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Preparing to Be Wrong

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Panel 5. Quantitative Analyses of Acquisition Outcome Drivers

Wednesday, May 4, 2016	
1:45 p.m. – 3:15 p.m.	**Chair: William Gates,** Dean, Graduate School of Business and Public Policy, NPS ***Consequences of BBP's Affordability Initiative*** Gregory Davis, Research Staff Member, Institute for Defense Analyses Lawrence Goeller, Defense Acquisition Analyst, Institute for Defense Analyses Stanley Horowitz, Assistant Director, Cost Analysis and Research Division, Institute for Defense Analyses ***Further Evidence on the Effect of Acquisition Policy and Process on Cost Growth*** David McNicol, Research Staff Member, Institute for Defense Analyses David Tate, Research Staff Member, Institute for Defense Analyses ***Preparing to Be Wrong*** Prashant Patel, Research Staff Member, Institute for Defense Analyses Michael Fischerkeller, Research Staff Member, Institute for Defense Analyses

Preparing to Be Wrong

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Abstract

Senior national security leaders face a diverse set of threats and greater uncertainty than in the past. They have called for adaptable or agile organizations and weapon systems to address this uncertainty. We focus on what this means for weapon system acquisition in terms of design, threats, and processes. Additionally, we show how metrics can be quantitatively used to help leadership understand the costs and benefits of adaptable and non-adaptable weapon systems.

Introduction

> *The United States is going to maintain our military superiority with armed forces that are agile, flexible, and ready for the full range of contingencies and threats.*
>
> —President Obama, January 5, 2012

Background

The imperative for U.S. forces to be adaptive to changing circumstances is driven by uncertainty regarding potential threats and operational environments, coupled with likely reductions in force structure and modernization accounts.[1] In many disciplines, time and time again, it has been demonstrated that expectations regarding the future are often wrong—sometimes very wrong, resulting in severe consequences. The Department of Defense (DoD) has not been immune from this tendency. The modesty these failures should engender is manifested in the importance accorded the idea of adaptability in recent pre-eminent strategic guidance documents.[2] Senior leaders are directing the DoD to prepare to be wrong. This perspective raises several questions: What is an appropriate conceptual definition of adaptability for the DoD? How does that definition apply to the different functions of the Department? And how could you operationalize and measure it in those functions? The first two questions have received some attention, the latter far less.

Not surprisingly, the concept of adaptability has recently been scrutinized and considered within a DoD context. An enterprise-level definition used by the Defense Science Board (DSB; 2011) is "the ability and willingness to anticipate the need for change, to

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[1] For example, now and in the future, there are no fewer than five interdependent domains for warfare: land, sea, air, space, and cyberspace. It has been rare in history for a new domain to be added to the short list of environments for warfare, and yet two such new domains, space and cyberspace, were added only recently (Gray, 2008–2009).

[2] See, for example, Office of the Secretary of Defense (2012) and Dempsey (2012).

prepare for that change, and to implement changes in a timely and effective manner in response to the surrounding environment" (p. viii). With this definition in hand, the DSB (2011, p. 30) reviewed the DoD enterprise and offered several recommendations, two of which motivated this paper: first, the call to align processes to the pace of today's environment—more specifically, to employ dynamic trade space analysis; and second, to reduce uncertainty through better awareness. Regarding the second, however, the approach taken here assumes that the DoD will make little progress in this regard and, therefore, should place equal if not more emphasis on explicitly accounting for uncertainty in its capability development and acquisition processes.

In Operation Iraqi Freedom and Operation Enduring Freedom, U.S. forces encountered an agile enemy adapting quickly in the tactical arena. In such operational environments, *survival* requires a local response. *Success*, however, depends on rapid response at all DoD enterprise levels (DSB, 2011, p. viii). In some instances, changes in the way our warfighters engage the adversary—modifying tactics, techniques, and procedures (TTPs) or concepts of operations (CONOPSs)—is the fastest, but not necessarily the most effective, response. In many cases, success depends on the introduction of new equipment, technology, or weapon systems.

The objective of this paper is to support warfighters in the achievement of success on the battlefield by enabling the DoD to assess the adaptability of current, in-design, and in-development weapon systems; determine how modernization upgrades may enhance or degrade adaptability; and design future weapon systems to be adaptable. In so doing, it seeks to offer an answer to the question: How do you operationalize adaptability in the DoD's technical capability base and its capabilities development process, and measure the degree to which the weapon systems resulting from those processes are adaptable (DSB, 2011, p. 36)?[3]

There are several incentives for focusing on weapon systems. Unlike other potential sources of adaptability (e.g., TTPs and CONOPSs), systems are long-gestation, long-lived assets whose design constraints prevail for decades. And these assets are costly—Research, Development, Test, & Evaluation (RDT&E) and procurement accounts combined are approximately one-third of the DoD's budget ($170 billion in 2013). Weapon systems are analytically tractable and amenable to rigorous examination and assessment, as they are subject to physical laws. Such analyses and assessments could serve as valuable inputs into strategies for developing adaptive TTPs, CONOPSs, skills, and organizations. For example, exposing operators to unutilized technical capabilities in current systems could encourage creative uses of the same.[4] Additionally, an assessment of current and in-

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[3] The DSB recommended that development and acquisition planning include adaptability as a specific requirement metric.

[4] How many of us understand the technical capabilities of our smartphones? If more did, it is reasonable to expect that heretofore unknown novel uses would be identified. Consider the extraordinary number and types of apps that have been developed by the iPhone and Android user communities, for example.

development systems that finds a lack of adaptability might suggest that a cost-effective investment strategy for achieving adaptability *now* may lie in those other arenas.[5]

This paper presents a set of concepts, working definitions, a framework, and a quantitative approach for evaluating adaptability in current, in-design, and in-development weapon systems and for supporting dynamic trade space analyses to enable the design of adaptive future systems.[6] It proceeds with a discussion of three distinct but related concepts: responsiveness, flexibility, and adaptability.

Concepts and Working Definitions

These concepts are not new to the physical systems analytical community. Their discussion here, however, is novel in that the lens through which they are considered is that of the defense of the nation. The concepts of responsiveness, flexibility, and adaptability are taken from the dynamic system and control theory fields and modified for use by the DoD.

- *Adaptability* is a measure of the change in the state variable of interest.
- *Flexibility* is a measure of the effort required to transition from state x_0 to x_1.[7] It is inversely related (or negatively correlated) to the effort required to transition to a new state. A system that is flexible requires less effort to be reconfigured to reach state x_1.
- *Responsiveness* is a measure of the time required to transition from state x_0 to x_1. Responsiveness is inversely related (or negatively correlated) to the time required. A system that is responsive requires less time to transition between states.

Considering these concepts within the context of the paper's objective, working definitions for assessing against and designing to adaptability are as follows:

- *Adaptability* is a measure of the potential set of missions (or possible states within a mission space) that can be supported.[8]
- *Flexibility* is an inverse measure of the costs of adapting (effort, capability tradeoffs, and dollar costs); the greater the costs to adapt, the less flexible the weapon system.
- *Responsiveness* is an inverse measure of the time required to adapt (i.e., transition within a mission space or between missions).

These definitions are distinct but related and apply equally well to weapon systems and their physical subsystems. The acquisition community will likely see a relationship

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[5] For a study on skills development, see Burns and Freeman (2010). Alternative assessment approaches might be more appropriate for alternative acquisition strategies. Other strategies could be grounded in procuring larger quantities of single-purpose platforms or based on a systems-of-systems approach to capability development.

[6] The Joint Requirements Oversight Council (JROC) recently sent a memorandum to all DoD Components and Agencies to encourage requests for Key Performance Parameter (KPP) relief if KPPs appear out of line with cost-benefit analysis. A dynamic trade space analysis methodology would be a useful tool for informing such requests. See Joint Requirement Oversight Council (2013).

[7] For alternate definitions, see Ferguson, Siddiqi, Lewis, and de Weck, 2007.

[8] For a discussion of possible states within the same mission space, see Conley and Tillman, 2012.

between these terms and the traditional acquisition parlance of performance (*potential*), dollar cost, and schedule.

Assessing and Designing for Adaptability

Weapon systems and platforms typically remain in service for long periods, during which change often occurs—some of which is manageable and some not. Routinely dynamic international, operational, and fiscal environments should encourage the DoD to assess the adaptability of its current and planned weapon systems and ensure that future systems are designed to facilitate adaptation to changing circumstances.

Assessing and designing for adaptability should not be confused with doing so for robustness.[9] Even though each concept refers to the ability of a system to handle change, the nature of the change as well as the system's reaction to it in each case is very different. Adaptability implies the ability of a design to satisfy *changing requirements*, whereas robustness involves satisfying a *fixed set of requirements* despite changes in the system's operating environment (Saleh, Hastings, & Newman, 2003). An adaptable design is an active way to deal with future mission and/or operating environment uncertainty, as it includes core design resource margins assessed as most likely to be relevant across a wide range of potential futures. This approach is intended to minimize risks and maximize opportunities. Conversely, a robust design is passive, as it focuses on a system performing a fixed set of requirements satisfactorily regardless of the future environment (de Neufville & Scholtes, 2011, pp. 6, 39).

Framework for Assessment and Design

Designing for adaptability requires discussions—early in the capability development process—of mission requirements (i.e., capabilities), design resources, technical limitations, operational constraints, dollar costs, and their coupling to physical and engineering relationships. These factors comprise a high-order framework that can also be used for assessing the adaptability of current and in-development systems. Why these factors? System capabilities (e.g., range, speed, payload, force protection, probability of kill) depend on how design resources (e.g., internal volume, weight, power) are consumed and supplied by physical subsystems (e.g., engine, armor, fuel) and operational constraints (e.g., transportability weight limit, high hot limits) and are further bounded by fiscal constraints. These factors, while few in number, comprehensively describe a system from both a user and technical perspective. Their relationships are illustrated in Figure 1.

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[9] Designing for adaptability should also not be confused with designing for an incremental acquisition approach to support an evolutionary acquisition (EA) strategy. In EA, a fixed requirement is met over time by developing several increments, each dependent on available mature technology. See Enclosure 2 of OUSD(AT&L), 2008.

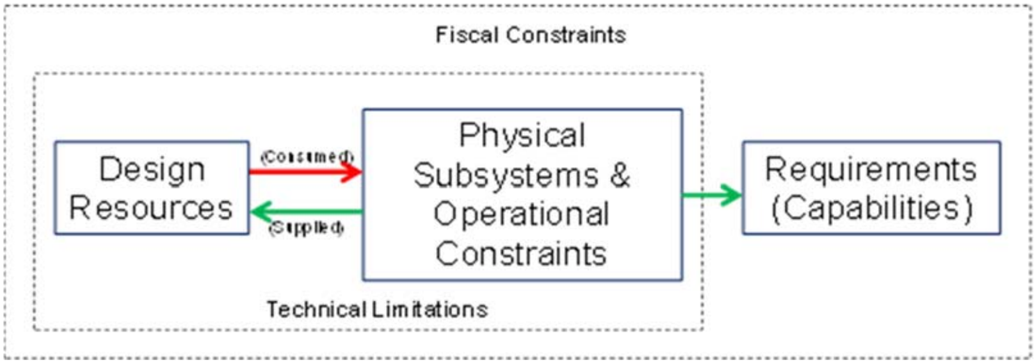


Figure 1. Relationships Comprising the Framework

Capability envelopes and adaptability draw from the same reservoir, (i.e., design resources and operational constraints). Consider, as an example, the potential adaptability and flexibility of a nominal infantry fighting vehicle (IFV) initially developed to support a cross-country terrain mission. The measure of adaptability will be the number of potential missions the vehicle could support, with a specific focus on assessing adaptability for urban operations. The measure of flexibility will be the dollar costs and tolerability of capability trades required in order to adapt.

Because this nominal vehicle was intended to traverse quickly across wide-open terrain, its original design sacrificed force protection for speed and range. Using the vehicle in urban operations would require significantly more force protection, thus requiring up-armoring. It is assumed that there are numerous bolt-on armor kits available at reasonable dollar cost that would satisfy this need; however, utilizing such kits would, in turn, consume additional *weight* and *power* design resources. That consumption would then result in reduced vehicle speed and range (capability tradeoffs).

The vehicle in this example could be assessed as adaptable, flexible, and responsive with regard to urban operations missions:

- Adaptable: the vehicle had unutilized design resources (*weight* and *power*) that enabled up-armoring to provide additional force protection required for a new mission (urban operations).
- Flexible: the dollar cost and capability tradeoff cost of adapting—force protection for speed and range—were reasonable and tolerable.
- Responsive: applying bolt-on armor is not a time-intensive activity.

The example highlights the fact that assessing adaptability is necessary, but not sufficient, for making decisions regarding potential system modifications/reconfigurations or initial designs. Flexibility and responsiveness should also be considered. Note that when adaptability requires capability tradeoffs, it should not necessarily be construed as negative, as the trades may be considered tolerable or even desirable. In the example, the loss of speed and range was deemed tolerable given the urban operating environment.

Focus on Design Resources

The framework suggests that design resource margins are the appropriate focus for both assessing and designing for adaptability. Why a margins-based approach when others have argued that modularity is the best route for "buying" adaptability? The focus on resource margins was not motivated by analytical or engineering preference; rather, it was driven by current defense strategic guidance and a review of the DoD's recent capability development and acquisition history.

Current guidance calls for developing “cutting edge” technical capabilities. This is not new guidance, as DoD has historically developed systems with the objective of achieving superior technical performance. But its implications are significant from an engineering perspective. Superior technical performance comes from integral designs, not modular ones. There is wide agreement on this point across engineering communities. Modularity comes with technical performance costs; it tends to favor “business performance” over technical performance (Holtta-Otto & de Weck, 2007; Whitney, 2004). It is not surprising, then, that a review of recent MDAPs (including some in the design phase) showed an overwhelming majority of the programs were/are being designed as highly complex, highly capable, integrated-architecture systems—for example, the F-22, F-35, DDG-51 Flight III, and GCV.

From an assessment perspective, then, the systems populating the assessment sample are almost entirely—if not entirely—integral rather than modular. From a design perspective, since it is assumed that the objective of retaining “cutting edge” capability will not be relaxed any time soon, integral designs will likely persist. Design resource margins are the most appropriate metric for measuring adaptability in integral systems and, therefore, are the focus of this approach.

With all of that being said, systems can certainly be designed as integral-modular hybrids. Even in that type of design, however, a focus on design resource margins is most appropriate for assessing or embedding adaptability. It is instructive to consider recent comments on the subject by Chief of Naval Operations Admiral Greenert (2012). In promoting payload modularity, Greenert argued the design of future platforms “must take into account up front the volume, electrical power, cooling, speed, and survivability needed to effectively incorporate new payloads throughout their service lives” (p. 4). Stated differently, the platforms *must be designed with margins* sufficient to handle future payloads.

The remainder of this paper applies the concepts, working definitions, and framework introduced above to the tasks of assessing the adaptability of current and planned weapon systems and supporting dynamic trade space analyses to enable the design of future adaptive systems.

Enhancing or Degrading Adaptability

As mentioned previously, capabilities and adaptability draw from the same reservoir of design resources, and those resources can either be consumed or supplied by physical subsystems. When assessing or designing for adaptability, uncertainty should be considered on the supply side (e.g., the state or trends of technology) as well as the demand side (e.g., the operating environment). On the supply side, it may be that future technological advancements in physical subsystems could supply future design resources to current platforms. For example, lighter armor could supply *weight* margin, and more efficient batteries could supply both *weight* and *internal space* margins. Considering the supply side enables assessments of the contributions that system upgrades would make to the adaptability of the system. Upgrades that consume design resources degrade future adaptability, while those that supply resources enhance it.

Proofs of Concept

Assessing the adaptability, flexibility, and responsiveness of current and in-development systems requires an understanding of mission requirements, key design resources and their utilization, physical subsystems, operational constraints, costs, and their interactions and relationships. In this section, several proofs of concept are offered to illustrate the assessment and design methodologies.

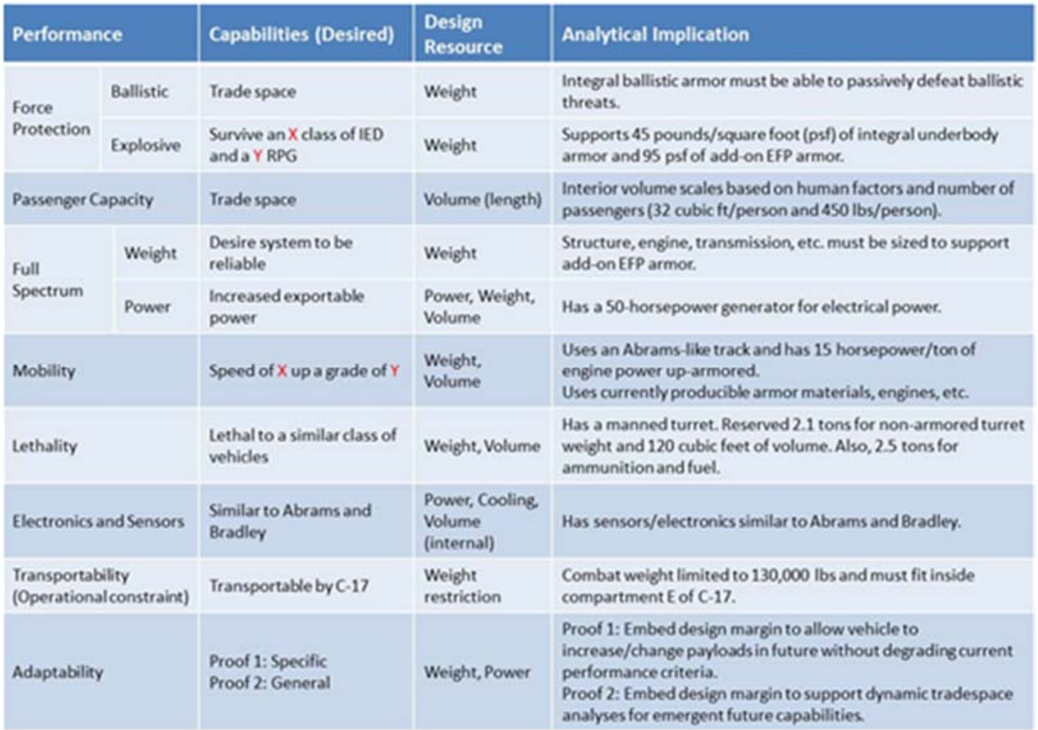
Designing and Dynamic Trade Space Analysis: Proofs of Concept

The approaches to designing for adaptability and supporting dynamic trade space analysis are nearly identical, absent the first item listed below:

- Decide whether the system will be developed to be generally or specifically adaptable. This requires explicit recognition of the level of uncertainty associated with the missions and/or environments in which the system is intended to operate.
- Identify the capabilities desired (and, more directly, the physical subsystems that will provide them) and the associated design resources that are either supplied or consumed by them.
- Develop a physics-based understanding of the interaction between capabilities desired, physical subsystems, and design resources.
- Identify operational constraints that limit performance.
- Identify costs.

In this section of the paper, a nominal IFV will be used to present two proofs-of-concept. The first example will demonstrate how adaptability can be rigorously considered in the design of a system. It will also highlight an important issue not yet addressed in our design discussion—strategic value versus tactical cost. The second example will illustrate a more complex dynamic trade space analysis. These proofs-of-concept offer stark examples of how adaptability and capability draw from the same reservoir (i.e., design resources and operational constraints). Table 1 details basic performance and technical assumptions that will be used in both proofs. The cells labeled “Trade space” in the Capabilities (Desired) column will be the focus of the dynamic trade space analysis.

Table 1. Nominal IFV Performance and Technical Assumptions



Performance		Capabilities (Desired)	Design Resource	Analytical Implication
Force Protection	Ballistic	Trade space	Weight	Integral ballistic armor must be able to passively defeat ballistic threats.
	Explosive	Survive an X class of IED and a Y RPG	Weight	Supports 45 pounds/square foot (psf) of integral underbody armor and 95 psf of add-on EFP armor.
Passenger Capacity		Trade space	Volume (length)	Interior volume scales based on human factors and number of passengers (32 cubic ft/person and 450 lbs/person).
Full Spectrum	Weight	Desire system to be reliable	Weight	Structure, engine, transmission, etc. must be sized to support add-on EFP armor.
	Power	Increased exportable power	Power, Weight, Volume	Has a 50-horsepower generator for electrical power.
Mobility		Speed of X up a grade of Y	Weight, Volume	Uses an Abrams-like track and has 15 horsepower/ton of engine power up-armored. Uses currently producible armor materials, engines, etc.
Lethality		Lethal to a similar class of vehicles	Weight, Volume	Has a manned turret. Reserved 2.1 tons for non-armored turret weight and 120 cubic feet of volume. Also, 2.5 tons for ammunition and fuel.
Electronics and Sensors		Similar to Abrams and Bradley	Power, Cooling, Volume (internal)	Has sensors/electronics similar to Abrams and Bradley.
Transportability (Operational constraint)		Transportable by C-17	Weight restriction	Combat weight limited to 130,000 lbs and must fit inside compartment E of C-17.
Adaptability		Proof 1: Specific Proof 2: General	Weight, Power	Proof 1: Embed design margin to allow vehicle to increase/change payloads in future without degrading current performance criteria. Proof 2: Embed design margin to support dynamic tradespace analyses for emergent future capabilities.

Designing for Specific Adaptability: Force Protection

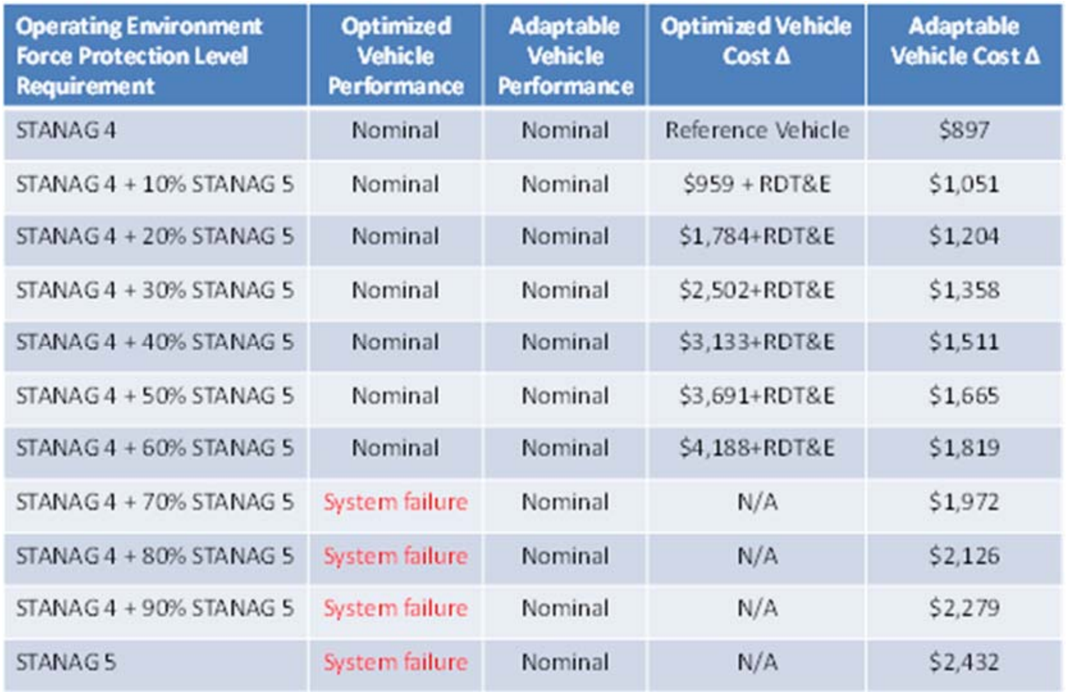
This proof explores potential vehicle designs that could enable future increases in ballistic force protection, thereby ensuring the IFV will remain operationally effective in increased-threat environments. It is assumed that a number of alternative futures have been assessed, resulting in a bounded range of potential force protection requirements—STANAG Level 4 to STANAG Level 5.

For any potential design considered in this proof, the performance objectives listed in Table 1 (e.g., mobility and reliability) must not be compromised if/when future upgrades to the vehicle occur. A design that supports adaptability to increase passive armor in the future must ensure now that the *weight* design resource is properly calibrated and supplied to enable this future addition. The primary physical subsystems that supply the *weight* resource are suspension and structure (see the Full Spectrum row in Table 1). *Weight* also interacts with the mobility requirement and drives the engine size.

Referring back to the bulleted items that constitute the approach to designing for adaptability, the first three have been satisfied: specific adaptability was selected; desired capabilities and their associated physical subsystems and design resources were identified; and the interactions between them were understood. The remaining two items are addressed as follows: it is assumed that the C-17 will remain the heavy airlift vehicle for the foreseeable future; therefore, the transportability *weight* limit of the C-17 will be considered an operational (and, therefore, design) constraint. Regarding cost assumptions, see Patel and Fischerkeller (2013).

Two vehicle designs were considered, to illustrate the relationships between their relative adaptability, flexibility, and responsiveness. One ("Optimized Vehicle") represents a vehicle designed optimally to support the lower bound force protection requirement—STANAG 4—with no margin incorporated for bolt-on armor upgrades to increase the force protection level. The other ("Adaptable Vehicle") represents a vehicle designed (with regard to suspension and structure) to supply the maximum possible weight design margin to support the addition of future force protection capability; in effect, it was designed to support bolt-on steel armor upgrades to increase force protection to the upper bound force protection requirement—STANAG 5. Table 2 shows the comparisons.

Table 2. Performance and Relative 100th Unit Procurement Costs ($K of BY2012)—Optimized vs. Adaptable Designs



Operating Environment Force Protection Level Requirement	Optimized Vehicle Performance	Adaptable Vehicle Performance	Optimized Vehicle Cost Δ	Adaptable Vehicle Cost Δ
STANAG 4	Nominal	Nominal	Reference Vehicle	$897
STANAG 4 + 10% STANAG 5	Nominal	Nominal	$959 + RDT&E	$1,051
STANAG 4 + 20% STANAG 5	Nominal	Nominal	$1,784+RDT&E	$1,204
STANAG 4 + 30% STANAG 5	Nominal	Nominal	$2,502+RDT&E	$1,358
STANAG 4 + 40% STANAG 5	Nominal	Nominal	$3,133+RDT&E	$1,511
STANAG 4 + 50% STANAG 5	Nominal	Nominal	$3,691+RDT&E	$1,665
STANAG 4 + 60% STANAG 5	Nominal	Nominal	$4,188+RDT&E	$1,819
STANAG 4 + 70% STANAG 5	System failure	Nominal	N/A	$1,972
STANAG 4 + 80% STANAG 5	System failure	Nominal	N/A	$2,126
STANAG 4 + 90% STANAG 5	System failure	Nominal	N/A	$2,279
STANAG 5	System failure	Nominal	N/A	$2,432

The performance columns in Table 2 show that both vehicles perform equally well up through an operating environment requiring a force protection level of STANAG 4 + 60% STANAG 5. They do so, however, through very different means. While both vehicles carry steel armor at STANAG 4, the Optimized Vehicle's force protection capability is increased by replacing steel with titanium armor. This must be a zero-sum weight exchange because the optimized vehicle was not designed to carry additional weight. Conversely, the Adaptable Vehicle was designed to carry additional weight and has its force protection capability increased through additional bolt-on steel armor. At STANAG 4 + 70% STANAG 5, the maximum weight the Optimized Vehicle can carry is exceeded, resulting in system failure. This is not the case for the Adaptable Vehicle. Not only can it still operate effectively in that environment, it can also accommodate additional bolt-on steel armor to operate effectively up to STANAG 5.

Flexibility is captured in the chart via the relative (Δ) cost columns. At STANAG 4, the Optimized Vehicle has a lower relative unit procurement cost, however, as requirements increase, costs increase sharply relative to the Adaptable Vehicle because more expensive titanium armor is needed to maintain desired mobility and reliability. Embedding adaptability made for a more flexible vehicle, as its upgrade costs are less sensitive to changes in requirements.

Finally, inferred but not captured directly in this chart is responsiveness. Steel armor must be stripped before titanium armor is applied to the Optimized Vehicle. This is far more time-intensive than bolting on steel to the Adaptable Vehicle. The Adaptable Vehicle, then, is more responsive.

Designing for General Adaptability: Dynamic Trade Space Analysis

This general adaptability proof illustrates a far-wider range of possible system adaptations and their dependencies. The technical and cost assumptions presented for the nominal IFV (Table 1) will again be used in this proof. This analysis will assume that an adaptable IFV is designed with a 20% *weight* margin, 100% *electrical power* margin, and a 33% *power* margin relative to the optimized design, to support future unspecified capabilities for currently unknown missions and operating environments. *Weight* and *power* were selected because they dominate the design, as can be seen in their relevance to nearly every capability desired in Table 1. *Power*, in particular, was selected because experience tells that it can be traded in the future to support many different types of capabilities either directly or indirectly. As such, it is a core design resource that supports adaptability to many potential futures. As before, the performance objectives highlighted in Table 1 (e.g., mobility, reliability, and transportability) must not be compromised in any potential design.

In order to illustrate one iteration of a dynamic trade space analysis, Figure 2 shows the cost, force protection, number of dismounts carried, and urban accessibility (percent of urban areas accessible) trade space for a vehicle designed with a 20% *weight* margin. This is a high-order analysis, a level at which adaptable design analyses should commence. The models behind this analysis are typically called *screening models* and represent simple, transparent, and readily understandable representations of the physical interactions of the physical subsystems.[10] Screening models allow numerous iterations, to consider potential adaptable designs relatively quickly. They provide the ability to explore the art of the possible with minimal expense (time and dollars). The time for more complex, engineering point models is later in the design phase, not sooner (de Neufville & Scholtes, 2011).

This dynamic trade space analysis illustrates a number of opportunities for consumption of that 20% *weight* margin in the future. For example, high urban accessibility would come at the cost of squad size and force protection.

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[10] The Institute for Defense Analyses has created a suite of screening models for GCV analysis. They were the basis for analyses presented in Figure 1.

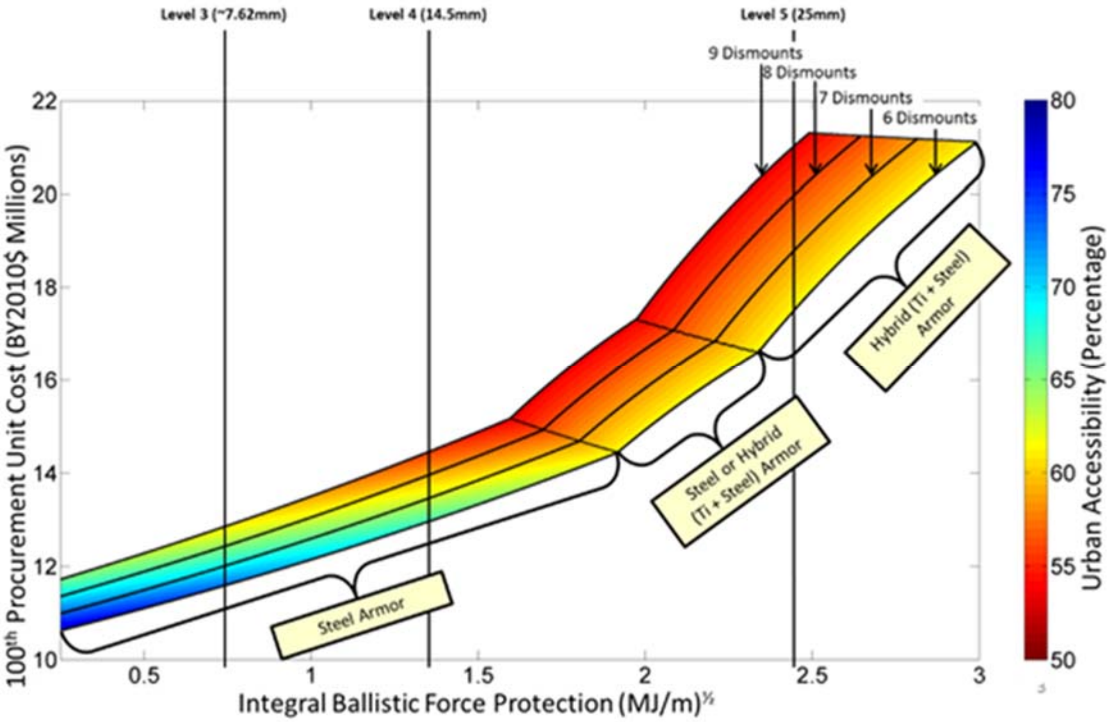

Figure 2. Dynamic Trade Space Analysis Supported by General Adaptability Design

Additional high-order analyses are also possible. Perhaps the 100% *electrical power* margin could be used for additional sensors and electronics. Would that affect internal volume available for dismounts? Would that additional weight consumption constrain future armor choices? Should mobility or transportability be traded? And so on. The multitude of questions one could ask is, again, a strong motivation for using these low-resolution analytical tools iteratively at the outset of the design process.

Strategic Value Versus Tactical Cost

The above analysis introduces an important aspect of designing for adaptability—*strategic value* versus tactical cost (i.e., nominal program costs). Equating the two, especially when planning for an uncertain environment, is a mistake. While the relative costs of the Optimized Vehicle at STANAG 4 are less, should future emergent threats demand higher force protection, the costs of up-armoring (and concomitant capability tradeoffs) arguably decrease its strategic value compared to that of the Adaptable Vehicle.[11]

As with insurance, the *strategic value* of a system should be assessed in terms of its contributions over all possible futures. Insurance and adaptability are justified by the value

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[11] Our example assumed a smooth design and development process. Often, however, requirements are changed post-Milestone B, which leads to cost growth. This cost is not considered in the example. In reality, then, it may very well be that tactical costs for optimized and adaptable platforms are often comparable as changes in requirements could more easily be addressed by adaptable designs (see GAO, 2011, pp. 14–15; Bolten et al., 2008).

they bring when relevant events occur, not by their continual use (de Neufville & Scholtes, 2011, p. 11). If we consider a “relevant event” as a future circumstance that requires the specification of new system requirements, several such events inevitably occur over the service lives of systems as new technologies or new threats emerge. At the right price, we willingly buy insurance as a hedge against uncertain future events. So, too should DoD as it faces an uncertain future. But how can decision-makers determine whether the price for adaptability is reasonable? Figure 3 illustrates a decision support chart that was constructed using the optimized and adaptable vehicle cost data presented in Table 2.

Selecting either an adaptable or optimized system is a “bet” on future trends rather than any one specific outcome. For this example, selecting adaptability is a “bet” that future adversaries will employ capabilities that would require significantly more force protection than is required in current systems. Conversely, selecting an optimized design is a “bet” that future adversaries will not employ capabilities that would require significant changes to current force protection levels.

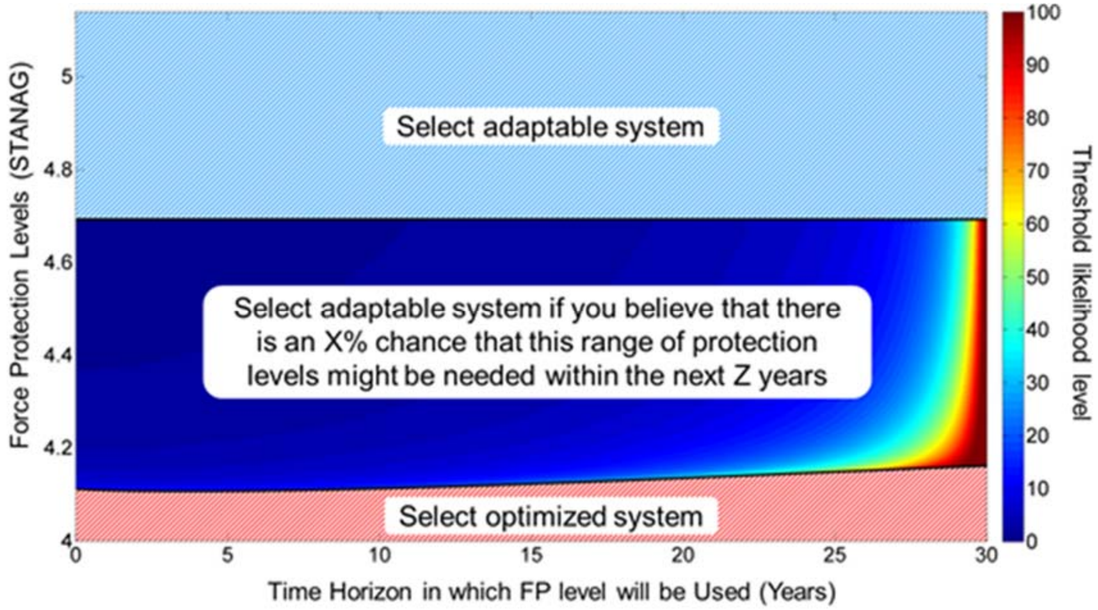

Figure 3. Capability Development and Acquisition Decision Support Chart

The following examples, constructed from referencing Figure 3, illustrate how the chart can *quantitatively* inform capability development and acquisition decisions. Specifically, we can describe the “bet” that leadership is making in more quantitative and rigorous terms.

An *adaptable* system provides the greatest strategic value if:

- Leadership is *confident* there is *at least a small chance* that adversaries will employ capabilities that would require force protection levels above STANAG 4.1, or
- The weight margin can be utilized for other emergent requirements.

An *optimized* system provides the greatest strategic value if:

- Leadership is *confident* that there is a *high chance* that adversaries will not employ capabilities that would require force protection levels above STANAG 4.1.

Costs from Table 2 are embedded in Figure 3 via a present value (PV) analysis of the optimized and adaptable systems. The Confidence Level contours (color code) represent the minimum annualized probability at which the adaptable system provides more value (e.g., lower PV).

The approach taken to create Figure 3 can be replicated to create similar capability development and acquisition support tools for other systems. It enables decision-makers to explicitly account for uncertainty in their choices and review the consequences of that accounting. While preferably brought to bear sooner, such an approach would be very beneficial at the Analysis of Alternatives decision point.

Which Resource Margins and How Much?

Effective implementation of a margin-based approach to designing adaptability into weapon systems requires *choosing which design resources* should be allocated margin (or not) and *calculating the size* of that margin such that additional system value in future uncertain environments could be realized by consuming (or supplying) them in those environments.

The designing-for-adaptability process presented previously informs resource margin decisions. In the proofs-of-concept, the capabilities were fixed values and the type and value of margin were known (the design resource of *weight* with the percentage of 20). In actual dynamic trade space analysis, all should be considered potential variables whose values (and also types, in the case of margins) would be determined for a final design through numerous exploratory analyses. Numerous iterations allow the analysts, operators, and other stakeholders opportunities to consider many different approaches to a design that satisfies known requirements and enables adaptability for unknown future requirements. The creative value of multiple iterations cannot be overstated and again, highlights the importance of using low-resolution screening models early in the design process.

As trade space within and across capabilities and margins is being explored, Key Performance Parameters (KPPs) grounded in long-term forecasts in which confidence is moderate to low should be considered first for trade as the design team seeks to embed a margin for potential future requirements. One need only perform a cursory review of a handful of System Threat Assessment Reports (STARs) to see several examples of moderate and low confidences being cited. Returning to a point made earlier, routine failures to accurately forecast futures should engender modesty. That modesty can be operationalized as design margins to increase the potential strategic value of a platform. A similar perspective could be taken when reviewing KPP threshold (required) and objective (desired) values. To the degree the differences in those values are based on different levels of confidence in near- vs. long-term forecasts, that delta should be considered trade space—plan for the relative certainty, prepare for the uncertainty.

This approach can and should, where appropriate, be complemented by experience. For example, the Navy incorporates power margins on ships as part of their service life allowances based largely on historical experience. Similarly, based on mission experience, the National Aeronautics and Space Administration (NASA) incorporates into all flight systems a 10% margin for power and 5° C thermal design margin to respond to post-launch uncertainties associated with the mission and environment, respectively (NASA, 2009, pp. 13, 82).

Conclusion

Adaptability, flexibility, responsiveness—these terms need not be empty descriptors of the force desired by the White House and the DoD. They can be operationalized as metrics against which the force can be assessed and towards which it can be designed. Current operational and fiscal realities call for an approach to enable those efforts. Absent one, the DoD risks stumbling forward into an uncertain strategic and operational future, possibly making significant force structure, modernization, and future weapon system design decisions that, at a minimum, do nothing to enhance the force's adaptability and could, quite possibly, facilitate its degradation.

A general utilization assessment of the current force's major systems' design margins would offer insights into the potential for adaptability to emergent circumstances in an uncertain future environment. A more focused look at those margins deemed most relevant to future missions and operating environments in which high confidence exists also would yield valuable and actionable insights.

Designs for incremental modernization programs or entirely new weapon systems, which are expected to be in the field for decades, should explicitly incorporate adaptability. When considering upgrades or new designs, the perspective of strategic value vs. tactical cost should rule the day. It was noted previously that the DSB recommended an adaptability requirement for all future systems. The DoD enterprise is populated by systems engineers, operators, and other stakeholders who are both intelligent and fallible; consequently, unanticipated threats and opportunities often emerge late in the course of development (post-Milestone B) and long after initial fielding. But changes in requirements need not be as cost-imposing as they often are; adaptable designs could provide opportunities to apply those costs toward achieving greater strategic system value by enabling systems to be modified to execute currently unknown missions and operate in currently unknown environments. Where uncertainty is abundant, an adaptability requirement should be non-negotiable—it must be a "need-to-have," not a "nice-to-have."

Preparing for an uncertain future is not an insurmountable challenge for the DoD. Significant RDT&E and procurement decisions that take adaptability into account can be informed by rigorous analyses and assessments. We hope this paper has offered useful concepts, working definitions, and approaches to inform an intelligent path forward that enables the DoD to prepare to be wrong.

References

Bolten, J. G., Leonard, R. S., Arena, M. V., Younossi, O., & Sollinger, J. M. (2008). *Sources of weapon system cost growth: Analysis of 35 Major Defense Acquisition Programs.* Santa Monica, CA: RAND.

Burns, W. R., Jr., & Freeman, W. D. (2010). *Developing more adaptable individuals and institutions* (IDA Paper P-4535). Alexandria, VA: Institute for Defense Analyses.

Conley, K., & Tillman, M. (2012). *The agility imperative* [Briefing]. Alexandria, VA: Institute for Defense Analyses.

de Neufville, R., & Scholtes, S. (2011). *Flexibility in engineering design*. Cambridge, MA: MIT Press.

Defense Science Board (DSB). (2011). Enh*ancing adaptability of U.S. Forces Part A: Main report*. Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics.

Dempsey, M. E. (2012). *Mission command white paper*. Washington, DC: DoD.

Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD[AT&L]). (2008). *Operation of the Defense Acquisition System* (DoDI 5000.02). Enclosure 2. Washington, DC: Author.

Ferguson, S., Siddiqi, A., Lewis, K., & de Weck, O. (2007, September). *Flexible and reconfigurable systems: Nomenclature and review.* Paper presented at 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2007), American Society of Mechanical Engineers, Las Vegas, NV.

GAO. (2011). *Defense acquisitions: Assessments of selected acquisition programs* (GAO-11-233SP). Washington, DC: Author.

Gray, C. S. (2008–2009, Winter). The 21st century security environment and the future of war. *Parameters*, 14–26.

Greenert, J. W. (2012, July). Payloads over platforms: Charting a new course. *Proceedings Magazine, 138/7/7*, 313.

Holtta-Otto, K., & de Weck, O. (2007). Degree of modularity in engineering systems and products with technical and business constraints. *Concurrent Engineering: Research and Applications, 15*(2), 113–26.

Joint Requirement Oversight Council. (2013). *Key performance parameter relief* (JROCM 015-13) [Memorandum]. Washington, DC: Author.

National Aeronautics and Space Administration (NASA). (2009). *Rules for the design, development, verification, and operation of flight systems* (NASA GSFC-STD-1000E). Greenbelt, MD: Author.

Office of the Secretary of Defense. (2012). *Sustaining U.S. global leadership: Priorities for 21st century defense.* Washington, DC: DoD.

Patel, P. R., & Fischerkeller, M. P. (2013). *Prepare to be wrong: Assessing and designing for adaptability, flexibility, and responsiveness* (IDA Paper P-5005). Alexandria, VA: Institute for Defense Analyses.

Saleh, J. H., Hastings, D. E., & Newman, D. J. (2003, December). Flexibility in system design and implications for aerospace systems. *Acta Astronautica, 53*(12), 927–944.

Whitney, D. E. (2004). *Mechanical assemblies: Their design, manufacture, and role in product development*. New York, NY: Oxford University Press.

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