E0)	1.00	1,900	$37,900
M210-230 (E3)	0.65	4,395	$117,031	12.7mm H2 (E1)	1.00	1,900	$50,189
M230 (E0)	0.65	4,395	$36,276	12.7mm H2 (E2)	1.00	1,900	$65,653
M260 (E0)	0.75	6,000	$36,246	12.7mm H2 (E3)	1.00	1,900	$122,270
M260-300 (E1)	1.00	6,150	$59,255	12.7mm H3 (E0)	1.00	2,350	$46,876
M260-300 (E2)	1.00	6,150	$77,512	12.7mm H3 (E1)	1.00	2,350	$64,274
M260-300 (E3)	1.00	6,150	$144,357	12.7mm H3 (E2)	1.00	2,350	$84,666
M300 (E0)	1.00	6,150	$44,746	12.7mm H3 (E3)	1.00	2,350	$157,680
Lethality / Armament	**20.0%**			12.7mm H4 (E0)	1.00	2,700	$53,858
7.62mm Basic (E0)	0.70	265	$12,600	12.7mm H4 (E1)	1.00	2,700	$71,321
7.62mm Basic (E1)	0.70	265	$16,685	12.7mm H4 (E2)	1.00	2,700	$93,297
7.62mm Basic (E2)	0.70	265	$21,827	12.7mm H4 (E3)	1.00	2,700	$173,753
7.62mm Basic (E3)	0.70	265	$40,649				
7.62mm Premium (E0)	1.00	635	$33,500				
7.62mm Premium (E1)	1.00	635	$44,362				
7.62mm Premium (E2)	1.00	635	$58,031				
7.62mm Premium (E3)	1.00	635	$108,075				

Mobility (in horsepower, hp) includes the engine, transmission, and suspension; M_1, M_2, M_3, M_4, M_5 represent *160, 210, 230, 260, 300 hp*, and most of the options represent upgrades from one measure of hp to the next-higher hp. For Protection-1 subsystem (T_1), H_3 and H_4 come with integral capability; the listed options map to H_1 and H_2. Lethality/Armament subsystem (T_2) has two options: *Basic* maps to H_1 and H_2, and *Premium* maps to H_3 and H_4. Protection-2 subsystem (T_3), has options mapped to each of the four hull configuration options. All options designated by E_1, E_2 or E_3 in their name are priced for their corresponding epoch using 95th percentile expected costs. As with RO1, expected costs are based on the triangular distributions shown in Table 1. The one decision rule for RO2 is that capability options can only be added. Of the remaining RO1 decision rules, dictating the order of vehicle platform upgrades is no longer applicable since the objective of RO2 development is to avoid changing vehicle platforms, and the order of capability upgrades is eliminated since any order or combination of capability upgrades is allowed through allocating adequate RC for each of the hull configuration options. Based on the subsystem/capability options listed in Table 7, along with the associated interoperability/compatibility constraints, the trade-space for this problem consists of approximately 1,552 system-set alternatives.

5.2. RO2 Results

Figure 17 displays all Pareto (non-dominated) system-set solutions produced by the combinatorial model (system-set numbers were assigned by the model), ranked by the multi-utility function (MUF) score, which is the performance metric. Since only seven solutions were identified, the CSTM two and three-dimensional viewing capability was not necessary for selecting solutions for system-level analysis; all seven were carried forward. Note that highlighted system-set 1674 is the only solution that includes a change to the hull configuration, and it is at the earliest and least costly epoch E_1. Although option $H_1(E_1)$ calls for extending H_1 at E_1, H_1 has sufficient payload (weight RC) to receive Protection-1 and Lethality capability upgrades. However, it won't be able to receive the added weight of Protection-2 capability upgrade before E_1. Therefore, the highlighted Protection-2 option was changed from $H_2(E_0)$ to $H_2(E_1)$, resulting in a cost increase of $12,289.

System-Set	Hull Configuration (H_i)	Protection-1 (T_1)	Protection-2 (T_3)	Mobility (M_i)	Lethality / Armament (T_2)	MUF	Weight (lbs)	Cost ($)
1677	H4	7.62mm H34	12.7mm H4(E0)	M300 (E0)	7.62mm Premium (E0)	1.000	18,335	$314,376
1675	H3	7.62mm H34	12.7mm H3(E0)	M300 (E0)	7.62mm Premium (E0)	0.985	15,885	$263,697
1676	H3	7.62mm H34	12.7mm H3(E0)	M260 (E0)	7.62mm Premium (E0)	0.935	15,735	$260,197
1671	H2	7.62mm H2(E0)	12.7mm H2(E0)	M230 (E0)	7.62mm Basic (E0)	0.855	13,165	$203,076
1672	H2	7.62mm H2(E0)	12.7mm H2(E0)	M210 (E0)	7.62mm Basic (E0)	0.825	13,090	$201,076
1674	H1(E1)	7.62mm H2(E0)	12.7mm H2(E0)	M160-210 (E1)	7.62mm Basic (E0)	0.825	11,701	$264,329
1673	H1	7.62mm H1(E0)	12.7mm H1 (E0)	M160 (E0)	7.62mm Basic (E0)	0.670	10,200	$165,805

FIGURE 17. RO2 PARETO SYSTEM-SETS FROM PERFORMANCE VS BURDENS MODEL

Figure 18 models the identified RO2 solution-sets. Note that six of the seven system-sets call for adding the capability options at the earliest point possible. This is not surprising since it's based on the earliest costs being the lowest. All capability options don't have to be incorporated at E_0, but the fact that they can be is a significant advantage to the DM. Moreover, the key point is that RC is the attribute that enabled that advantage. The next step determined how much utility is coupled with that RC.

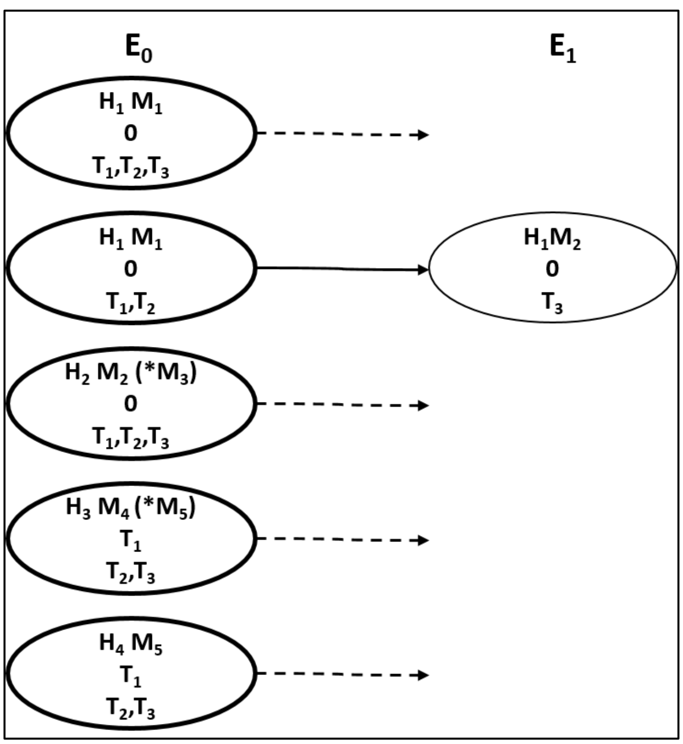

FIGURE 18. RO2 SYSTEM-SETS THAT ACHIEVE ALL REQUIREMENTS

For RO2, three decision criteria were added: Power RC, Required Capability Met, and Volume RC; Figure 19 displays the RO2 Goals Hierarchy. Calculations for Power RC and Volume RC, along with Payload, are highlighted in Table 8. Required Cap (Capability) Met is the respective MUF value from Figure 17. Power RC is the difference between the alternative's assigned level of horsepower and the horsepower required at the alternative's curb weight. Volume RC is the percentage difference between the volume of the alternative and the volume of alternative #1673. All input data for the RO2 MAU system model, along with the RIW for each criterion, are provided in Table 9.

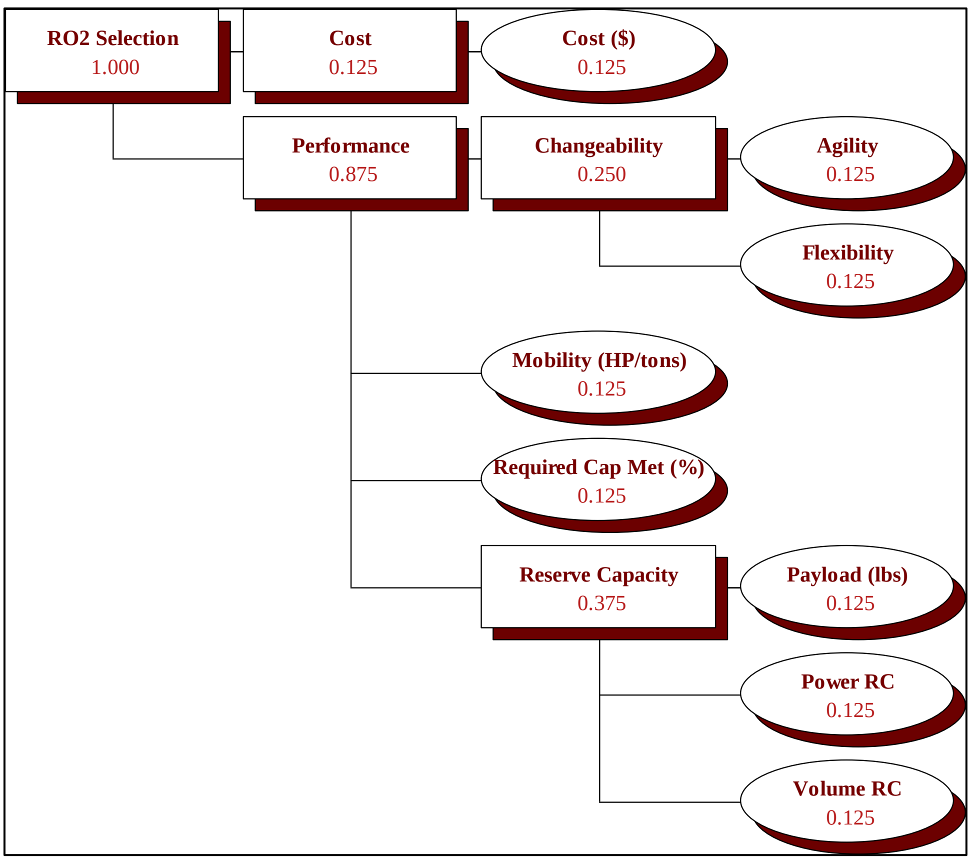

FIGURE 19. RO2 GOALS HIERARCHY FROM THE MAU MODEL

TABLE 8. DATA CALCULATIONS FOR RO2 POWER RC, PAYLOAD & VOLUME RC

System-Set Alternatives	GVWR (lbs)	Current Weight (lbs)	Required HP@CW	Assigned HP	Volume (ft^3)	Power RC	Payload (lbs)	Volume RC
#1671 H_2	14,400	13,165	130	230	631.8	0.77	1,235	0.06
#1672 H_2	14,400	13,090	130	210	631.8	0.62	1,310	0.06
#1673 H_1	10,200	10,200	100	160	596.3	0.60	0	0.00
#1674 H_1 (E_1)	14,400	11,701	130	210	631.8	0.62	2,699	0.06
#1675 H_3	17,650	15,885	190	300	861.4	0.58	1,765	0.44
#1676 H_3	17,650	15,735	190	260	861.4	0.37	1,915	0.44
#1677 H_4	20,000	18,335	220	300	1,219.4	0.36	1,665	1.04

TABLE 9. INPUT DATA FOR RO2 SYSTEM-SET ANALYSIS

Criterion	Agility	Cost ($)	Flexibility	Mobility (HP/tons)	Payload (lbs)	Power RC	Required Cap Met (%)	Volume RC
RIW	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
System-Set Alternative								
#1671 H_2	High	203076	Med-High	34.9	1235	0.77	0.86	0.06
#1672 H_2	High	201076	Med-High	32.1	1310	0.62	0.83	0.06
#1673 H_1	High	165805	Med-High	31.4	0	0.60	0.67	0.00
#1674 H_1 (E_1)	Med-Low	276618	Low	35.9	2699	0.62	0.83	0.06
#1675 H_3	Med-High	263697	Medium	37.8	1765	0.58	0.99	0.44
#1676 H_3	Med-High	260197	Medium	33.0	1915	0.37	0.94	0.44
#1677 H_4	Med-High	314376	Medium	32.7	1665	0.36	1.00	1.04

Resulting stacked-bar rankings of the system-set alternatives, based on total utility, are displayed in Figure 20. Since the costs are not represented by a distribution, there are no uncertainty markings as in Figure 14.

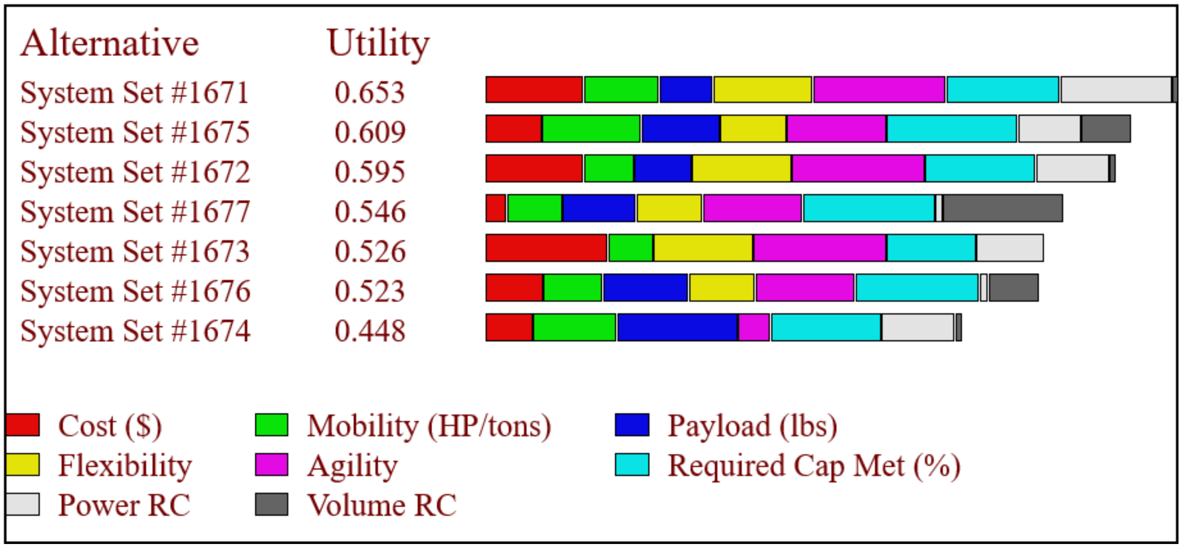

FIGURE 20. RANKING OF RO2 SYSTEM-SETS BASED ON TOTAL UTILITY

RIW sensitivity analysis reveals an overall robust model; see Figures 30-37 in Appendix D for a sensitivity graph for each criterion (labeled "measure" in LDW®). Agility and Flexibility exhibit no sensitivity, indicating that no change to either criterion's RIW would result in a change in the top-ranked alternative. Any one of the changes listed in Table 10 would result in the respective change of the top-ranked alternative. Each of the criteria in Table 10 exhibit low sensitivity with respect to RIW.

TABLE 10. RIW SENSITIVITY FOR RO2 CRITERIA

Criterion	RIW Change Req'd to Change Top-Ranked Alternative	New Top-Ranked Alternative
Cost	> 47.4%	#1673 H1
Mobility	> 29.1%	#1675 H3
Payload	> 29.6%	#1675 H3
Power RC	< 0.7%	#1675 H3
Req'd Cap Met	> 34.4%	#1675 H3
Volume RC	> 22.1%	#1677 H4

Additionally, the MAU model allows direct comparison between any two alternatives to identify strengths and weakness. Figure 21 illustrates the comparison between the two top-ranked alternatives: top-ranked #1671 is superior with respect to (wrt) Power RC, Cost, Flexibility, and Agility; second-ranked #1675 is superior wrt Volume RC, Mobility, Payload, and Required Capability Met. See Figures 38-39 in Appendix D for additional comparisons of the three top-ranked alternatives.

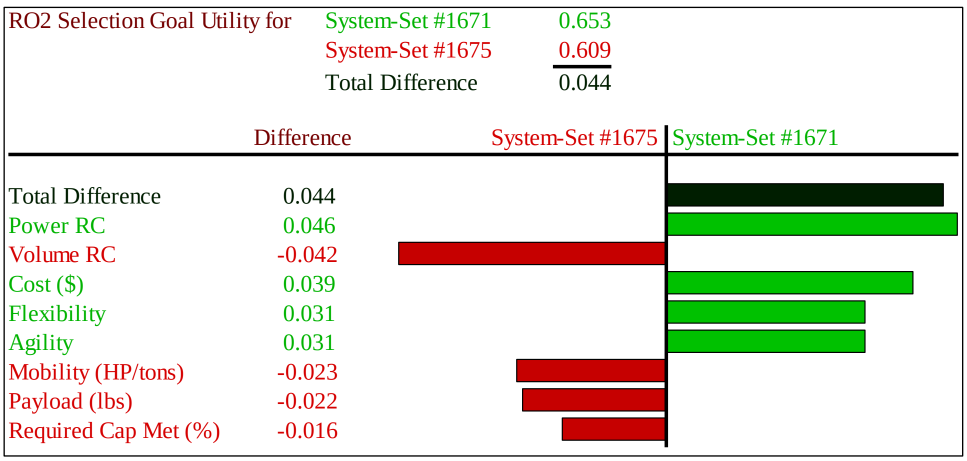

FIGURE 21. COMPARISON BETWEEN RO2 #1 AND #2 RANKED SYSTEM-SETS

As demonstrated for RO1, the MAU tool's scatter diagram capability is a way to directly compare multiple alternatives. In Figure 22, all seven system-sets are compared wrt Cost vs Mobility vs Payload criteria, though any three criteria can be selected. By referring to Table 8 or 9, it can be determined that each of the four circle sizes corresponds to one of the four hull configuration options. From this chart, it can be concluded that in order to increase Payload in the top-ranked system-set alternative (#1671), without degrading Mobility, #1675 would have to be the selected system-set, with the associated cost increase. As illustrated in Table 10, increasing the RIW for the Mobility, Payload, Power RC, *or* Req'd Cap Met criterion by the corresponding amount listed, would also result in #1675 becoming the top-ranked system-set. Note that this relationship is comparable to the one observed in RO1.

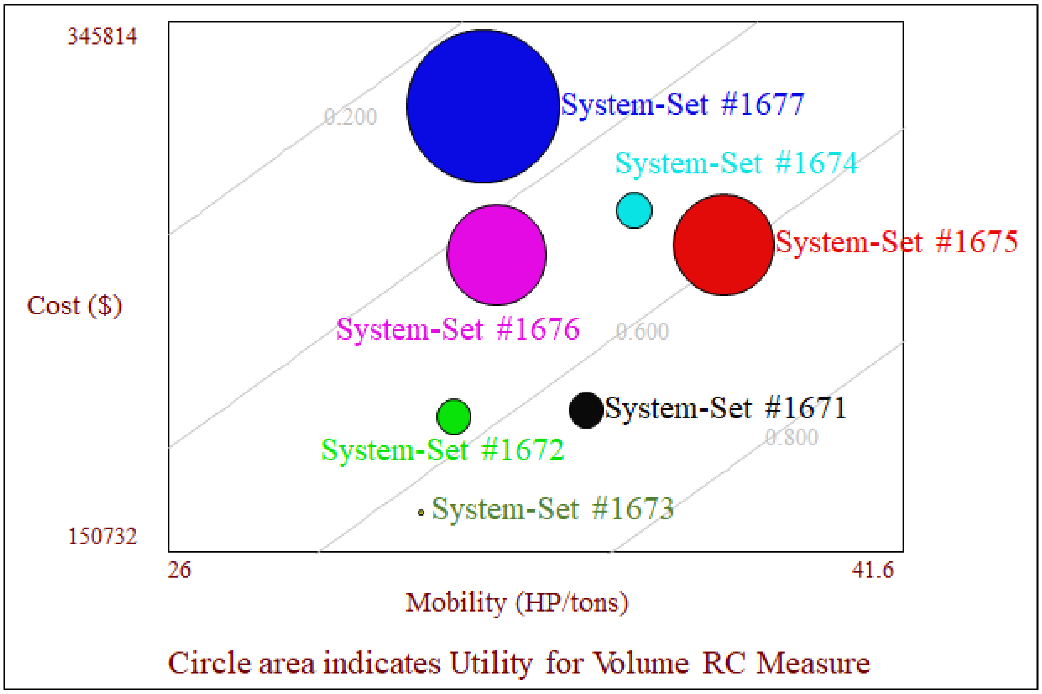

FIGURE 22. SCATTER DIAGRAM COMPARING ALL RO2 SYSTEM-SETS

CHAPTER 6: SUMMARY, ANSWERS AND FUTURE RESEARCH OPPORTUNITIES

6.1. SUMMARY OF RESEARCH OBJECTIVES RESULTS

Considering the results from RO1 and RO2 in context of the three-way relationship illustrated in Figure 5, it can be said that multiple solution-sets were assessed that achieved identical system capability need though they varied in costs due to different amounts of RC. Although RC increases system cost by growing the system platform, the associated utility reveals that the additional cost may be worth the benefits. In both RO1 and RO2 scenarios, the preferred solution-sets were those that did not include a change of/to the initial vehicle platform: #10 and #14 in RO1, and the six of the top seven Pareto system-sets in RO2. This outcome illustrates the advantage of having sufficient RC as early as is feasible in the system life cycle to minimize change costs and increase system changeability.

Moreover, though less-costly solution-sets may be initially preferred based on cost alone (#10 in RO1), after other important decision criteria are integrated into the study and assessed from a utility perspective, even the most costly alternatives may became competitive. In RO1, #10 dominated all other alternatives with respect to cost. However, once the other decision criteria were included, an alternative that cost more than twice the dominant low-cost solution-set became a contender. Likewise to a smaller degree, in RO2 an increase of 9.6 percentage points for the Volume RC RIW, which is not wholly unreasonable, would result in the highest-cost alternative (#1677) becoming the top-ranked system-set.

In multiple ways the resulting framework provides enhanced insight into the trade-space. The CSTM viewing capability facilitates identification and selection of strong-potential solutions for system-level analysis. For system-level analysis, the MAU tool, LDW®, allows the DMs and stakeholders to immediately view how “what-if” excursions of adjusting criteria RIW impact the ranking, and to better understand the relationship among multiple criteria.

6.2. RESEARCH QUESTIONS ANSWERED

The principal question that this research set out to address is “How can set-based design be enhanced and applied to the engineering of resilient systems?” The three avenues for *improving* SBD that this research addressed are enhancement, expansion, and extension.

First, SBD was *enhanced* by establishing a practical quantitative trade-space framework that provides the opportunity for quantifying changeability, by means of flexibility and agility, and using associated metrics to evaluate the relationship between RC and changeability. For this research, simple metrics were defined for flexibility and agility; however, the opportunity exists for more comprehensive and informative ways to define and quantify those attributes. Additionally, the framework *enhanced* SBD by allowing DMs to express preferences for all alternatives with respect to each criterion, thus improving the quality of information needed in determining which solution-set delivers the most utility. For this research, the preference or value-based approach produced (in RO1), or demonstrated potential to produce (in RO2), a different ranking of system-set alternatives compared to the ranking from an approach based strictly on performance versus cost.

Second, SBD was *expanded* by establishing a practical quantitative trade-space framework that is capable of evaluating an expansive trade-space on-the-fly, allowing for a much greater number of subsystems to be included in a study, which is expected to result in more and better opportunities for engineering resilient systems. For this research, capability need was constrained to two levels of armor protection and one level of lethality, resulting in a very limited trade-space that demonstrated only a minute fraction of the CSTM tool’s full capability.

Lastly, SBD was *extended* by establishing a practical quantitative trade-space framework that explicitly carries a set of possible system solutions past the point of the initial fielding of the system by considering changeability, as enabled through designed-in RC to accommodate additional volume, weight, power, cooling, and computing. Though RC facilitates changeability, it is recognized that more RC is not necessarily always better. The objective is to identify a balanced RC that provides an optimal degree of changeability, resulting in a more resilient yet cost-effective system that is able to easily and rapidly accept necessary improved capabilities.

6.3. FUTURE RESEARCH OPPORTUNITIES

An opportunity for future research is to expand the trade-space by including technology options that are still being developed and show potential for being superior to current options. This would further expand SBD by potentially providing more capability options that are technically superior, permitting more and better choices for the DM. Moreover, this would likely extend the trade-space to cover a longer operational period that better aligns with the system's design service life.

Another stream of research could explore dealing with intelligent adaptive adversaries, and within that context, identifying capability need and examining how system-sets can be assessed for system resiliency with respect to multiple adversary responsive moves.

APPENDIX A: REAL-WORLD EXAMPLES OF LONG-LIVED SYSTEMS THAT HAVE UNDERGONE UNPLANNED UPGRADES

The following are just a few examples of the many long-lived major military systems that have undergone multiple unplanned capability upgrades.

1. **C-130**. The U.S. primary tactical airlift aircraft is the C-130 Hercules, used by the Air Force, Navy, Marine Corps and Coast Guard; over 40 variants/versions operate in more than 60 nations. The C-130 Hercules is the longest continuously produced military aircraft at over 60 years. Older model C-130s currently make up a significant portion of the entire fleet and are the focus of modernization issues. The age of the fleet has created parts and avionics obsolescence issues, along with structural fatigue, that may impact the overall capability of the aircraft in the future. The C-130A joined the Air Force inventory in December 1956. Currently, the C-130H and C-130J are the most common models in the Air Force inventory. As of 2014, the average age of the Air Force C-130H active fleet was 39 years; 75% of the avionic pieces-parts will be considered to be obsolete by FY2023. Diminishing Manufacturing Sources (DMS) is a significant issue for the C-130H fleet, primarily because the C-130H has old and outdated avionics; 22% of the avionics are already obsolete according to the Air Force Life Cycle Management Center. This was magnified by the decision to cancel the C-130 Avionics Modernization Program (AMP), which was originally planned to address DMS issues within the fleet. Assuming current international/U.S. regulations for aircraft Communication Navigation Surveillance/Air Traffic Management (CNS/ATM) requirements follow current implementation timelines, a significant portion of the C-130 fleet may be restricted access to certain European airspace as early as 2017. The current fleet of C-130H models do not have the required avionics capabilities anticipated in certain U.S. airspace and in areas surrounding busy U.S. airports as soon as 2020. With ongoing capability upgrades to bring

the C-130J fleet (the model still in production) into compliance with currently forecasted aviation regulations, its service life will extend to 2040. Another major modification currently being accomplished on the C-130 fleet to extend the service life is the replacement of the center wing box, a critical fatigue component of the C-130 fleet due to the stresses of flying missions over such a long period of time. (Heisler 2014.)

2. **M113 Armored Personnel Carrier**. The U.S Army's M113 first entered service in 1960; major vehicle upgrades occurred in 1964 (M113A1), 1979 (M113A2), and 1987 (M113A3). Each upgrade consisted of new or improved engines and transmissions, and other changes included an overhauled suspension subsystem, optional external fuel-tanks, and armor protection. Most recently, under the Armored Personnel Carrier Life Extension (APCLE) program, 341 Canadian M113A2 series vehicles were upgraded: 183 were stretched and fitted with six road wheels, while the remaining 158 vehicles were upgraded to M113A3 standards, retaining five road wheels. The U.S. Army stopped buying M113s in 2007, with 6,000 vehicles remaining in the inventory. The U.S. Army planned to retire the M113 family of vehicles by 2018, seeking replacement with the GCV Infantry Fighting Vehicle program. But since the GCV program was cancelled in 2014, the replacement of the M113 has fallen to the Armored Multi-Purpose Vehicle (AMPV) program. However, fielding of the AMPV is not scheduled until 2022. [https://en.wikipedia.org/wiki/M113_armored_personnel_carrier]

3. **Stryker**. First fielded in 2002 and based on already-existing vehicle platforms, the U.S. Army's Stryker ground combat vehicle was originally named the Interim Armored Vehicle and scheduled to be replaced by the products of the Future Combat System (FCS) Program. When the FCS Program was cancelled in 2009, the service life of the Stryker immediately became extended indefinitely. Most of the Stryker's upgrades have been in response to the

evolving threat. In 2004, a slat-armor cage was installed on the vehicles as an intermediary protection against rocket-propelled grenades. In 2010, major unplanned improvements centered on modifying the vehicle hull to a double-V design to protect against improvised explosive devices (IEDs). Associated upgrades included increased armor, suspension and braking subsystems, and blast-attenuating seats. Current Stryker Engineering Change Proposal (ECP) efforts are focused on improving command, control, communications, computers and intelligence (C4I) capabilities, to include necessary in-vehicle network and electrical power upgrades. The most recent major upgrade centered on the addition of a 30mm cannon and turret to a percentage of the M1126 Stryker (flat-bottom hull) infantry carrier fleet. The upgrade required a new 55,000 pound suspension and wider tires; fielding is scheduled to begin in July 2018. There are 10 variants of the flat-bottom hull (original) Stryker and seven variants of the double-V hull Stryker. The unit production cost of the infantry carrier variant has increased from $1.42M in 2003 to $4.9M in 2012. [https://en.wikipedia.org/wiki/Stryker]

4. **Assault Amphibious Vehicle (AAV)**. The U.S. Marine Corps' AAV was first produced in 1972 to transport Marines from ships to shore. It underwent a service-life-extension program (SLEP) in 1984, upgrading the engine, transmission, and weapon subsystems, and improving the overall maintainability of the vehicle. In 1998, the AAV underwent a Rebuild-to-Standard Program to again upgrade the engine and suspension, and restore its reliability, availability and maintainability (RAM) to meet original requirements. This effort extended the AAV's expected service life to 2013, when it was scheduled to be replaced by the Advanced Amphibious Assault Vehicle (AAAV; renamed the Expeditionary Fighting Vehicle (EFV) in 2003); the EFV Program was cancelled in 2011. The latest engineering efforts are related to survivability upgrades for approximately 30-40% of the AAV fleet. Survivability upgrades are focused

principally on improving the underbelly blast protection of the flat-bottomed AAV7A1, which is currently capable of providing protection only against anti-personnel mine-levels of blast. The additional armor, seats, and other survivability enhancements add approximately 11,000 pounds to the vehicle, requiring improvements to the marine drive train, powertrain, and modification to the suspension system. The AAV service life end is now planned for 2030 (58 years of service), to be replaced by the in-development Amphibious Combat Vehicle (ACV). [https://en.wikipedia.org/wiki/Assault_Amphibious_Vehicle; http://www.janes.com/article/75737/usmc-aav7a1s-set-for-survivability-upgrades]

APPENDIX B: REAL-WORLD EXAMPLE OF CONSEQUENCES OF NOT ACHIEVING RESERVE CAPACITY REQUIREMENTS

The Oliver Hazard Perry-class Guided-Missile Frigate (FFG-7) of the U.S. Navy provides an excellent example of the consequences of not achieving reserve capacity (RC) requirements. Modernization potential is the ability of a warship to accept new equipment to avoid obsolescence. The long life of warships (25 or more years) and relatively short life of systems installed on the ships (7 to 10 years) made modernization potential important. Over its lifetime, a warship will usually have much of its original equipment replaced by new, more capable systems. From the outset of the program, space, weight, and stability margins for growth in the FFG-7 were minimized. The low margins were linked to the Navy's determination to restrain the size and cost of the ship. As a result, the FFG-7, unlike most new warships, was unable to accommodate any new equipment beyond what was planned, unless compensating removals were included. The two areas of particular concern were the reductions in (1) the service life weight RC, and (2) the future RC.

The service life weight RC allows for weight increases occurring during the life of the ship. Normally, the RC for a ship this size would be about 150 tons. The RC in the FFG-7, however, was only 50 tons, or 100 tons less than normal. The future growth weight RC is established to allow for *unknown*, but anticipated future modifications and new equipment approved by the Chief of Naval Operations. This margin is intended to make new ships more adaptable to changing requirements, the increasing threat, and changes in technology. In the FFG-7, there was no RC for unplanned future ship characteristic changes, which require additional space or increases in the ship's weight.

In addition to the tight weight margins, opportunities for future growth were even further constrained by very limited space on the ship. These space limitations could make some necessary future improvements impractical if compensating equipment removals cannot be made. This, in turn, could affect the capability of the ship to perform its mission against an increasing enemy threat.

These limited opportunities for future ship modifications were a serious matter because major modernizations are almost always required in order to maintain an effective ship. Historically these modernizations have usually required space, weight, and stability reservations. The absence of weight and space margins for fitting new equipment beyond those already planned meant added risk that needed mid-life modernizations to keep the ships abreast of an increasing threat throughout their life will prove impractical.
[http://www.globalsecurity.org/military/systems/ship/ffg-7.htm]

APPENDIX C: RESEARCH OBJECTIVE 1 DETAILS

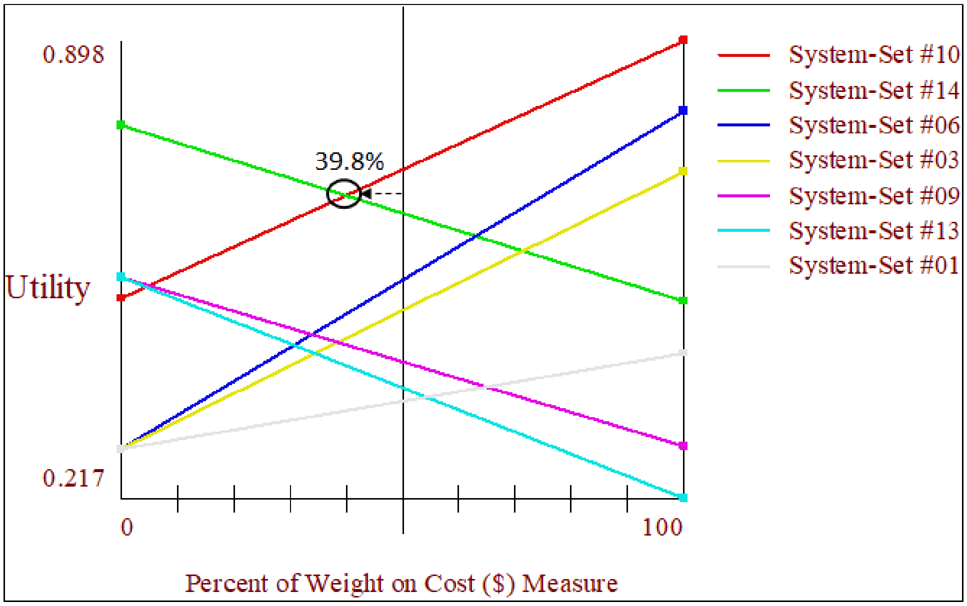

FIGURE 23. RO1 RIW SENSITIVITY FOR COST CRITERION

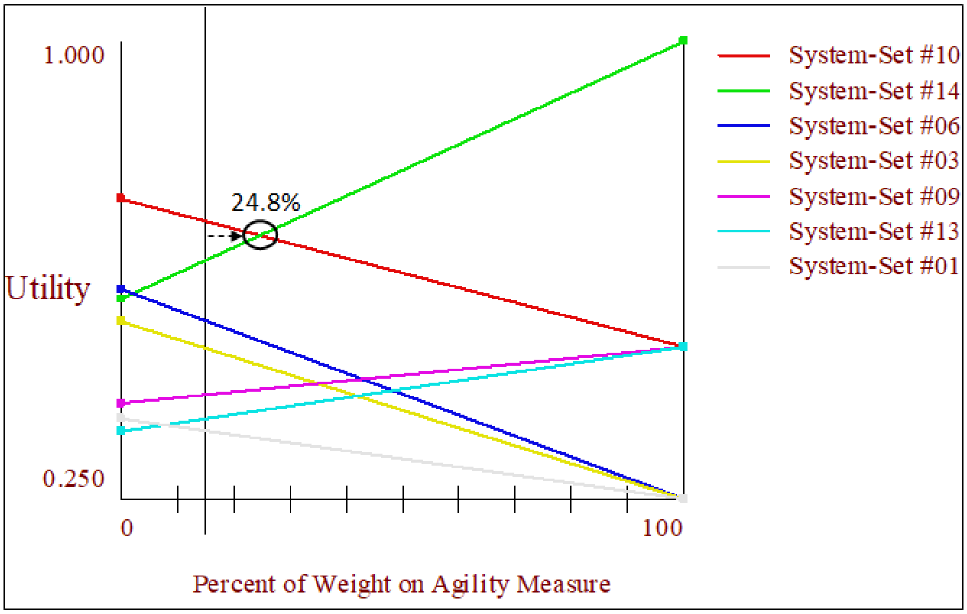

FIGURE 24. RO1 RIW SENSITIVITY FOR AGILITY CRITERION

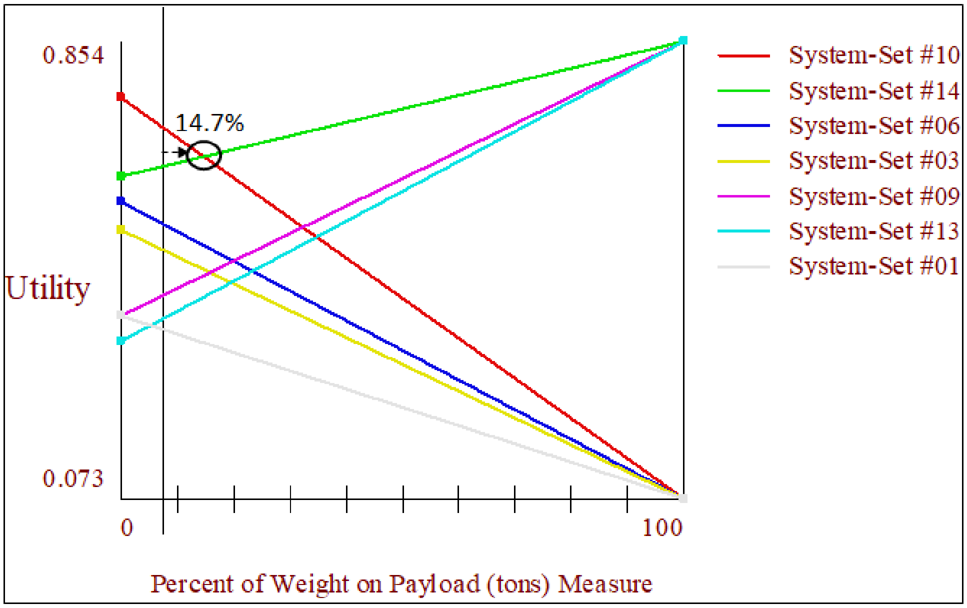

FIGURE 25. RO1 RIW SENSITIVITY FOR PAYLOAD CRITERION

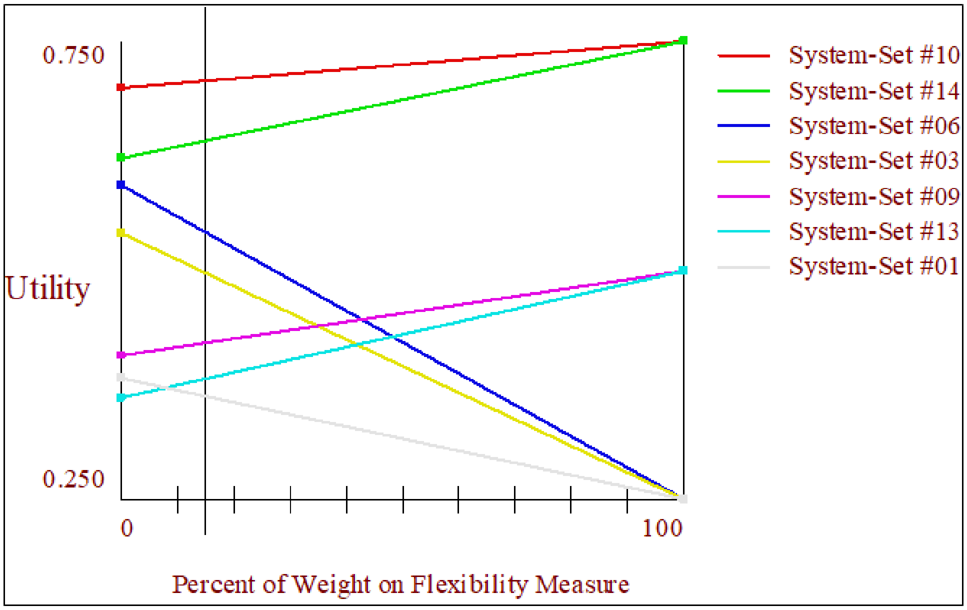

FIGURE 26. RO1 RIW SENSITIVITY FOR FLEXIBILITY CRITERION

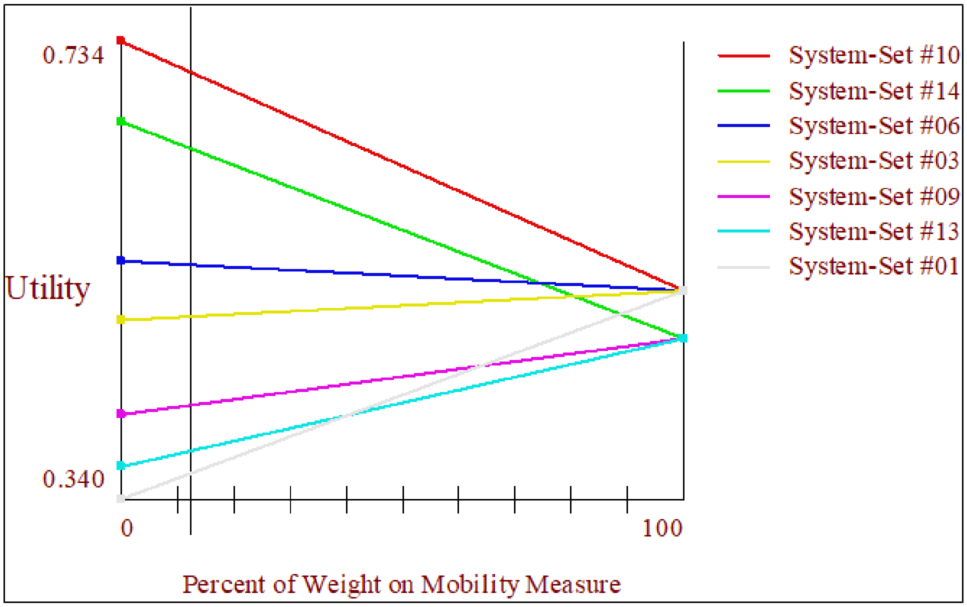

FIGURE 27. RO1 RIW SENSITIVITY FOR MOBILITY CRITERION

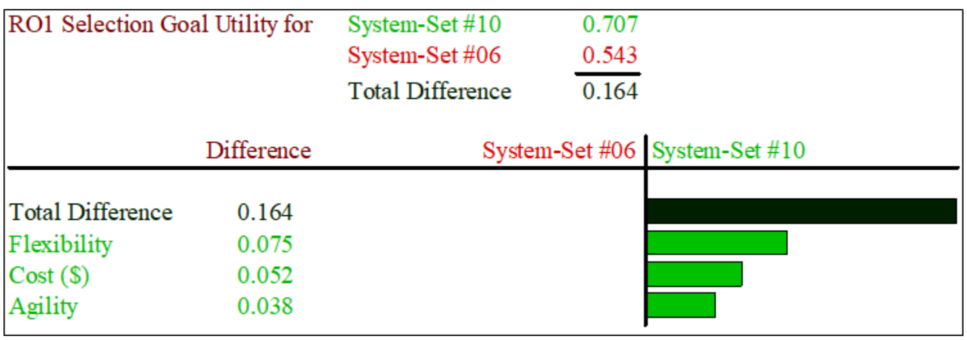

FIGURE 28. COMPARISON BETWEEN RO1 #1 AND #3 RANKED SYSTEM-SETS

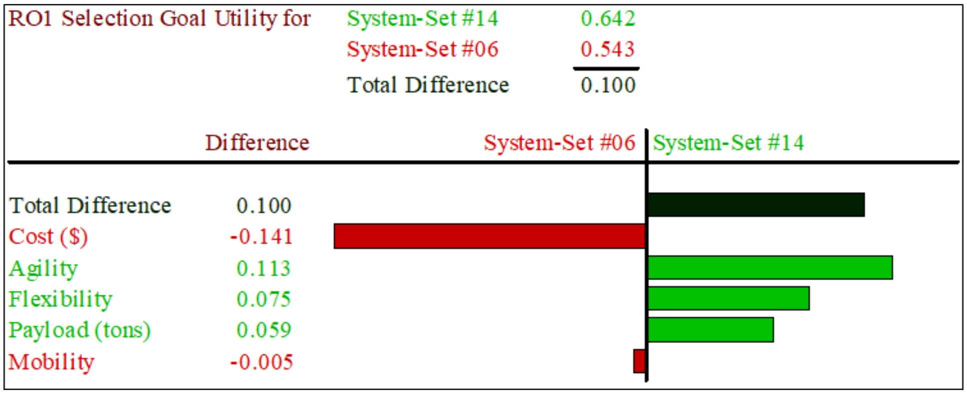

FIGURE 29. COMPARISON BETWEEN RO1 #2 AND #3 RANKED SYSTEM-SETS

APPENDIX D: RESEARCH OBJECTIVE 2 DETAILS

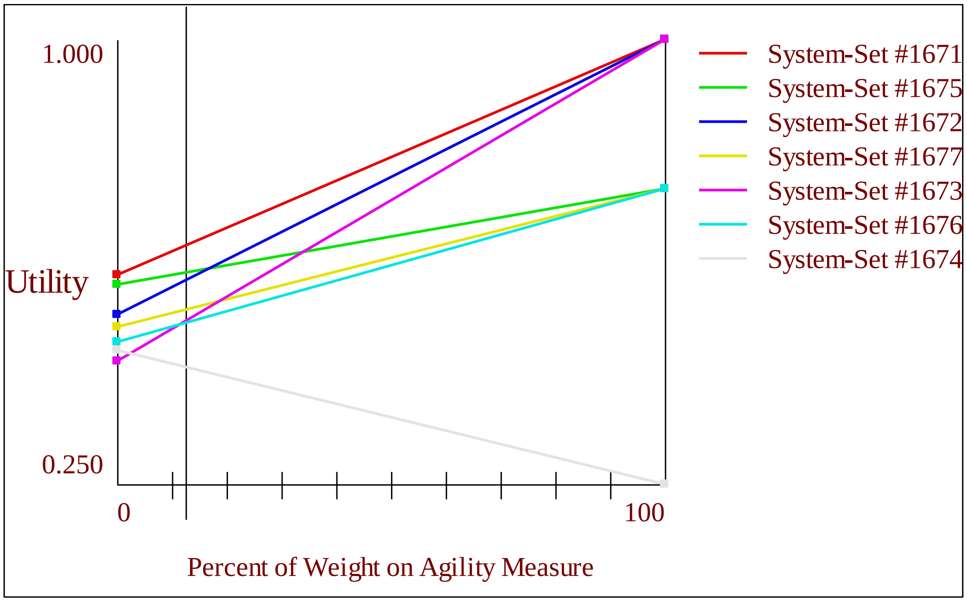

FIGURE 30. RO2 RIW SENSITIVITY FOR AGILITY CRITERION

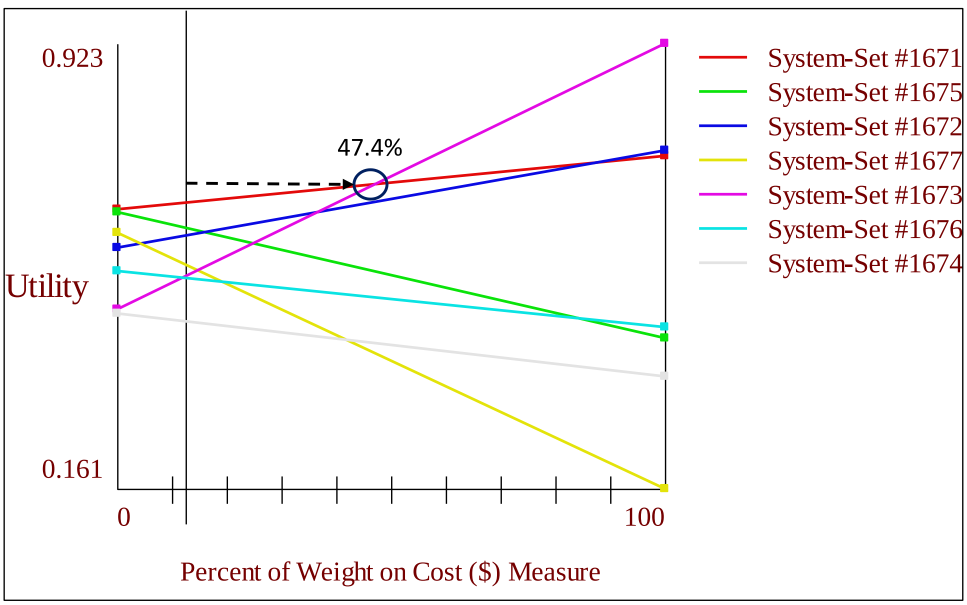

FIGURE 31. RO2 RIW SENSITIVITY FOR COST CRITERION

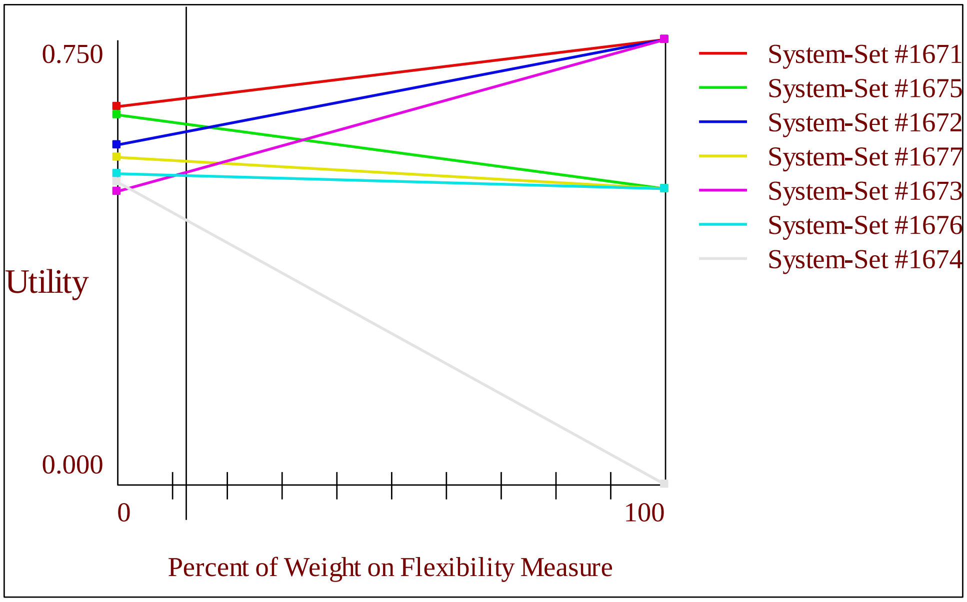

FIGURE 32. RO2 RIW SENSITIVITY FOR FLEXIBILITY CRITERION

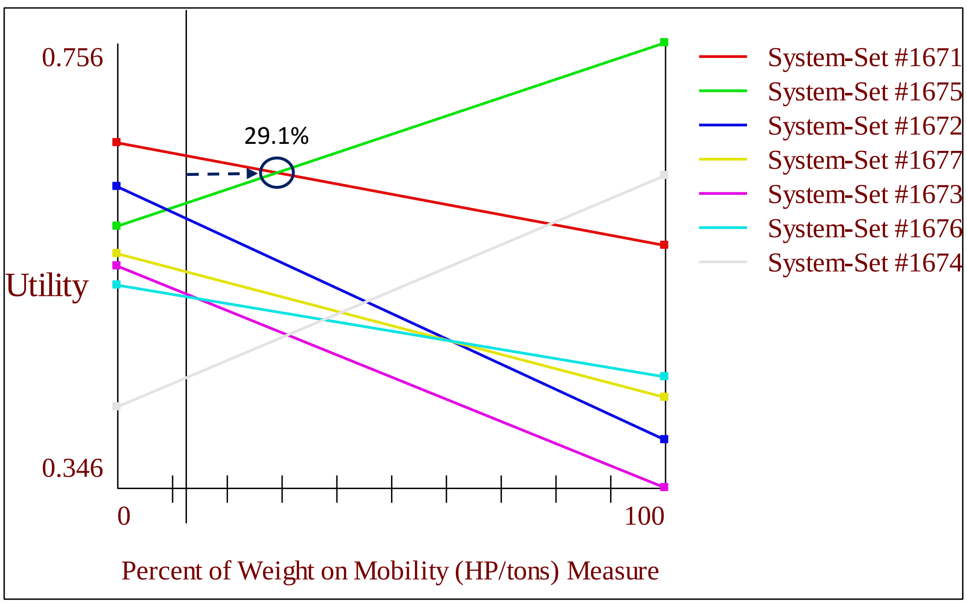

FIGURE 33. RO2 RIW SENSITIVITY FOR MOBILITY CRITERION

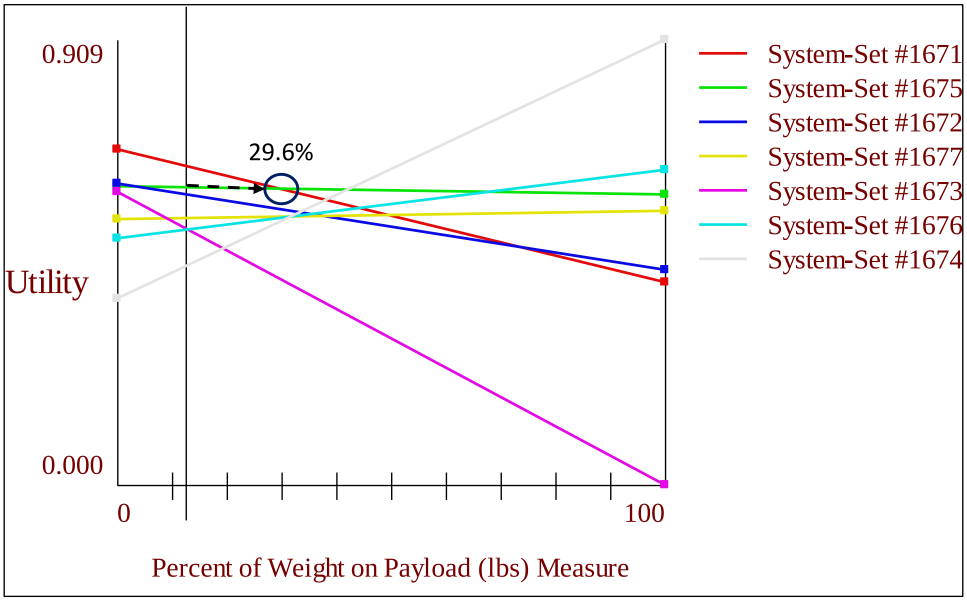

FIGURE 34. RO2 RIW SENSITIVITY FOR PAYLOAD CRITERION

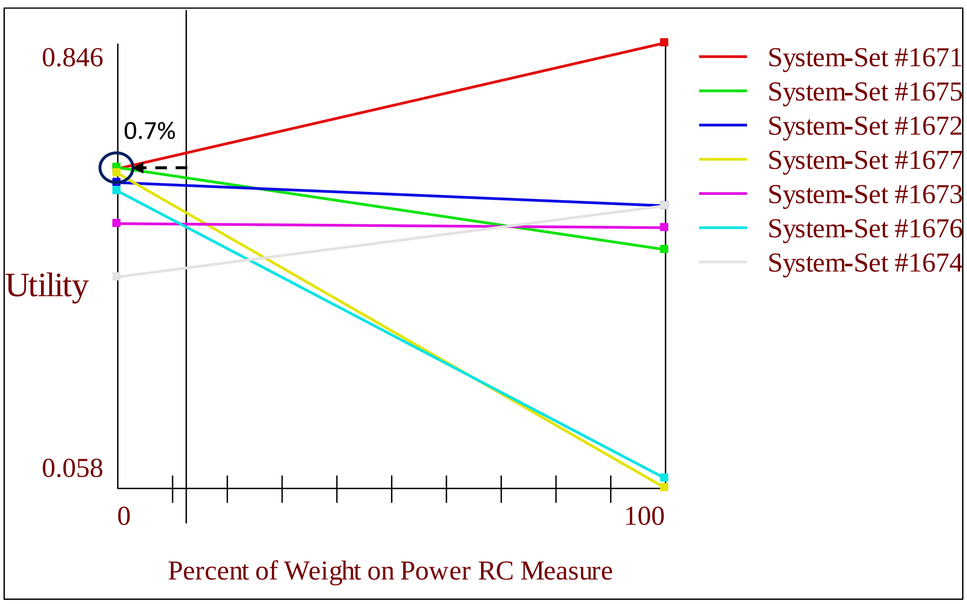

FIGURE 35. RO2 RIW SENSITIVITY FOR POWER RC CRITERION

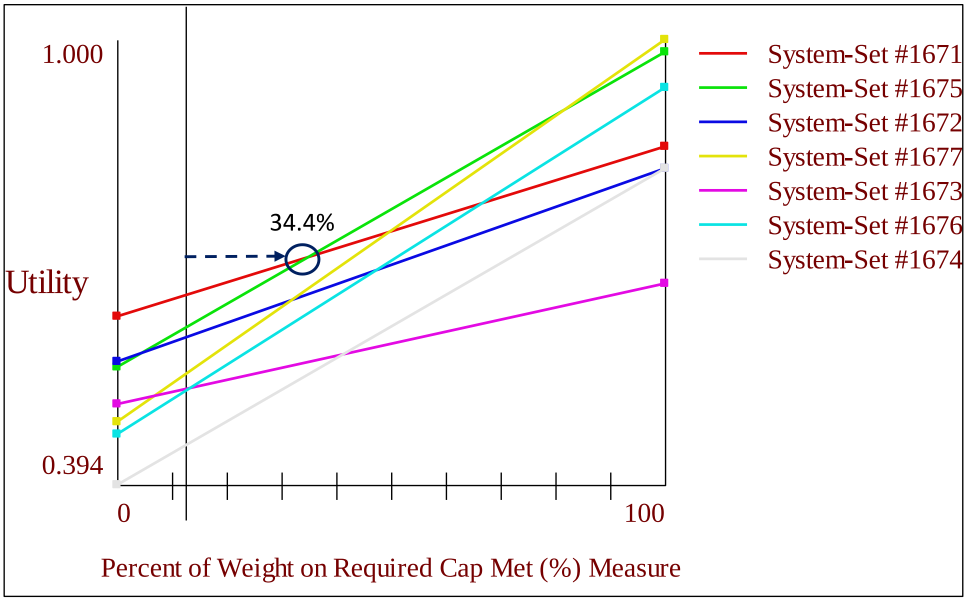

FIGURE 36. RO2 RWI SENSITIVITY FOR REQ'D CAP MET CRITERION

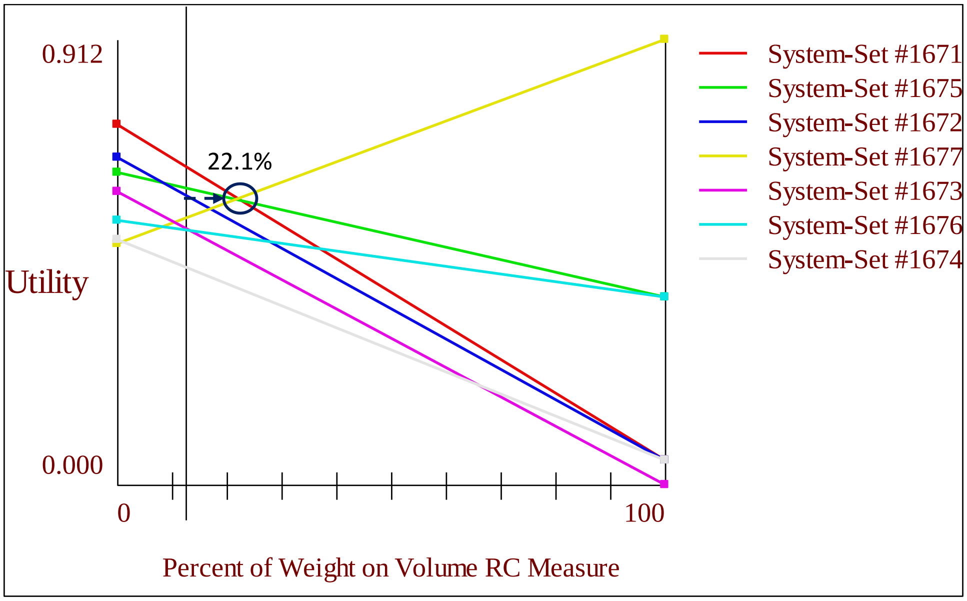

FIGURE 37. RO2 RWI SENSITIVITY FOR VOLUME RC CRITERION

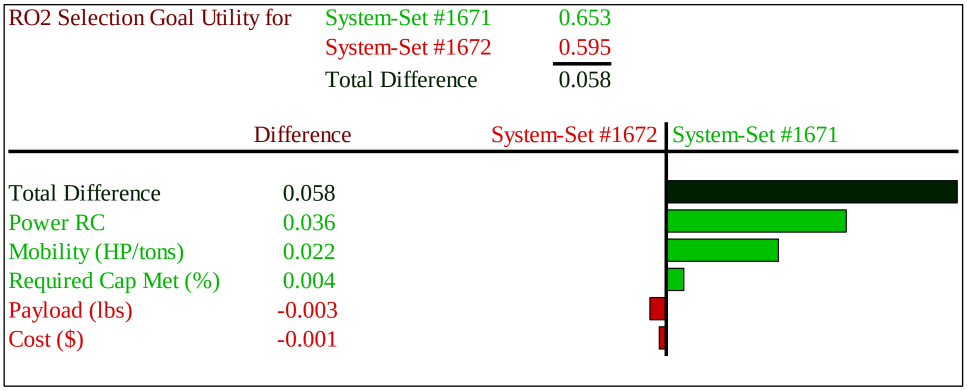

FIGURE 38. COMPARISON BETWEEN RO2 #1 AND #3 RANKED SYSTEM-SETS

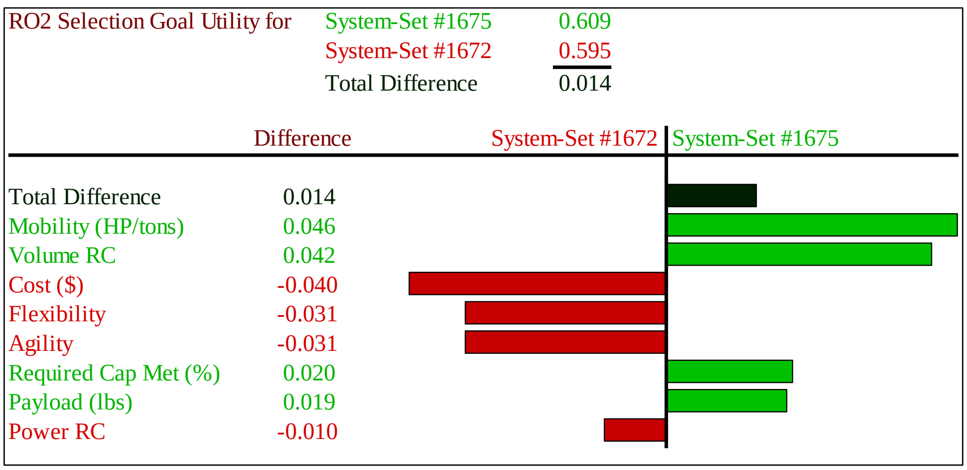

FIGURE 39. COMPARISON BETWEEN RO2 #2 AND #3 RANKED SYSTEM-SETS

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ABSTRACT

ENHANCING SET-BASED DESIGN TO ENGINEER RESILIENCE FOR LONG-LIVED SYSTEMS

by

GREGORY DAVIS HARTMAN

May 2018

Advisors: Dr. Ratna Babu Chinnam and Dr. Gary Witus

Major: Industrial Engineering

Degree: Doctor of Philosophy

At the heart of Set-Based Design is the concept that down-select decisions are deferred until sufficient information is available to make a decision, i.e., a set of possible solutions is maintained. Due to the extended service lives of many of our current and future systems, the horizon for accurately predicting the system's requirement is shorter than the service life, so the needed information to down-select to a single optimized solution is unavailable at the time of fielding. Set-Based Design can, however, be extended to explicitly carry a set of possible solutions past the point of the initial fielding of the system by considering changeability, as enabled through designed-in reserve capacity to accommodate additional volume, weight, power, cooling, and computer performance. Proposed is an analytical framework that enhances Set-Based Design to engineer resilient systems with cost-effective post-production growth capability by means of reserve capacity and illustrate it through a case study.

AUTOBIOGRAPHICAL STATEMENT

Gregory Hartman was born in Columbus, OH, USA. He attended The Ohio State University, graduating with a Bachelor of Science in Secondary Mathematics Education, and received his commission as a U.S. Marine Officer through Naval Reserve Officer Training Corps. He spent the majority of his military career as a Field Artillery Officer, Operations Analyst, and Operations/Intelligence Analyst, and retired as a Major. Also while serving in the Marine Corps, Greg graduated from George Mason University in Fairfax, VA with a Master of Science in Operations Research/Management Science, and from Boston University with a Master of Science in Business Administration.

After departing the Marine Corps, Greg enjoyed a career as an operations research analyst at Marine Corps Systems Command and General Dynamics Land Systems. While at General Dynamics, he pursued a Ph.D. in Industrial Engineering at Wayne State University, Detroit MI, achieving his degree in December 2014.

He currently enjoys life in Michigan with his best friend, Mary, along with her grown son who lives nearby. Greg and Mary also enjoying spending time in Ohio, as well as California and Florida with his three grown children and three grandchildren, and North Carolina with her grown daughter.