



Defense Acquisition Research Journal

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The Art of Managing Choices

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Better Buying Power or Better Off Not? Purchasing Technical Data for Weapon Systems

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In September 2010, then-Under Secretary of Defense for Acquisition, Technology and Logistics Ashton Carter directed program managers to routinely analyze the business cases behind procuring the technical data packages and rights to new weapon systems. In this article, the author recounts some of the historical difficulties with procuring technical data for fielded systems, and presents a heuristic economic model outlining the problems that PMs should consider before making an offer.

Initial Capabilities Documents: A 10-Year Retrospective of Tools, Methodologies, and Best Practices

*Maj Bryan D. Main, USAF, Capt Michael P. Kretser, USAF,
Joshua M. Shearer, and Lt Col Darin A. Ladd, USA*

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The Joint Capabilities Integration & Development System (JCIDS) is 10 years old and ripe for review. A central output document of the JCIDS process is an Initial Capabilities Document (ICD) used by the Department of Defense to define gaps in a functional capability area and define new capabilities required. The research team analyzed 10 years of ICDs to identify methods and trends. The team found that several methodologies were favored and a convergence emerged in format and necessary content. Additionally, potential shortfalls in current best practices of interest to implementers and decision makers are identified. Guidelines and best practices are presented to create more effective, concise, and complete ICDs.

A Proposed 2025 Ground Systems “Systems Engineering” Process

Robert E. Smith and LTC Brian D. Vogt, USA

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The U.S. Army’s mission reflects a strong impetus to provide flexible and adaptable ground vehicles that are rapidly fieldable. Emerging manufacturing technology, such as three-dimensional printing, is making mass customization possible in commercial industry. If the Army could produce tailored military ground vehicles that incorporate mission-specific tactics, it would outperform generic systems. To produce such systems, a new systems engineering (SE) process should be developed. Virtual environments are central to the proposed SE/2025 process because they provide a sandbox where soldiers and engineers might directly collaborate to codevelop tactics and technologies simultaneously. The authors’ intent is to describe how ground vehicle systems might be developed in 2025 as well as to describe current efforts underway to shape the future.

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From the Chairman and Executive Editor

The theme for this edition of the *Defense Acquisition Research Journal* is “The Art of Managing Choices,” as the articles contained herein provide tools, techniques, and even food for thought when it comes to decision making.

The first article, “Valuation of Real Options as Competitive Prototyping in System Development,” by Diana I. Angelis; David N. Ford; and COL John T. Dillard, USA (Ret.), explains how the use of a financial tool called the real option valuation model can be used to evaluate choices for major weapons systems, despite the lack of monetary-based benefits. In the second article, “Better Buying Power or Better Off Not? Purchasing Technical Data for Weapon Systems,” James Hasik proposes an economic model that will allow program managers to price technical data packages, to help choose whether and how to purchase them.

“Initial Capabilities Documents: A 10-Year Retrospective of Tools, Methodologies, and Best Practices” by Maj Bryan D. Main, USAF; Capt Michael P. Kretser, USAF; Joshua M. Shearer; and Lt Col Darin A. Ladd, USAF, distills the methodologies, format, and necessary content that decision makers and implementers favor to create more effective, concise, and complete Initial Capabilities Documents. Rounding out this edition, in “A Proposed 2025 Ground Systems ‘Systems Engineering’ Process,” the authors Robert E. Smith and LTC Brian D. Vogt, USA, argue that virtual environments and new manufacturing methods will be key to decision making in the 21st century, allowing soldiers and engineers to codevelop tactics and tailored ground systems.



The featured book in this issue's Defense Acquisition Professional Reading List is the provocatively titled *Grounded: The Case for Abolishing the United States Air Force* by Robert M. Farley, which argues for a game-changing choice regarding the DoD's newest Service. Aleisha R. Jenkins-Bey, assistant editor for the *Defense Acquisition Research Journal*, reviewed the book.

Finally, I encourage prospective authors to consider submitting their manuscripts for the Defense Acquisition University Alumni Association's 2015 Acquisition Symposium, following the guidelines in the Call for Papers in this issue. The deadline for submission is December 5, 2014.



Dr. Larrie D. Ferreiro
Executive Editor
Defense ARJ



DAU Center for Defense Acquisition Research

Research Agenda 2014

The Defense Acquisition Research Agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broader defense acquisition community throughout the government, academic, and industrial sectors. The purpose of conducting research in these areas is to provide solid, empirically based findings to create a broad body of knowledge that can inform the development of policies, procedures, and processes in defense acquisition, and to help shape the thought leadership for the acquisition community.

Each issue of the Defense ARJ will include a different selection of research topics from the overall agenda, which is at: <http://www.dau.mil/research/Pages/researchareas.aspx>

Affordability and cost growth

- Define or bound “affordability” in the defense portfolio. What is it? How will we know if something is affordable or unaffordable?
- What means are there (or can be developed) to measure, manage, and control “affordability” at the program office level? At the industry level? How do we determine their effectiveness?
- What means are there (or can be developed) to measure, manage, and control “Should Cost” estimates at the Service, Component, program executive, program office, and industry levels? How do we determine their effectiveness?
- What means are there (or can be developed) to evaluate and compare incentives for achieving “Should Cost” at the Service, Component, program executive, program office, and industry levels?

- 
- Recent acquisition studies have noted the vast number of programs and projects that do not make it successfully through the acquisition system and are subsequently cancelled. What would systematic root cause analyses reveal about the underlying reasons, whether and how these cancellations are detrimental, and what acquisition leaders might do to rectify problems?
 - Do Joint programs—at the inter-Service and international levels—result in cost growth or cost savings compared with single-Service (or single-nation) acquisition? What are the specific mechanisms for cost savings or growth at each stage of acquisition? Do the data support “jointness” across the board, or only at specific stages of a program, e.g., only at research and development or only with specific aspects, e.g., critical systems or logistics?
 - Can we compare systems with significantly increased capability developed in the commercial market to DoD-developed systems of similar characteristics?
 - Is there a misalignment between industry and the government priorities that causes the cost of such systems to grow significantly faster than inflation?
 - If so, can we identify why this misalignment arises? What relationship (if any) does it have to industry’s required focus on shareholder value and/or profit, versus the government’s charter to deliver specific capabilities for the least total ownership costs?

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Keywords: *Real Options Valuation Model, Real Options Theory, Analysis of Alternatives, Technology Development, Javelin*

Valuation of Real Options as Competitive Prototyping in System Development

 *Diana I. Angelis, David N. Ford, and
COL John T. Dillard, USA (Ret.)*

A Real Options Valuation Model is developed to recommend how to value technology when benefits cannot be measured in monetary value. Expected values of effectiveness are used to select the preferred alternative. The methodology is illustrated using three guidance system technologies in the Army's Javelin program. The strategy created multiple real options that gave the Army the right (without the obligation) to select one guidance system technology based on the outcome of technology development tests. Results indicate the Army paid less than the total value of the options, but could have increased net savings by paying different amounts to test each alternative. The analysis method provides a logical and defensible approach to the analysis of alternatives under technology development uncertainty.

Real options can be described along several dimensions, including ownership, the source of value, complexity, and the degree to which the option is available.

Competitive prototyping along the path of technology development has long been an important aspect of acquisition program strategies. Emphasis in this method reemerged in policy documents again in 2007 as a way to reduce technical, cost, and schedule risk by leveraging the economic forces of competition and innovation diversity (Young, 2007). Academics understand these fundamentals and their multiple benefits as “real options.” This article describes the application of a Real Options Valuation Model to the three candidate guidance technologies during the early development of the Javelin anti-tank missile system. A short introduction to Real Options Theory is followed by a description of the Javelin guidance technology options. Next, a model for measuring the effectiveness of the three guidance technologies is presented and the cost effectiveness of each alternative based on “cost per kill” under deterministic and probabilistic assumptions examined. Finally, a decision tree approach is used to model the value of each option, given the probability of success and the costs to recover from failure.

Real Options

Real Options Theory is one means of structuring and valuing flexible strategies to address uncertainty (Courtney, Kirkland, & Viguerie, 1997). An option is a right without an obligation to take specific future actions depending on how uncertain conditions evolve (Brealey & Meyers, 2000). Real options apply Real Options Theory to tangible assets. The central premise of Real Options Theory is that, if future conditions are uncertain and changing the strategy later incurs substantial costs, then having flexible strategies and delaying decisions can add value when compared to making all strategic decisions during preproject planning (Amram & Kulatilaka, 1999a, 1999b). By providing managers with tools to respond to changing conditions, real options can increase benefits, limit costs, or both. When used to limit costs of development programs such as in the current work, real options are a form of risk management.

The design of an option compares one or more alternative strategies that may be used in the future to a reference strategy that is committed to in the present. To use an option, conditions are monitored and potentially converted into a signal that is compared to trigger conditions using an Exercise Decision Rule. The result is a recommendation on whether to abandon the reference strategy and adopt the alternative strategy (to “exercise” the option) or to keep using the reference strategy. For example, in stock purchase options, the Exercise Decision Rule is to buy a stock if the price rises above a certain price and the exercise signal is the stock price. The decision delay is incurred while the option holder waits to see if the stock price rises above the exercise price. Options help managers learn by having them wait to see (through monitoring) how uncertainty evolves, thereby helping them make better choices. Therefore, delayed decision making is an important feature of real options. To use real options, one must define the exercise signal and exercise decision in the context of a set of observable variables and the exercise of the option in operational terms.

Real options can be described along several dimensions, including ownership, the source of value, complexity, and the degree to which the option is available. A common topology categorizes real options according to the type of managerial action applied, including options that postpone (holding and phasing options), change the amount of investment (growth, scaling, and abandonment options), or alter the form of involvement (switching options). The study of real options can focus on the monetary valuation of the flexibility or on the design and impacts of real options on decision making in practice (managerial real options). Both of these aspects of real options can improve program management and add value. Although some real options can be purchased and exercised at low cost (e.g., the option to have salaried employees work overtime), decisions about real options become challenging when significant costs are required to obtain, maintain, or exercise the flexibility that may add value. The option cost is what must be paid to acquire the flexibility to change the strategy. Option maintenance costs include benefits lost by delaying the decision and costs to keep the flexibility available. Option exercise costs are the costs of changing the strategy. A wide variety of mathematical models have been developed to estimate the monetary value of options. These models use the characteristics of the asset and the benefits and costs of an option to estimate its value. Option valuation began with efforts to price options on financial assets (e.g., shares of stock, bonds) and other market-traded assets. Initially,

closed-form solutions to very specific situations with stringent limits were developed (e.g., Black & Scholes, 1973). Later models, such as the binomial lattice model (Cox, Ross, & Rubinstein, 1979), were developed that could be used to value a wider variety of options and assets.

Real Options Valuation Models have been effectively used to demonstrate how real options can increase project value, including through engineering design....

The valuation of real options differs from that of financial options in that the underlying assets are real assets that are often not traded and represent, for example, contingent decisions to delay, abandon, expand, contract, or switch project components or methods. Conventionally, researchers have estimated the value of real options based on approaches used to value financial options. Real options valuation methods have been developed and analyzed (Borison, 2005; Brealey & Meyers, 2000; Dixit & Pindyck, 1994; Kulatilaka, 1995; Lander, 1997; Lander & Pinches, 1998; McDonald, 2006; Quigg, 1993; Teisberg, 1995; Trigeorgis, 1993, 1995, 2005) and used to value strategies in many domains, including specific aspects of product development (Amram & Kulatilaka, 1999a; Brennan & Trigeorgis, 2000; Dixit & Pindyck, 1994; Kemna, 1993; Miller & Lessard, 2000; Trigeorgis, 1995). Examples include valuation of options to hedge technology investment risk (Benaroch, 2001), and application to design modularity (Baldwin & Clark, 2000), research and development resource allocation (Sharpe & Keelin, 1998), and maximum price contracts for construction project options (Bounkendour & Bah, 2001). Real Options Valuation Models have been effectively used to demonstrate how real options can increase project value, including through engineering design (Baldwin & Clark, 2000; Ford, Lander, & Voyer, 2002; Park & Herath, 2000; Zhao & Tseng, 2003), testing, and learning through pilot projects (Benaroch, 2001; Sadowsky, 2005), schedule control (Ford & Bhargava, 2006), and financing (Cheah & Garvin, 2008; Ho & Liu, 2002). Other research has demonstrated the application of real options, for example, to natural resources and land development; flexible manufacturing; research, development, and innovation; mergers and acquisitions; leases; and the labor force.

Much of the formal modeling of real options has focused on valuing (in monetary terms) options for specific asset characteristics (e.g., value, uncertainty) and option designs (timing, exercise trigger conditions, and exercise costs). But researchers have identified common modeling assumptions that do not apply to typical product development projects (Lander & Pinches, 1998). Specifically, most Real Options Valuation Models assume that: (a) future asset behavior and value conform to well-defined processes, (b) markets are complete and arbitrage opportunities are available, (c) sources of uncertainty are few and independent, (d) payouts or other costs of delaying decisions are small, and (e) planners have one or few options. None of these assumptions hold well for product development environments, where asset value behaviors are not well-defined or market-based, many sources of uncertainty exist and interact, delaying decisions can be very costly, and planners usually have, practically speaking, unlimited options. In addition, Alessandri, Ford, Lander, Leggio, and Taylor (1999) describe problems posed by assuming that asset performance and option holder activity are independent, when in fact product development option holders (i.e., project managers) purposefully and significantly manipulate the linkages between uncertainties and project values.



In contrast to a focus on option valuation, managerial real options work to improve decision making by structuring risky circumstances faced by practitioners into real options and facilitating option design and implementation. Managerial real options address many of the challenges of using Real Options Valuation Models to improve risk management (Garvin & Ford, 2012; Triantis, 2005). Structuring risk management challenges in development programs as real options requires describing challenges with standard real options parameters and structures (Miller & Lessard, 2000). Thereby, real options can improve managerial understanding of risks and help managers prepare for risk management strategy design (Amram & Kulatilaka, 1999a, 1999b; Bierman & Smidt, 1992; Courtney, et al., 1997; Kensinger, 1988). Potential benefits of real options applied to product development stem from several sources, including: a broader range of strategies considered, a focus on objectives instead of solutions, sensitivity to multiple project futures, more frequent testing of plans, and increased awareness of the value of flexibility (Ford, Lander, & Voyer, 2004).

Consider the example of the use of options to manage technology development risk for the Department of Energy's \$2.4 billion National Ignition Facility (Ceylan & Ford, 2002). The National Ignition Facility (NIF) needed to develop slabs of laser glass to be used in the testing of nuclear weapons and research. Laser glass procurement required the production of high-quality glass slabs called "blanks." No existing glass production technologies could produce the volume of glass blanks needed. The ability of glass firms to develop the required new technologies and the quality of the glass produced if the production technologies were feasible, were very uncertain as were costs and development schedules. Although NIF had relationships with experienced laser glass vendors, none could guarantee successful development within the required time a priori. Therefore, the NIF program managers funded the development of new laser glass production technology. NIF needed a higher likelihood of success than any one vendor could provide, so it chose to hire two firms to simultaneously begin initial development of a technology to produce the blanks and to fund these development efforts in phases. Program managers explicitly incorporated the flexibility to choose at several stages to: (a) continue funding both companies and their technology development, (b) fund only one company going forward, or (c) discontinue funding both companies and explore alternative sources for the blank development. The choice at each stage was based on what the managers had learned about the likelihood of success of the developing firms in meeting expectations (benefits) and the cost of continuing to fund the research

and development. Through real options analysis (but not formal option valuation), NIF managers were able to assess the cost effectiveness of their options at each stage. This analysis assisted managers in project management decision making by providing a reliable decision tool. See Alessandri, et al. (2004), Cao, Ford, and Leggio (2006), and Ceylan and Ford (2002) for more detail and an analysis of the use of real options in managing risk at NIF. The NIF example illustrates the critical role of managerial decision making in the application of real options to risk management in development programs.

Specific and required decisions in the management of risk in an actual development program created the need and opportunity for real options.

The current work integrates the managerial and valuation aspects of real options. Specific and required decisions in the management of risk in an actual development program created the need and opportunity for real options. A simple and intuitive approach is used to estimate the value of options as the difference between the values of the program with and without the options (e.g., by assuming uncertainty impacts future performance versus assuming a single specific and known future). The valuations are used to recommend managerial actions and improve the understanding of the risk and its management.

Javelin Technology Options

Anti-tank weapons have been important to meeting Department of Defense objectives since the appearance of armored vehicles on the modern battlefield in World War I. From the 1960s through 1970s, the M67 90mm recoilless rifle was used as a primary mounted and dismounted infantry weapon against tanks and armored personnel carriers. This weapon was replaced by the DRAGON anti-tank weapon system, introduced in the late 1970s, which had a wired command link that was employed to guide the missile to a target that was optically tracked by the gunner. The DRAGON system was developed in the 1960s as a response to the Soviet development of the AT-3 SAGGER manpack missile system, carried in a fiberglass container about the size of a small suitcase. But the DRAGON system had reliability problems, and limited range and

lethality, and it was difficult for gunners to aim the missile and track the target. In the 1980s, the goal was to replace DRAGON with a weapon with increased range and lethality and less weight (a later requirement emerged for the ability to be launched from inside an enclosure [e.g., buildings and bunkers]). The Advanced Anti-Armor Weapon System–Medium (AAWS–M) project grew into the Javelin anti-tank missile program. Javelin required several emergent technologies in order to successfully attain program requirements. A number of the subsystems were based upon these immature technologies. The target locating and missile guidance subsystems were particularly troublesome technical issues. Three very different technologies—a laser-beam riding (LBR) system, a fiber-optic (FO) guided system, and the forward looking infrared (FLIR) system—were initially considered in a 27-month technology development phase, aimed at not constraining the eventual materiel solution. Each of the three potential technologies generally offered the needed capabilities and represented acquisition options.

The Advanced Anti-Armor Weapon System–Medium (AAWS–M) project grew into the Javelin anti-tank missile program.

Three contractor teams were formed to develop competing prototype guidance technologies for the Javelin. Only one team was to be chosen for follow-on advanced development and then production. Ford Aerospace was teamed with its partner, Loral Systems, offering the LBR missile. Hughes Aircraft was teamed with Boeing, offering an FO guided missile. Texas Instruments was teamed with Martin Marietta, offering an imaging infrared or FLIR missile system. With the LBR system, the gunner identifies the target visually and points a laser beam at the target throughout flight. After launch, the missile continuously corrects its flight to match the line of the laser (to “ride” the laser beam) to the target. The FO system includes a coil of very long and fine optical fiber that connects the launch unit, operated by the gunner, to a camera in the nose of the missile. The gunner flies the missile to the target using a joystick controller device. The FLIR scans the view in front of the gunner and generates a thermal-based image of the target area. Once observed through the Command Launch Unit, or thermal sight, the gunner switches to a staring array in the missile to acquire the target

by narrowing brackets in the viewfinder around the target with a thumb switch. After launch, the missile continuously corrects its flight path using a tracking algorithm that employs optical correlators oriented upon visible and distinct target features.

Each candidate system had specific advantages and disadvantages:

- The Ford/Loral LBR required an exposed gunner and man-in-loop throughout its rapid flight. It was cheapest at an estimated \$90,000 cost per kill—a figure that was comprised not only of average unit production cost estimates, but also reliability and accuracy estimates. It was fairly effective in terms of potential combat utility, with diminishing probability-of-hit at increasing range. Top-attack on armor would be dependent upon precision fusing and detonation, and accuracy of downward-firing explosively formed projectiles from shaped charges.
- The Hughes/Boeing FO guide prototype enabled an unexposed gunner (once launched) and also required man-in-loop throughout its slower flight. It was judged as likely costlier, but less affected by accuracy throughout range with its automatic lock and guidance in its terminal stage of flight, and offered target switching. It was also more gunner training- and learning-intensive, but could attack targets from above, where the armor was thinnest.
- The FLIR prototype offered completely autonomous fire-and-forget flight to target after launch, but was perceived as both the costliest and the most technologically risky alternative. The gunner would only be initially exposed during target engagement. It would be the easiest system upon which to deliver user training and effective to maximum ranges by means of its target acquisition sensor and guidance packages. It used top attack as a more effective means of armored target defeat, but would also have a flat trajectory capability for direct fire against targets under cover of bridges, trees, buildings, etc.

Effectiveness of Technology Options

To choose a technology option, the Javelin development team performed an analysis of alternatives based on the relative benefits and costs of each alternative, (i.e., each alternative’s cost effectiveness). Cost-effectiveness analysis is appropriate whenever dollar values cannot

TABLE 1. ANTI-TANK MISSILE GUIDANCE SYSTEM EFFECTIVENESS

Objective			LBR		FO		FLIR	
Measure	Weight		Value	Score	Value	Score	Value	Score
Lethality		0.3						
P(H)*P(K)**	0.7		5	1.05	4	0.84	7	1.47
Top attack	0.3		6	0.54	7	0.63	9	0.81
Total	1.0							
Tactical Advantage		0.3						
Weight	0.4		9	1.08	5	0.6	3	0.36
Time to engage	0.3		8	0.72	7	0.63	5	0.45
Time of flight	0.2		7	0.42	5	0.3	5	0.3
Redirect capability	0.1		10	0.3	10	0.3	0	0
Total	1.0							
Gunner Safety		0.3						
Required training	0.2		5	0.3	1	0.6	10	0.6
Exposure after launch	0.8		2	0.48	8	1.92	10	2.4
Total	1.0							
Procurement		0.1						
Ease of procurement	1.0		8	0.8	6	0.6	4	0.4
Total	1.0							
MOE (Total)***		1.0		5.69		5.88		6.79

*P(H) = Probability of hit
**P(K) = Probability of kill
***MOE = Measure of effectiveness

be assigned to benefits, as is the case for most defense systems (Office of Management and Budget, 1992). To evaluate the effectiveness of each Javelin guidance system alternative, we use a simple hierarchical model based on the acquisition objectives identified for the anti-tank missile—lethality, tactical advantage, gunner safety, and procurement.¹ Our multiobjective effectiveness model is based on concepts developed in decision science (Buede, 1986; Keeney, 1982; Keeney, 1988). The first three objectives deal with the operational effectiveness of the missile, while the procurement objective recognizes that transaction costs and technology issues make some alternatives easier to procure than others. Under each objective, we can use metrics to measure how well the objective is achieved. The objectives and corresponding metrics (measures) are shown in Table 1. The table also shows the relative importance of objectives and the relative importance of each measure with respect to an objective by the weight assigned to each objective and measure.

The metric values achieved by each technology are converted to a notional value measured on a scale of 0 to 10, indicating the value the Army assigned to the actual level of performance. A notional measure of effectiveness (MOE) achieved by each of the three alternatives is shown at the bottom of Table 1. The scores shown in Table 1 for each metric (measure) are calculated by multiplying the value for the measure times the weight for that measure times the objective weight. The notional MOEs in Table 1 are consistent with the Army's Source Selection Evaluation Board (SSEB) preference for the three guidance technologies, in that the SSEB preferred FLIR over the other two guidance systems and perceived the FO system as being slightly better than the LBR system.

Cost-Effectiveness Analysis

The previous section considered only the relative effectiveness of the three guidance alternatives. To select the best alternative, we must also consider the development and procurement costs. Table 2 shows notional values for the cost per missile for each alternative and the total program

TABLE 2. ANTI-TANK MISSILE COST

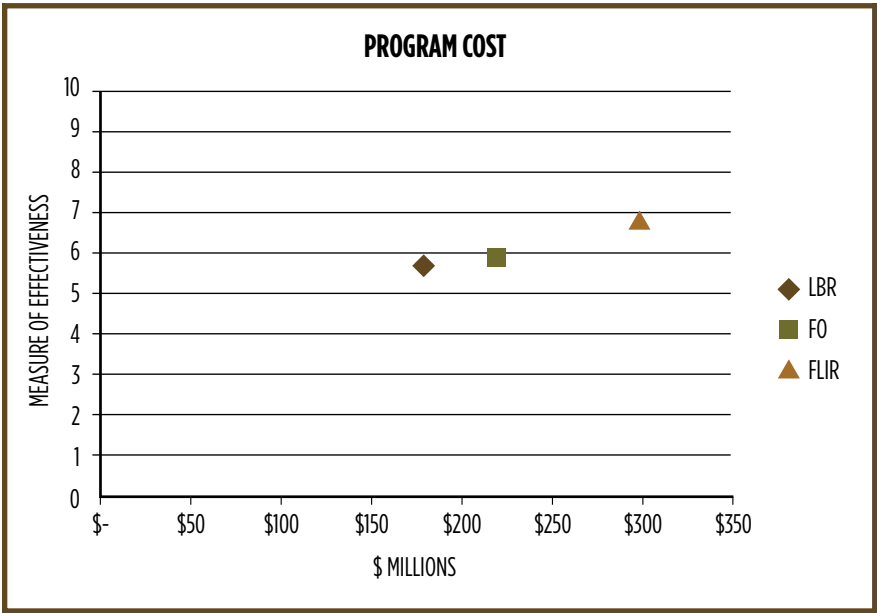
	LBR	FO	FLIR
Cost/missile (\$M)	\$0.09	\$0.11	\$0.15
Program Cost (\$M)	\$180	\$220	\$300

cost for each alternative assuming 2,000 missiles are procured. A cost versus effectiveness graph is shown in Figure 1. The total program cost and MOE for each alternative are shown on the graph.

Figure 1 illustrates that no alternative dominates another, meaning no alternative is both cheaper and more effective than another. Thus, we must look at the marginal benefit and marginal cost to evaluate the alternatives. The LBR alternative is the least costly and least effective. We compare it to the FO alternative in Table 3 and note that the marginal cost of choosing FO over LBR is \$40 million. Table 3 also shows the difference in values for each of the effectiveness measures used to calculate the MOE between the two alternatives. A positive change represents an increase in effectiveness, while a negative difference indicates a decrease in effectiveness. A similar analysis for FO versus FLIR is shown in Table 4.

While Figure 1 gives us an overall picture of the cost versus effectiveness of the three alternatives, Tables 3 and 4 show what is gained and lost at the margin when going from one technology to the next. Arguably, this is captured in the overall MOE, but decision makers are often interested

FIGURE 1. ANTI-TANK MISSILE TOTAL PROGRAM COST VS. EFFECTIVENESS



in seeing what specifically they are getting for their investment. In addition, because the MOE is a combination of different metrics that are not necessarily interchangeable, it would not make sense to simply calculate the ratio of MOE to cost. Instead, the marginal analysis defines the trade-off space, but not the solution, for the decision makers.

The previous cost versus effectiveness analysis assumed that all the guidance technology development efforts would be equally successful and achieve the calculated MOEs. But at the start of the proof-of-principle effort, there was no assurance that any of the technologies would be successfully developed. In fact, the probability of success differed between the three alternatives. A notional assessment of the probability of success² for each option is given in Table 5.

Table 5 also shows the expected MOE based on the given probability of success for each option. The expected MOE is the product of the MOE shown in Table 1 and the probability of success.

Table 5 incorporates uncertainty into the estimate of the benefits (as measured by the MOE) of each alternative. However, it does not incorporate uncertainty into the costs of those alternatives. Each of the alternatives has an expected cost based on the uncertainty associated with the technology development. If the development effort fails, we assume the Army will have to pay some additional cost to finish developing the technology and achieve the anticipated level of effectiveness (MOE). We refer to this additional cost as the “cost to fix” the technology. If the technology development phase is successful, then the cost to exercise the option will be the total program cost from Table 2 and is shown as “cost to implement” in Table 6. If the technology development phase fails, the cost of the alternative will be the cost to implement plus the cost to fix the technology. The total expected cost of each alternative is given in Table 6.

The values shown in Table 6 assume that one of the technologies will be picked based on the cost-versus-benefit analysis presented above and that, whichever technology is chosen, there is an additional cost to achieve the anticipated effectiveness (MOE) if the development phase fails. Figure 2 incorporates uncertainty into our analysis, showing expected cost (from Table 6) versus expected effectiveness (from Table 5).

TABLE 3. MARGINAL ANALYSIS OF COST AND EFFECTIVENESS FOR LBR AND FO

Marginal Analysis	LBR	FO	Difference
Program Cost (\$M)	\$180	\$220	\$40
P(H)*P(K)	5	4	-1
Top attack	6	7	+1
Weight	9	5	-4
Time to engage	8	7	-1
Time of flight	7	5	-2
Redirect capability	10	10	0
Required training	5	1	-4
Exposure after launch	2	8	+6
Ease of procurement	8	6	-2

TABLE 4. MARGINAL ANALYSIS OF COST AND EFFECTIVENESS FOR FO AND FLIR

Marginal Analysis	FO	FLIR	Difference
Program Cost (\$M)	\$220	\$300	\$80
P(H)*P(K)	4	7	+3
Top attack	7	9	+2
Weight	5	3	-2
Time to engage	7	5	-2
Time of flight	5	5	0
Recall capability	10	0	-10
Required training	1	10	+9
Exposure after launch	8	10	+2
Ease of procurement	6	4	-2

TABLE 5. PROBABILITY OF DEVELOPMENT SUCCESS AND EXPECTED MOE FOR JAVELIN TECHNOLOGY OPTIONS

	LBR	FO	FLIR
Probability of success	0.6	0.5	0.4
Expected measure of effectiveness	3.414	2.94	2.716

TABLE 6. EXPECTED COST OF JAVELIN GUIDANCE TECHNOLOGY ALTERNATIVES WITHOUT OPTION TO TERMINATE PROJECT

	LBR	FO	FLIR
Probability of success	0.6	0.5	0.4
Cost to implement (\$M)	180	220	300
Probability of failure	0.4	0.5	0.6
<i>Cost to fix</i>	<i>50</i>	<i>70</i>	<i>90</i>
Total cost to implement given failure (\$M)	230	290	390
Expected Cost (\$M)	200	255	354

TABLE 7. VALUE OF JAVELIN GUIDANCE TECHNOLOGY OPTIONS

	LBR	FO	FLIR
Probability of success	0.6	0.5	0.4
Cost to implement	180	220	300
Probability of failure	0.4	0.5	0.6
Cost if project is terminated	0	0	0
Expected cost with option	108	110	120
Expected cost w/o option	200	255	354
Value of option	92	145	234

Using the expected cost and expected MOE, we see that both the FO and FLIR guidance systems are dominated by the LBR system, since it is both cheaper and has a higher MOE. This analysis suggests that, based on the information available at the beginning of the program, the LBR technology should be chosen.³

Value of Technology Options

A real-options approach differs from the choose-early approach above in that it purposely delays making a decision while more or better information is gathered. The value of a real option is derived from the difference between the expected net value (benefits less costs) of an investment and the net value of that investment given that it succeeds. In the Javelin case, the option value lies in the flexibility to terminate the development of a technology if it is not successful.⁴ To develop a simple option valuation model for the Javelin guidance technologies, we note that the benefits are given by the MOE as shown in Table 1. If we do not use a real-options approach, then the costs of each alternative are shown in Table 6.

Using a real-options approach, the Army pays for the option to find out whether the technology development succeeds before making a final choice. If the development succeeds, we have achieved the MOE shown in

FIGURE 2. ANTI-TANK MISSILE TOTAL EXPECTED PROGRAM COST VS. EXPECTED EFFECTIVENESS

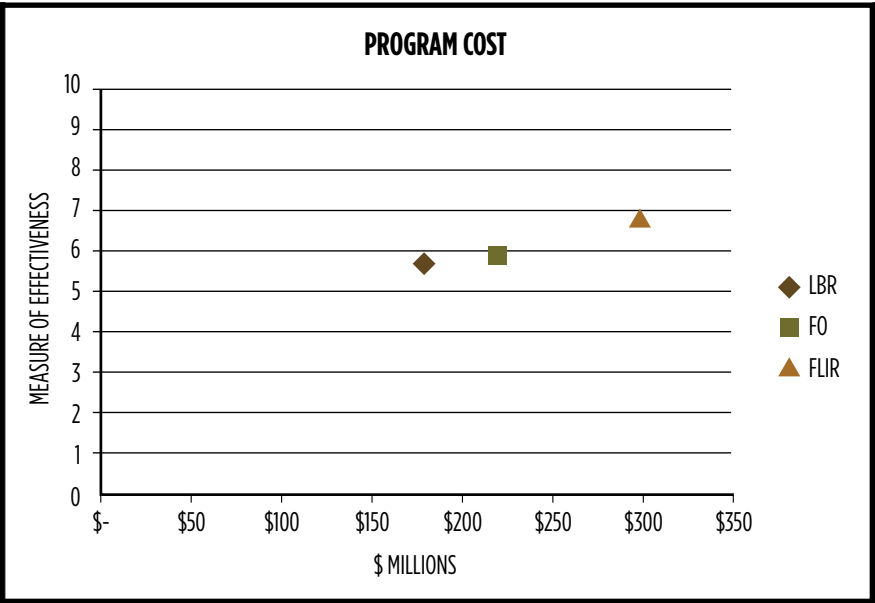


Table 1 and can proceed with the project if we prefer that option (based on the cost versus effectiveness analysis presented in the previous section). If the development fails, we terminate the project and there is no further cost. The value of the option is given by the difference between the expected value of the project with no option (from Table 6) and the expected value of the project with the option to terminate. The calculations are shown in Table 7.⁵

The values of the options for each alternative are different because different levels of uncertainty are associated with each technology. For example, uncertainty on the two relatively mature technologies (LBR and FO) was lower than for the new technology (FLIR). Given that we are willing to pay for the technology with no options, the more uncertain the technology, the more we value the option to terminate the project if the technology development fails. The values shown in Table 7 are maximums in the sense that if we pay any more than the option value, we would have been better off not using an option. If we pay less than the option value, we experience real cost savings by not expending funds on an unsuccessful technology.

Suppose the Army preferred the LBR technology (based on the cost versus effectiveness analysis presented in the previous section). They should pay no more than \$92 million for the option to terminate the project. But the Army decided to buy options for all three technologies, so the total amount that they spend on options should not exceed the value of the option for the preferred technology. Since the value of the LBR option is \$92 million, if they allocated the option value equally across all the alternatives, they should spend no more than about \$30 million for each option, which is exactly what the Army did.

But allocating the option value equally across the alternatives is not economically optimized, given that some technologies are more uncertain than others. It would be more rational to allocate the option value based on the level of uncertainty that we are trying to resolve. Using the probability of failure in Table 7 as a notional measure of risk, we can allocate the option value in proportion to that risk, giving 27 percent of the total option value to LBR, 33 percent to FO, and 40 percent to FLIR. Going back to our previous example, if the Army prefers the LBR technology, then the total cost of the option should not exceed \$92 million. That means the Army should pay about \$25 million for the LBR option, \$30 million for the FO option, and \$37 million for the FLIR option. Doing so allocates the dollars based on risk while keeping the total cost equal

to the option value of the preferred alternative. Again, we note that \$92 million is a maximum. To realize any cost savings from the option, the Army must pay less than \$92 million for all three options.

The Army's Choice

The Army's Cost and Operational Effectiveness Analysis (COEA) indicated that the LBR was the preferred alternative based on weighted cost/efficiency factors. At the same time, the SSEB actually chose the FLIR alternative because of a bias toward fire and forget. This difference illustrates the importance of choosing decision criteria that accurately reflect the needs and preferences of warfighters for analysis of alternatives. Although time of flight and gunner survivability were not stated requirements in the AAWS-M Joint Required Operational Capability document per se, fire and forget nevertheless translated into greatly enhanced gunner survivability and overwhelmingly appealed to user representatives. The resulting decision by the SSEB reflected this preference. In June 1989, a full-scale development (now called Engineering and Manufacturing Development, or EMD) contract was awarded for the AAWS-M project to the joint venture team of Texas Instruments and Martin Marietta. At the macro level, the Office of the Secretary of Defense viewed the program as acceptable regarding risk because of its 27-month technology development phase, use of multiple prototypes (real options) for a technical solution, and subsequent 36-month plan for full-scale development. But at the program office level, it was known to be one of high risk in several technical areas. Focal Plane Array (FPA) technology was still immature and would be gauged today at approximately Technology Readiness Level (TRL) 5 (on an increasing scale of 1–9), despite its successful technology-development phase results.

About 18 months into the EMD phase, serious technical problems around FPA attainment of specified sensitivity and production yield, system weight, tracker algorithm, and other areas doubled the expected cost of development and added about 18 more months to the originally planned 36 months to complete. Over that next year, the program sought a new baseline with many different revised program estimates—climbing from 36 months' duration and \$298 million in cost, to 48 months' duration and \$372 million in cost, and finally, 54 months and \$443 million for the total cost and duration of this phase. Within that year, the program was restructured, given the new baseline, and finished largely within its new parameters. The additional 18 months added to the 36-month phase helped resolve the uncertainties and complexities of system development without additional schedule slippage.

Today, Javelin is viewed as being a totally successful weapon system, despite its much earlier programmatic shortcomings in development. It is being used in combat operations and has continued through many full-rate production contract periods. Over 1,000 Javelin missiles have been fired in Operations Iraqi Freedom and Enduring Freedom since March 2003, with close to 98 percent reliability. The system design has continued to be upgraded—not as blocks of capability, but with incremental software, warhead, and producibility enhancements.

Javelin missiles have been fired in Operations Iraqi Freedom and Enduring Freedom since March 2003, with close to 98 percent reliability.

Conclusions

Several observations can be made from our analysis of the Javelin guidance technology acquisition process.

The first is that the benefit of weapon systems, or in this case missile guidance systems, is not measured in dollars. This makes using a traditional option valuation model (based on benefits less costs) difficult. Instead, we must use the principles of multiobjective decision making to develop an MOE for each alternative. The MOE can be compared to the cost to define the trade space for the decision maker.

While the MOEs calculated in this article (Table 1) aligned with the preferences of the SSEB, which were heavily weighted towards gunner safety, it is possible that the initial Army COEA did not adequately consider what turned out to be the most important objective—gunner safety. If we remove that objective from Table 1 and assign equal weights of 0.45 to Lethality and Tactical Advantage, leaving Procurement with a weight of 0.1, the revised MOEs would yield a result similar to the Army's COEA, with LBR receiving the highest MOE. However, it is also possible to select FLIR as the preferred alternative based on Figure 1 (cost-effectiveness) if the SSEB considered effectiveness to be much more important than

cost, basically concluding that the FLIR was worth the extra money. Both cases illustrate the subjective nature of effectiveness analysis and why it is so important to explicitly model objectives and preferences.

Second, we note that the three proposed guidance technologies had different levels of risk. We used this information to calculate the expected MOE for each alternative, thus incorporating uncertainty into the analysis. The probabilistic MOE can be compared to the expected cost (in our case, cost per kill) to present a risk-adjusted trade space for the decision maker. To the best of our knowledge, neither the COEA nor the SSEB used a quantitative risk-adjusted trade space as presented in Figure 2 in their analysis, although it is likely that they considered technology risk qualitatively. The risk-adjusted model presented in this article would have provided a clearer picture of the impact of technology uncertainty on the trade space.

Third, we show that a real-options approach allows us not only to incorporate uncertainty in our analysis, but also to calculate the value of the option based upon risk. This leads to different option values for different alternatives based on the technology maturity. Using this approach, the Army should have offered each development team a different amount of money to develop their proposed technology. Doing so would have better allocated the dollars to manage risk.

Fourth, we note that the final cost to fix the FLIR guidance technology selected by the Army turned out to be significantly higher than the \$30 million originally paid to develop the technology. This is in line with what our Real Options Valuation Model suggested, since the FLIR technology was always anticipated to be the riskiest.

The use of risk-based Real Options Valuation Models allows us to estimate the value of flexibility in acquisition decisions. Understanding this value allows program managers to assign program dollars based on risk and supports the efficient use of limited program resources. Program managers can develop more effective capabilities more efficiently by improving and expanding their understanding of the potential and use of real options in acquisition. Future research can facilitate these improvements by investigating the role of real options in other development phases such as development for production, the impacts of imperfect information obtained through options that inaccurately indicate the feasibility of a technology, and other aspects of real options in acquisition.

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Endnotes

1. The objectives, metrics, weights and values used in this example were developed by the third author, a program manager for the Javelin who was deeply involved in the Army evaluation process. The Services procuring the Javelin system did not actually use this exact methodology for the selection of the Javelin guidance technology, but used something similar for a weighted decision analysis of the three alternatives.
2. The probabilities of success and failure as well as the costs for each technology were estimated by the third author based on extensive experience as a program manager for the Javelin.
3. The Army's actual Cost and Operational Effectiveness Analysis (COEA) also found that the LBR was the preferred alternative.
4. The focus in the current work is on the technology development phase and the feasibility of the technologies (e.g., as measured with the TRL), as opposed to their readiness for production. We assume that the options provide perfect information on the feasibility of the technology.
5. The expected cost with option assumes perfect information relative to the success of the technology development effort.



Keywords: *Technical Data, Data Rights, Better Buying Power, Heuristic Economic Model, Cultural Change*

Better Buying Power or Better Off Not? *Purchasing Technical Data for Weapon Systems*

 **James Hasik**

In September 2010, then-Under Secretary of Defense for Acquisition, Technology and Logistics Ashton Carter directed program managers to routinely analyze the business cases behind procuring the technical data packages and rights to new weapon systems. In this article, the author recounts some of the historical difficulties with procuring technical data for fielded systems, and presents a heuristic economic model outlining the problems that PMs should consider before making an offer.

With tighter spending constraints, continued underperformance could become dangerous on the frontline.

2

In September 2010, then-Under Secretary of Defense for Acquisition, Technology and Logistics Ashton Carter issued a broad memorandum on acquisition reform to the heads of the military services and defense agencies (Carter, 2010). Covering five major themes, with 23 individual initiatives, but published in just 10 pages, the memorandum called for a thorough rethinking of how the Pentagon went about acquiring goods and services—an approach aimed at developing “better buying power.” Indeed, Better Buying Power was the document’s chosen title—a term intended as a quiet rallying cry for better performance in the business of defense.

Background

Underperformance and Shrinking Budgets

As the largest buyer by far of weapons worldwide, and the monopsony buyer in the largest market, the U.S. Government ought to be a more powerful buyer, Carter believed, extracting better terms than it had historically. Why the sudden imperative? As Carter told an assemblage of industrialists in a progress report 10 months later, their generation had “grown accustomed over the post-9/11 decade to circumstances in which we could always reach for more money.” The problem, he continued, was that “those days are gone” (Marshall, 2011). Amidst a financial crisis and a nearly global recession, the military budget clearly would be decreasing. With tighter spending constraints, continued underperformance could become dangerous on the frontline.

To be fair, there had been some remarkable success stories in the wars in Afghanistan and Iraq with rapid, off-the-shelf procurements. But many developmental programs had lurched from delay to cost overrun. The plight of the Army was remarkably bad. Twenty-two of the Service’s major weapon systems programs had been cancelled since 1995, at a cost of \$32 billion for materiel never fielded (Capaccio, 2011). Perhaps this should not have been news. Carter had previous experience in the Pentagon, and was a professor of public policy at Harvard’s Kennedy School of Government. As such, he likely agreed with Asher and

Maggelet's assertion of almost three decades prior that "schedule and cost growth in DoD weapon systems acquisition have been recognized as an economic fact of life" (1984, p. iii). He simply believed in breaking that supposition.

The dilemma with which Carter and his team had grappled was "how to incentivize lower prices in the short run without ruining suppliers' incentives to commit assets, incur risk, and innovate for the long run."

Aiming to do so, Carter's planners took in more than one hundred ideas for reforms, and whittled the list down to the 23 they considered "long-ball hitters" (McFarland, 2011, p. 7). There were clear themes: the word "incentive" appears 13 times in the memorandum, and the word "competition" fully 50. In particular, as a former chief industrial strategist at the Pentagon observed, "Better Buying Power has taken aim at eradicating what it views as a sclerosis of comfortable contractor incumbency... and reads like a monopsonist's playbook for defense in the 21st century" (Grundman, 2010, p. 3). The dilemma with which Carter and his team had grappled was "how to incentivize lower prices in the short run without ruining suppliers' incentives to commit assets, incur risk, and innovate for the long run" (Grundman, 2010, pp. 1, 3). That long run would last a bit, for after Carter moved up to become the new deputy secretary of defense, incoming acting Under Secretary Frank Kendall (2011b) issued a two-page memorandum largely staying the course of Better Buying Power.

How easily the strategy would be implemented by program managers might be another question. In the ensuing pages, I recount some of the historical difficulties with procuring technical data for fielded systems, and present a heuristic economic model outlining the problems that program managers (PM) should consider before making an offer.

The Technical Data Package Explained

Competition amongst prospective contractors is one natural way of inducing lower prices. So, under the heading “Promote Real Competition,” and subheading “Remove Obstacles to Competition,” one of those 23 instructions called for the Services to “Require Open Systems Architectures and Set Rules for the Acquisition of Technical Data Rights.” Specifically, Dr. Carter (2010) wrote that:

At Milestone B, I will require that a business case analysis be conducted in concert with the engineering trades analysis that would outline an approach for using open systems architectures and acquiring technical data rights (TDRs) to ensure sustained consideration of competition in the acquisition of weapon systems. (p. 10)

This was not strictly a revolutionary thought. Prior to Carter’s initiative, the John Warner Weapon Systems Acquisition Reform Act (WSARA) of 2009 had mandated that the acquisition strategy for any Major Defense Acquisition Program (MDAP) provide a plan to ensure at least the competition throughout a system’s life cycle. The WSARA listed 10 possible measures to consider; buying the technical data package (TDP) was one of those (Byrd, 2010, p. 10). Carter’s memorandum moved that from *probably should* to *definitely should* consider. The Army then got its own recommendation from the Decker-Wagner Army Acquisition Review Panel, which recommended buying TDPs during development, so long as that was “consistent with the risk-reward” (Decker-Wagner, 2011, p. xvi).

But what precisely are TDRs and TDPs? While sometimes conflated, the terms are not synonymous. The Defense Acquisition University’s Glossary (2005, p. B-181) defines the TDP as “a relatively complete package of design and manufacturing information” consisting of “drawings, quality assurance provisions, standards, performance requirements, quality assurance provisions, and packaging details.” Depending on the contract terms under which a weapon system was developed, TDRs confer some degree of legal authorization “to use, duplicate, or disclose” those data, potentially to a competing contractor (p. B-78). Thus, the TDP is the actual intellectual content of the TDRs, but possession of one is not possession of the other. Frankly, neither is necessary for ensuring competition before a system enters initial production, but both figure strongly for ensuring competition afterwards. If the government lacks the data and rights thereto, the contractor that designed a weapon system will undergo a “fundamental transformation” from applicant

to incumbent (Williamson, 1988, p. 80), and stand alone as sole source for reorders, upgrades, overhauls, or possibly even spares. The government may still stand before the contractor as a monopsonist, as the only domestic buyer of heavy weapons, and the veto authority on arms exports. But even then, the buyer-seller relationship would be a bilateral monopoly—a problematic negotiating situation. One of the chief interests in acquiring TDPs and TDRs should thus be clear: with a full understanding of how to produce and maintain a system, the government can open a second source—a potential alternative to the incumbent.

A Brief History of the Government's Stance on Technical Data

With such benefits, one might presume that the government has always and everywhere wanted its data, but the policy has varied over time. Naturally, the government rarely acquires technical rights to wholly



commercial items—there is simply no reason to own the blueprints for making readily available items such as standard screws in-house. But even with noncommercial items developed at governmental expense, through the end of World War II, both the War and Navy Departments rarely acquired TDRs. Contractors were hardly willing to sign them away, having a natural interest in exclusivity, as sole possession would forestall competition. Even the government may not want to push too hard for TDRs. As noted earlier, Williamson’s “fundamental transformation” to incumbency brings stability to the business relationship. The presumption of future quasi rents from monopolistic competition may encourage long-run innovation, which the monopsonist must take care not to kill, as defense is presumably a long-run game (Grundman, 2010, p. 1).

For decades, contractors had little to fear. Armed Services Procurement Regulation No. 9 ensured that whatever technical data the government might acquire alongside its armaments, it would otherwise not possess “any right to reproduce anything else called for by this contract” (McKie, 1966, p. 5). Thus, TDPs frequently—TDRs almost never. But in 1955, the escalating cost of new aircraft led the Defense Department to assert that the aforementioned clause was not so restrictive, and that the government’s data rights could be extended to competing suppliers without royalty. Faced with such severe regime instability, quite a few contractors rebelled. Over the next 10 years, the Pentagon’s technical data regulations underwent four revisions, culminating in a state of considerable rights for contractors (Maizel, 1986, pp. 236–245). As those rights remained inadequately defined, a flurry of litigation ensued, until passage of the 1983 Defense Procurement Reform Act and the 1984 Competition in Contracting Act emphasized assertion of greater governmental rights (Maizel, 1986, pp. 270–271).

In 1993, however, the Clinton administration entered office determined to “reinvent government” with thoroughly businesslike practices. Buying suppliers’ technical data was not (and still is not) common commercial practice, so the mandate was considerably relaxed, and particularly for off-the-shelf products. Sharp reductions in the Pentagon’s procurement workforce in the 1990s simultaneously eroded in-house technical expertise, albeit with little contemporaneous worry, for contractors were deemed more than capable of maintaining their own technical data. By the late 1990s, the practice reached its apex in the Total System Product Responsibility (TSPR) concept, in which a single contractor was paid for the delivery and long-term maintenance of a

system, in a single long-term contract. The agency problems in that approach led to some spectacular failures, such as the ongoing debacle of the Space-Based InfraRed System (SBIRS; see Hasik, 2004)—still unavailable for its deemed role in ballistic missile detection and tracking, some 15 years after its inception.

The Bush administration almost entirely continued the Clinton administration's policy, though it had largely backed away from the TSPR concept by the end of its second term. Congress was busy rewriting laws as well. In 2007, the John Warner National Defense Authorization Act mandated that PMs of MDAPs assess “the merits of a priced contract option for the future delivery of technical data that were not acquired upon initial contract award, and the potential for changes in the sustainment plan over the life cycle of the system” (Government Accountability Office [GAO], 2011, p. 9); note that Senator Warner's has been a popular name to invoke in these matters). In 2009, the WSARA had yet more fully declared a new policy, and the following year Better Buying Power had effectively declared “TSPR RIP” (Grundman, 2010, p. 4). At that point, in policy directives enacted even before Carter's (2010) memorandum was written, PMs, according to GAO's (2011) report, were required to:

1. assess the data required to design, manufacture, and sustain the system as well as to support re-competition for production, sustainment, or upgrade;
2. address the merits of including a priced contract option for future delivery of data not initially acquired;
3. consider the contractor's responsibility to verify any assertion of restricted use and release of data; and
4. address the potential for changes in the sustainment plan over the life cycle of the weapon system or subsystem. (p. 11)

With Carter's emphasis, PMs would henceforth think long and hard about the data and the data rights—if they could quite understand the difference, the advantages, and which benefits might remain elusive.

Historical, Challenging Cases in the Technical Data Approach

Buying data is not a panacea simply because intellectual capital (IC) is not synonymous with intellectual property (IP) (Gallop, 2011, p. 38). As noted earlier, possession of the data does not necessarily confer rights to the data. Conversely, the rights to produce a system may exist separate from the data needed to do so. Moreover, neither IC nor IP constitute individual skills or organizational knowledge per se, and some technologies are quite firm-specific. Consequently, technical drawings are just the start of opening a second source. As there have long been alternative methods of second-sourcing worth considering, such as directed licensing or functionally equivalent purchases, one analysis (Sellers, 1983) of nearly 30 years ago from the Defense Systems Management College took a dim view of the salience of purchasing TDPs:

Although theoretically sound, this method is perhaps the most hazardous of all the second-sourcing methodologies. It is not well-suited for use in highly complex systems or systems with unstable designs or technologies. (p. 14)

In other words, with most modern weapons.

As an example, consider the case of the Japanese F-2 fighter jet program. In the early 1990s, General Dynamics (predecessor in Fort Worth to Lockheed Martin) began working with Mitsubishi Heavy Industries to help produce a less-expensive domestic supplement to the Japanese Air Self-Defense Force's F-15 jet fighters—seemingly, a Japanese analog to the F-16. Indeed, the F-16 served as the basis for the program, with diagrams, production licenses, and technology transfer assistance forthcoming. Howls continued for some time about the “giveaway of advanced aerospace technology to America's most relentless rival” (Lorell, 1995a, p. 2), but the eventual result was unimpressive (Garretty, 2002, pp. 35–37, 42–43). Between 1995 and 2011, following the initial prototypes, only 94 combat-capable F-2s were built, in a 60/40 work-sharing agreement with Lockheed Martin, for approximately \$104 million each. In short, for all its trouble, the Japanese government got not a lot of technology transfer, and a shockingly expensive derivative of an otherwise economical airplane. The U.S. General Accounting Office concluded as early as 1992 that the technology transfer process for the F-2 had simply been “too strict” for cost-effective coproduction (Lorell, 1995b, p. 361).

Consider further the case of an American purchase of a TDP, gone very wrong: that of the M119 105 mm howitzer, née the British Light Gun. In the late 1980s, the U.S. Army bought the TDP and the TDRs from Royal Ordnance (RO), the British government's arsenal for artillery and munitions, for licensed production at the Watervliet and Rock Island Arsenals. Management at RO did not fully understand what the U.S. Army meant by a TDP, as howitzer production for the rather smaller British Army was a craft-oriented, fix-it-on-the-shop-floor process. Though RO was then a crown corporation of an allied state, the U.S. Army considered suing the organization for providing a package wholly inadequate for establishing a new production line with fully trained workers (Schaller, 1996, p. 42). The TDP was also technically inaccurate: its original estimate for tooling costs was \$8 million, but actual costs eventually exceeded \$23



million. The license fee from RO for the TDRs was initially just £1.15 million, but RO's subsequent charge for fixing the deficiencies in the TDP—representing scores of engineering man-years for which it had not originally been contracted—was \$4.75 million. Accordingly, the Army's attempt at concurrent engineering at Rock Island went particularly badly, and even after that, the Army's Research, Development, and Engineering Center, Watervliet, and Rock Island spent another \$3 million fixing yet further deficiencies in the TDP.

As noted, original sources have a natural, built-in advantage of tacit knowledge about their own products, and whether omissions from TDPs are just omissions or conscious commissions of opportunism, defects therein are typically “almost always the case” (Sellers, 1983, p. 14; see also Witte, 2002). Those fighters and howitzers serve today, but as the examples show, even ultimate successes with TDPs can cost “an incredible amount of time and money” (Schaller, 1996, p. 39).

Back in the 1980s, the Army's project officer for the M119 was a junior civil servant named Kevin Fahey. Today, Fahey is the Department of the Army's program executive officer (PEO) for Ground Combat Systems, and an official pushing to procure technical data, rights and all. In 2009, pursuant to the WSARA, his staff began calling Army contractors possessing proprietary designs to inquire about buying what it could. Reports from at least one contractor reveal a remarkable lack, at least initially, of economic sense on the government's negotiating team. The Army's initial position presumed (and apparently innocently) that the contractor would only seek compensation for the engineering man-hours needed to reproduce the drawings. When apprised of the need to pay separately for the rights, in compensation for possibly lost future profits, the Army's negotiators did quickly come around (anonymous, personal communication, 2009).

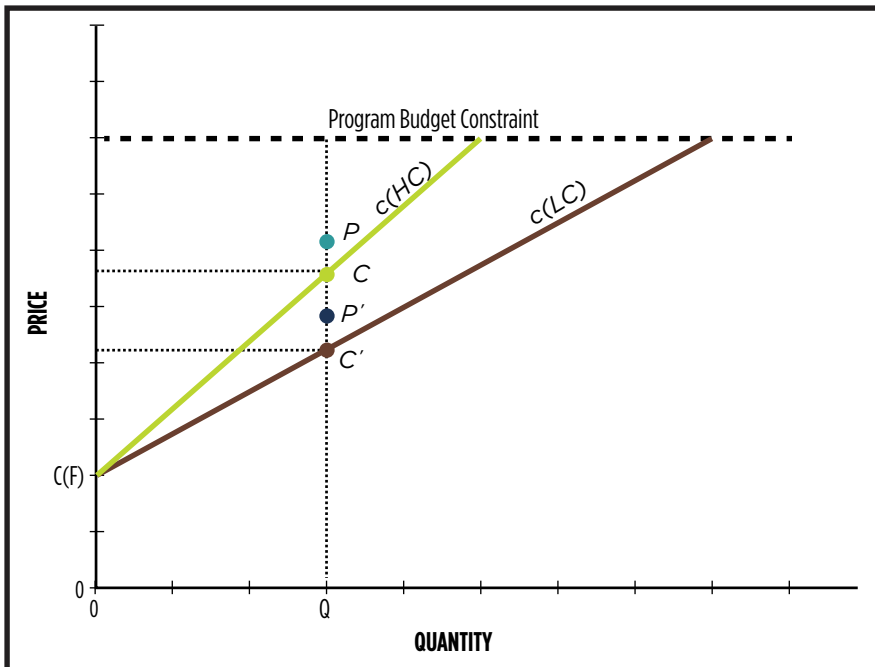
That is, if the government is investing in a competitive process, the potentially displaced contractors will assign the avoidance of that process some value. That technology transfer is costly, both in purchase price and learning costs, and so paybacks on this investment have been observed generally to take at least 3 years (Daly & Schuttinga, 1982, p. 63). Statistical estimates of learning curves tend to be highly unreliable (see Alchian, 1963), and can even turn negative with “organizational forgetting” (Benkard, 2000), so the error range on those payback estimates can be considerable. The government must also maintain that internal expertise, and continue to update the TDP as the system is upgraded

over time (Sellers, 1983, p. 14). With problems like these, unsurprisingly, second sourcing has historically been used less to reduce price than to deal with primary suppliers' quality problems (see Lyon, 2006).

A Simple Economic Model for Pricing Technical Data

Price, though, is the emphasis of Better Buying Power, and so purchasing data have become, whether at Fahey or Carter's direction, a proactive and presumptive option. Buying data early in a program (as Carter's [2010] memorandum directs) is very appealing (House Armed Services Committee, 2010, p. 8), but pricing is problematic for equipment already in production. Much of the volume of procurement in defense, after all, is not for wholly new systems, but for new units of systems already fielded, or for modifications to those systems. With its monopsony power, the government can apply implicit, even unwitting pressure on contractors who sell largely to military customers. Loss of goodwill from outright refusal of a sale at any price may be unpalatable.

FIGURE 1. TWO CONTRACTORS, FIXED MARGIN, KNOWN COSTS



Facing that double bind, a contractor may seek a defensible position by marketing its irreproducible tacit knowledge, inextricably proprietary processes, and efficient embeddedness with the customer (Uzzi, 1996).

How the PM will respond is more problematic. Buying data only makes sense if the second run can amortize the costs of the production shift plus the purchase of that data. The quantities and prices to which contractors would respond optimally are likely less clear. Dixit (2002, pp. 707–708) provides the beginnings of a model, stipulating a competition involving two contractors, with higher and lower internal costs. The government may have buying power, but it does not know which contractor is which, and so the lower cost contractor can represent itself as higher cost, and conceivably earn fat margins. Auditing under profit regulations can drive down this margin somewhat, but only imperfectly: management can pad its accounts with featherbedding, and slack off from the pursuit of factor efficiencies, buying a comfortable life at public expense. Dixit's assumptions here are quite plausible in studying military procurement, where the government often has quite imperfect information of any contractor's cost or quality. However, his prescribed solution, a menu of two price-and-quantity combinations by which the contractors will efficiently self-identify as either high- or low-cost, is essentially unknown in our realm.

And yet, if we used his model, we would still not have considered pricing the data, for the government must pay in advance simply to hold the competition at all. To accommodate this complication, and to conform to a recognizable military procurement mechanism, I offer an alternative model, shown in Figure 1. Here, the PM attempts to procure a certain quantity of weapons, specified by budget planners, minimizing cost, in a single round of procurement. Arriving at Milestone B, the PM has an offer of Q units at total cost P from the incumbent contractor, which has designed and prototyped the weapon. The PM, however, suspects the incumbent to be high-cost. A competent second source, thought by the PM to be low-cost, markets its capabilities as a production alternative, notionally at price P' . (We assume invariant quality between contractors.) The respective firm-specific cost curves for the weapon are shown with marginal costs (slopes) c_{HC} and c_{LC} . For simplicity, we assume the same fixed start-up cost CF , and a constant margin, fixed and audited by the government, of $P - C = P' - C'$. The lower cost firm is thus not incentivized to pad its costs for a greater prize.

Purchasing data rights could activate the second source, which would then presumably win the competition. By inspection, we see that the PM's reservation price for the data is $C - C'$ (equivalent to $P - P'$ with the fixed margin). We imagine that the incumbent might sell, even if selling means exit: the profit margin $P - C$ can be taken as the incumbent's reservation price. If the incumbent ascertains in advance that this margin will not exceed the government's reservation price (if $C - C' > P - C$), then negotiations are possible. Because we have stipulated a fixed margin of $P - C = P' - C'$, by substitution the preceding condition reduces to $P' < C$. That is, if the challenger's price is less than the incumbent's cost, and profit is the contractor's primary motivation, the incumbent and the government may make a deal. It is important to note, though, that if the cost curves are close, buying out the incumbent's margin will save the customer little.

If the challenger's price is less than the incumbent's cost, and profit is the contractor's primary motivation, the incumbent and the government may make a deal.

Tools, Rules, and Schools on the Path Towards Technical Data

This is all simple, but again problematic, for neither the PM nor the second source can be certain of C' , and thus P' . The PM presumably understands the broad technical nature of the program, but the PM is not a production manager, with the same operational understanding of a PM's contractor counterpart. The PM's should-cost analysis (directed separately in Better Buying Power) may help understand those costs, but anecdotally, the should-cost analysis does not begin well. Commercial best practice in supplier management holds that should-cost briefings should be transparent in their assumptions and analyses, so that suppliers can correct customers' misimpressions and find common ways to remove costs from the shared value chain. According to one prominent analyst, in several cases the government's men have been dropping the should-cost figure on the table and declining to provide further insight (B. Callan, personal communication, 2012). This is no way to do business.

The soliciting second source also presumably understands its own production capabilities generically, but lacks the specific TDP and the tacit knowledge built during the development of the system. The original source might know its own production capabilities reasonably well, but not precisely, for it is only now planning to bring the weapon into actual production. The original source, therefore, will presumably know even less about the second source's costs. Even in the best of times, the original source commonly calculated breakpoints of economic order quantities, economic production rates, and minimum sustaining rates, despite their official acronyms and emphasis in the education of the PM, can be "surprisingly difficult to pin down" (Schilling, Hagewood, Snodgrass, & Czech, 2011, p. 43). If just the estimated slopes of the cost curves differ from reality, any of the players in the game may find themselves in the situation depicted in Figure 2, making decisions on faulty information, with hazardous results.

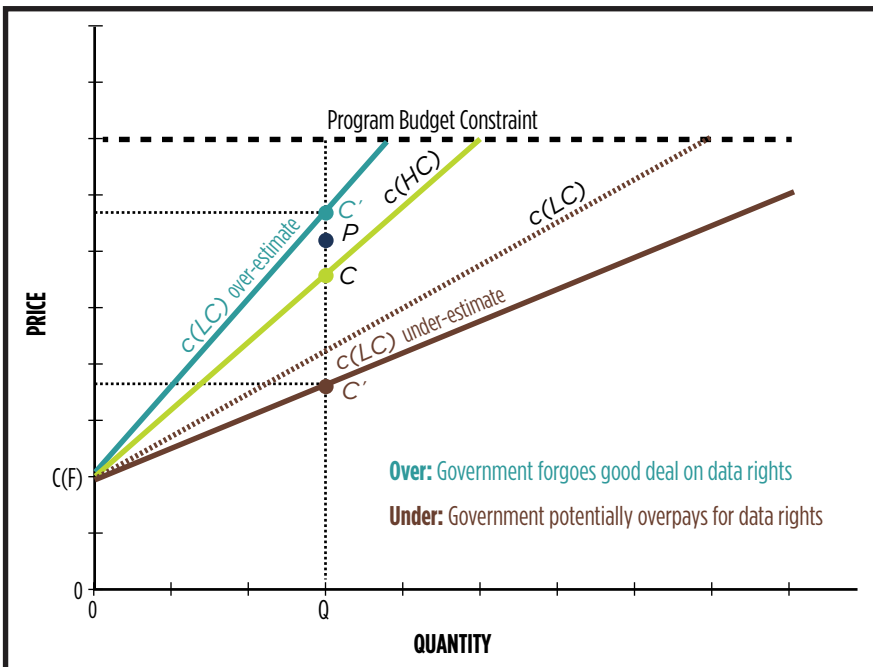
The key, to cite Decker-Wagner (2011), is hewing to that "estimated risk-reward" (p. 105). Cost-benefit analyses can get complicated if policy-makers have "highly unstable and often incomprehensible" preferences (Zaharidias, 2008, p. 517). All parties may wonder if the budget will fall, or gyrate from year to year. The PM will likely last in the job for but a few years, while the PM's counterparts may stay in their jobs for many more; if the contractor's rationality is bounded, the PM's may be more so. The problem is thus tripartite, strategic, probabilistic, asymmetric, and frankly quite challenging. Without a clear path to a solution, and slight punishments for dodging policies, PMs could just walk away from the problem. Indeed, many have. In the GAO's (2011) audit (p. 13) of compliance with the 2007 and 2009 statutes, none of the 12 program management offices sampled had fully undertaken all four of the mandated analyses of data rights acquisition.

Alternatively, if pushed hard, but without the analytical tools to tackle the question, the policy of just considering buying technical data could become inefficiently self-executing. Without data rights, competition is more challenging, but competition is the clear dictum of Better Buying Power. Buying-in reduces organizational uncertainty, even if the actual business case is marginal, which can appeal more to the PM, as agent, than the PM's principal—the PEO or assistant secretary. If buying data means "sticking it to the contractors," the newly emphasized practice can become, in Selznick's famous phrase, "infused with value beyond the technical requirements of the task at hand" (1957, p. 17). PMs might then underthink and overreact, reflexively offering to buy technical data at heuristically determined prices. In a rush to do a deal, these prices

may prove excessive, and thus sticking it to no one but the government itself. To defend the work, the program offices may simply shade their business cases to justify their preferred paths of less resistance. And thus, we would find defense fulfilling Behn's assertion (1995, p. 321) that "constraining people from doing anything wrong often simultaneously constrains them from doing anything right."

Fearing that the memorandum's guidance could become ossified as such a presumed rule (Buy all TDPs!), the current Under Secretary of Defense for Acquisition, Technology and Logistics (USD[AT&L]) Frank Kendall has "tried hard to communicate...that our guidance is just that—guidance" (Kendall, 2011a, p. 3). If Better Buying Power aims to implement 23 game-changing elements of guidance, then in the words of one reporter at the roll-out press briefing (Gates & Carter, 2010), this "might seem to require a cultural change within the Department of Defense." The response by the former USD(AT&L) was noncommittal, with the emphasis on changing behavior versus cultural change:

FIGURE 2. TWO CONTRACTORS, FIXED MARGIN, UNKNOWN COSTS





DR. CARTER Cultural change is—I always say I don’t do cultural change; it’s too hard. So we’re—this is directing specific actions. And the actions that we want are pretty specific, and the cause-and-effect is pretty specific, I think you’ll find as you read this, and the metrics by which we measure the effects are spelled out in the document. So culture’s too hard for me. Behavior—that’s what we’re after. (p. 3)

Conclusions and Recommendations

Although Carter’s (2010) memorandum lays out metrics for other initiatives, it does no such thing regarding data rights—one of a PM’s more challenging economic analyses. If there is direction, it is toward mere consideration. To be sure, issuing new formal rules could be counterproductive, as the PM’s managerial judgment under uncertainty is essential to the pursuit of better value. Given the complexity of the business case that the USD(AT&L) now demands at every MDAP’s Milestone B, some better tools would be important.

Better still might be actually tackling what Carter calls “too hard”—the culture. While complex weapons acquisition should be an eyes-open process, it simply cannot be an arms-length transaction. The Pentagon’s procurement institutions should inculcate in managers a strategic sense for mutually dependent relationships with long-term incentives for sustained innovation. The pursuit of such fuzzy objectives by PMs best relies on informal rules subject to the judgment of more senior officials (see Ingraham, Moynihan, & Andrews, 2008), and the conscious development of an organizational culture congruent with the leadership’s objectives in a commonly understood “unity of purpose” (Gulick, 1937, p. 39).

Change would require adjusting the government’s ways of thinking—its fundamental school of thought about supplier management. Carter effectively introduced a slew of new rules into the Pentagon’s bureaucracy, but he and his successor have developed few mechanisms for affecting the behavioral change beyond issuing a memorandum. Exhortations are no way to develop a sound business process (Deming, 1982, pp. 65–70), much less to develop 23 such processes. Pricing technical data in each of the Pentagon’s programs is but one of those, and a very challenging one at that.

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Keywords: *Initial Capabilities Document (ICD), Methodologies, Joint Capabilities Integration and Development System (JCIDS), Joint Acquisition, Capabilities Based Assessment (CBA)*

Initial Capabilities Documents: A 10-Year Retrospective of Tools, Methodologies, and Best Practices

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The Joint Capabilities Integration & Development System (JCIDS) is 10 years old and ripe for review. A central output document of the JCIDS process is an Initial Capabilities Document (ICD) used by the Department of Defense to define gaps in a functional capability area and define new capabilities required. The research team analyzed 10 years of ICDs to identify methods and trends. The team found that several methodologies were favored and a convergence emerged in format and necessary content. Additionally, potential shortfalls in current best practices of interest to implementers and decision makers are identified. Guidelines and best practices are presented to create more effective, concise, and complete ICDs.



As a historically unstable process, it may come as a surprise to many acquisition practitioners that the formal written procedures and processes that embody the Defense Acquisition System and Joint Capabilities Integration and Development System (JCIDS) are now over 10 years old. During this time, the Department of Defense (DoD) has published significant revisions and updates to the JCIDS-related documents, including Department of Defense Instruction (DoDI) 5000.02 and the *Joint Capabilities Integration & Development System Manual* (DoD, 2013; Joint Requirements Oversight Council [JROC], 2012). The current system's longevity may be partially attributable to its utilization of modern management approaches, further enabled by a slow convergence of the Joint Strategic Planning System set in motion by the Goldwater-Nichols Act (Goldwater-Nichols, 1986). With its focus on joint development and deconfliction of capabilities, JCIDS uses a portfolio management approach and streamlined documentation to elevate user requirements relatively quickly and vet them against current capabilities. Further, its emphasis on knowledge management ensures that all stakeholders can view the process and its outcomes as the key documents percolate through the JCIDS process.

Early analysis of the JCIDS process by the U.S. Government Accountability Office (GAO, 2008) identified variable product quality. Attempts were made at creating user's guides to improve document quality (JROC, 2012; Joint Chiefs of Staff [JCS], 2009); however, these documents did not fully address the analysis techniques contained therein. As a key component of process quality, the ability to select, use, and report an appropriate analysis technique is an item of interest for authors, stakeholders, and portfolio managers. Therefore, this effort reviewed the content, tools, and methodologies recorded in the past 10 years' Initial Capabilities Documents (ICD) created as a part of the JCIDS process.

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As one of the first products created in JCIDS, ICDs are important because they validate requirements derived through an analysis of current capabilities and capability gaps. Additionally, they are signed by senior service members and are the basis for program acquisitions. Further, due to their recommended brevity, it is important that ICDs contain the correct level of detail to identify the key assumptions, limitations, and boundary conditions contained or referenced in their analyses. A lack of analytical clarity at this stage may lead to misdirected resources further in the process (GAO, 2008).

Of particular interest were the methodologies that implementers and decision makers were choosing to use in developing ICDs. Through this process, it was possible to identify a series of best practices and guidelines to improve ICD quality, and thus aid in the evolution of JCIDS.

Background

The JCIDS process was created as a response to a 2002 memorandum from the Secretary of Defense to the Vice Chairmen of the Joint Chiefs of Staff to study alternative ways to evaluate requirements (JCIDS, 2014). At the time of this memorandum, the governing document was Chairman of the Joint Chiefs of Staff Instruction 3170.01B (CJCSI, 2001) and was titled the Requirements Generation System. The purpose of JCIDS was to streamline and standardize the methodology to identify and describe capabilities' gaps across the DoD, and to engage the acquisition community early in the process while improving coordination between departments and agencies.

The GAO's (2008) report indicated that "the JCIDS process has not yet been effective in identifying and prioritizing warfighting needs from a joint, department-wide perspective" (GAO, 2008, para. 1). This report outlined the shortfalls and gaps in the JCIDS process in its 5-year life span, furthering the redesign of the process. Additionally, the report outlined several recommendations for the DoD, including developing a more analytical approach within JCIDS to better prioritize and balance capability needs as well as allocating the appropriate resources for capabilities development planning.

The current documentation for both creating and implementing ICDs are the *Capabilities-based Assessment (CBA) User's Guide* and the JCIDS manual. These documents were released in 2009 and 2012 respectively

as a part of the process to address the issues found by the 2008 GAO report. The impact of these documents in improvements to the JCIDS process has yet to be determined, but will be discussed in this article.

Focus and Methodology

The research team used the Knowledge Management/Decision Support (KM/DS) system to examine the JCIDS process. The KM/DS Web site is the repository for the documents created through or as a byproduct of the JCIDS process. Included in this study are ICDs, Joint Capabilities Documents (JCD), Capability Development Documents, and other supporting documents that are a part of this process. To focus this research, the team specifically studied the core documents—ICDs and JCDs—to better understand what kinds of methodologies are being implemented by the various Services to convey the gap information under study.

Of those entered in the KM/DS system, there were over 1,000 ICDs and JCDs in various phases of the JCIDS process covering the period January 1, 2002 to December 31, 2012. The team decided to focus on only those documents that were considered ‘Validated’ and ‘Final,’ with the expectation of little to no revision remaining for these documents in the near future. These criteria reduced the number of the documents under review to 225 ICDs/JCDs. The team of four researchers split the ICDs/JCDs evenly across year and type to ensure similar exposure to the complete population available. At the completion of the review, the researchers met and discussed commonalities and anomalies found in

TABLE 1. ATTRIBUTES FOR ANALYSIS

Attributes			
ACAT Level	DOTMLPF-P Analysis	Measures of Effectiveness	Threshold Values Defined
Lead FCB	Formatting	UJTL Traceability	Objective Values Defined
Supporting FCBs	Analysis Described	Number of Gaps	Number of Pages
Current Milestone	Capabilities Defined	Gap Prioritization	Attributes Listed

documents of interest, and in the population in general. For purposes of this article, the term ICD will be used to describe both the ICDs and JCDs unless specified otherwise.

The team formulated an initial set of generally accepted methodologies for a baseline to identify, categorize, and sort the currently used methodologies within the ICDs. They did not solely consider this set of techniques, but allowed for an expansion of the list to detect emergent techniques.

Ultimately, it was the intention of the research team to observe and report on best practices for future ICD writers.

Additionally, an analysis was performed on key metrics and areas of interest to see if there were any correlations or observations that could be made about various components of the ICDs. These attributes were chosen as they were key areas of interest or sections in the *Capabilities-based Assessment (CBA) User's Guide* and the JCIDS manual. By examining these attributes, the team was able to determine to what extent past ICDs have followed current guidance. Some of the components considered in the analysis can be found in Table 1.

Ultimately, it was the intention of the research team to observe and report on best practices for future ICD writers. As such, we focused on finding those ICDs that best embodied the intentions found in the *Capabilities-based Assessment (CBA) User's Guide* (JCS, 2009) and the JCIDS manual (JROC, 2012).

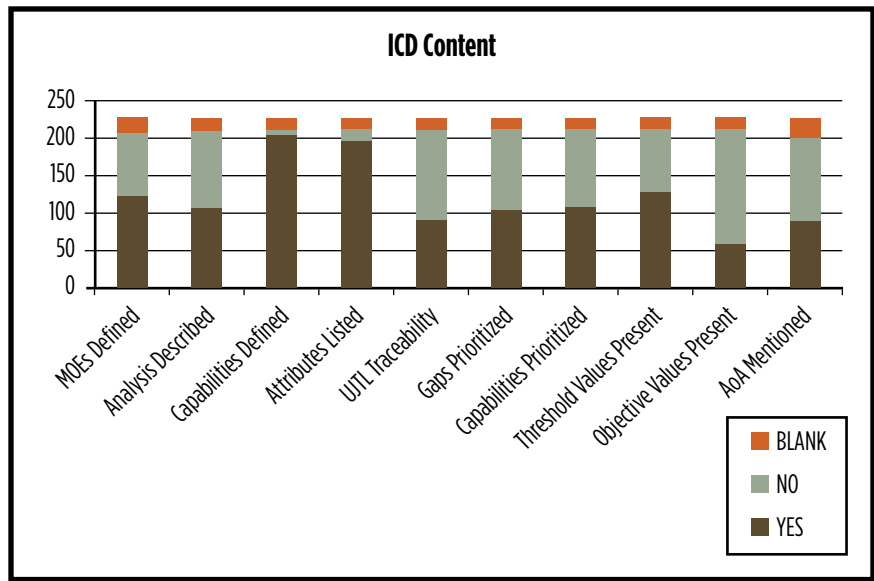
Results

The team examined several ICD characteristics that are presented in the JCIDS manual and were expected to be used in most ICDs (Figure 1). The team found that of the features prescribed by the *JCIDS manual*, many were not present in the majority of ICDs reviewed. Less than half of the ICDs described what analysis was done to identify capability gaps. Over 90 percent of the ICDs reviewed define a specific capability while some ICDs do not have a well-defined end state.

Nearly half of the ICDs analyzed defined their Measures of Effectiveness (MOE), described their analysis, prioritized gaps and capabilities, and defined minimum values for required capability attributes. The presence of these characteristics provides additional information to the reader and improves the fidelity of the ICD; their absence leaves commonly questioned areas open for discussion. The 2012 JCIDS manual requires threshold values, but description of the analysis has been left open to the document creator, and many choose not to describe it. In fact, the manual states a preference to “avoid unnecessary rigor and time-consuming detail.” Applying and documenting some level of rigor seems necessary and useful for documenting how gaps were identified and showing how the capability requirements were justified. The prioritization of gaps and capabilities helps decision makers understand those components that are critical when resources are limited to address the full capability gap, but allows for partial capability fulfillment or a subset of smaller gaps to be filled.

The inclusion of an Analysis of Alternatives (AoA) is an interesting additional piece of content as it is no longer part of the *Capabilities-based Assessment (CBA) User’s Guide*, and is done in subsequent work of the

FIGURE 1. ICD CONTENT ANALYSIS

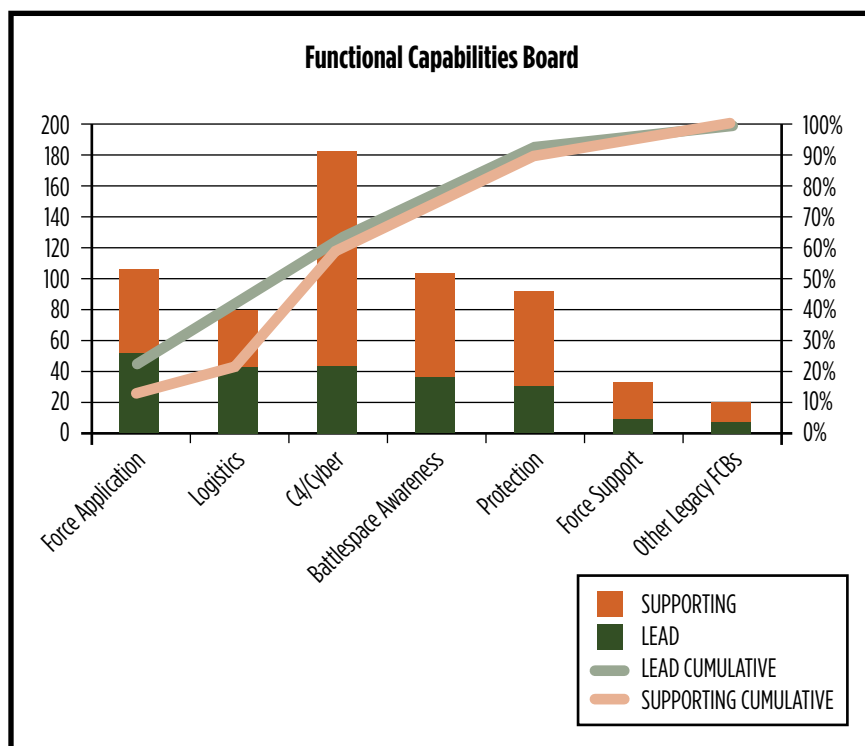


Note. AoA = Analysis of Alternatives; MOEs = Measures of Effectiveness; UJTL = Universal Joint Task List.

JCIDS process. Nearly one-third of all ICDs included some form of an AoA, whether in the form of a brief paragraph or a full documentation found in attachments or enclosures. Most documents that contained a complete AoA were from the first 5 years, a period of time in which the content of ICDs was still in flux. Including an AoA would presuppose a preferred materiel solution—something not within the scope of documenting a capability gap.

Also, less than 25 percent of the ICDs surveyed contained objective values for the capabilities to be met. While it has become more common for threshold values to be defined for capabilities, objective values can only be seen in less than half of those cases. One might expect to see objective values used more frequently to quantify desired capabilities beyond the minimums. Including objective values is expected to aid the process owner in determining if a recommended solution is able to meet the objective of closing the specified gap.

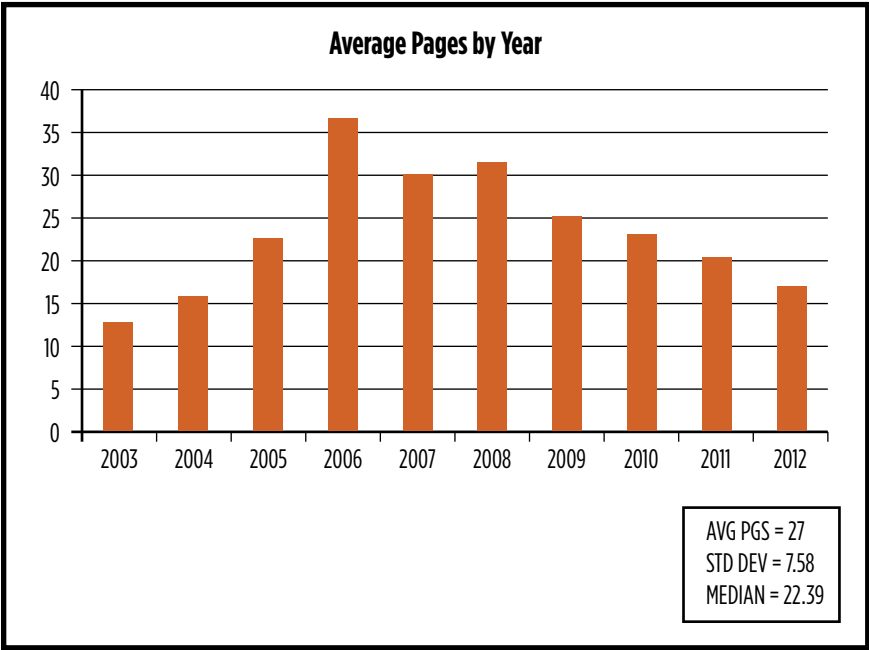
FIGURE 2. NUMBER OF FUNCTIONAL CAPABILITIES IN ICDs ANALYZED



Identifying the Functional Capabilities Boards (FCB) to which ICDs were assigned provided insight as to what types of capabilities have been defined and what priorities have been dictated. FCB and associated Joint Capability Area (JCA) categories include Force Support (formerly Force Support and Building Partnerships); Battlespace Awareness; Force Application; Logistics; Command, Control, Communications, and Computers (C4)/Cyber (formerly Net-Centric, Command and Control, and C4/Cyber); and Protection. Previous FCBs, including Special Operations and Test, are listed in Figure 2 under “Other Legacy FCBs.”

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FIGURE 3. AVERAGE NUMBER OF PAGES FOR ICDs IN CORRESPONDING YEARS



Each ICD is assigned a lead and supporting FCB. Figure 2 shows ICDs arranged by lead FCB with Force Application being the most prominent lead FCB. The prominence of Force Application over Force Support led the team to conclude that validated ICDs are more likely to focus on the direct needs of the warfighter and less likely to focus on capabilities of supporting processes. At the same time, a significant number of ICDs listed net-centricity and C4/Cyber as supporting FCBs.

The research team decided early on to capture the length of ICDs as the *Capabilities-based Assessment (CBA) User's Guide* specifically states that ICDs should be no longer than 10 pages, with separate allowance for appendices (JCS, 2009). Figure 3 presents the average ICD page length without appendices; quality and meticulousness were not necessarily correlated with quantity of pages. ICDs were meant to be concise documents that outline the necessary capabilities while still answering the required content.

The drastic increase in length of ICDs is potentially a result of a change in the process by which capability gaps were outlined. As with most processes, uncertainty in a new method allows for an increase in the breadth and depth of the information found within ICDs. As page length has been steadily decreasing over the last few years, it would suggest that sponsors have become more comfortable with the process and have become more efficient at outlining the information needed.

One final note concerning page length was to evaluate the relation of page length to Acquisition Category (ACAT) level. Would larger projects lend themselves to taking more pages to explain the research and identify the gaps? These two factors were examined, and between ACAT Levels I, II, and III the mean page length was 25.53, 23.35, and 21.02 respectively. While the difference between ACATs I and III are statistically significant using a t-test with an alpha of .05, the difference (on average) is roughly four pages.

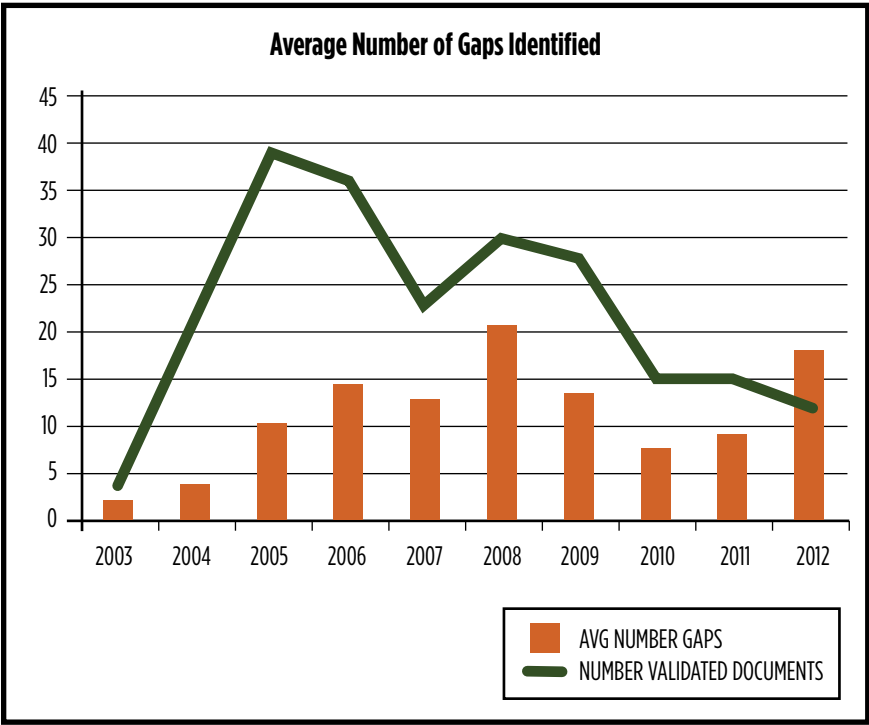
Within the time period analyzed, a total of 2,779 gaps were identified; the average number of gaps identified in an ICD are shown in Figure 4. Additionally, Figure 4 illustrates the fluctuation in the number of ICDs validated each year. The GAO (2008) report noted that JCIDS was ineffective in properly prioritizing capabilities and suggested that nearly all ICDs submitted were accepted. Since the inception of the JCIDS process, 2012 was the first year that the average number of gaps exceeded number of ICDs validated. This suggests that ICDs are identifying more gaps per document, creating documents that are tackling larger and

more complex problems than before. It appears that the JCIDs process has matured, and the process has become more efficient as a result of the GAO report.

The research team noted that many ICDs had “too few” gaps identified (only one or two, or none at all) leading to the conclusion that the methodology employed was not optimal as there are probably more gaps that have yet to be identified, and several documents identified “too many” gaps. It was very difficult to understand and prioritize identified gaps when too many were identified (several contained over 50 gaps).

Figure 5 is a representation of the most frequently used methodologies from 2002 to 2012, displaying the percentage of ICDs covered by the methodology. The top five methodologies were chosen for representation as they represented those methodologies that were implemented in greater than 10 percent of ICDs, whereas the remaining methodologies were typically used in one to two ICDs only. Each ICD employed

FIGURE 4. AVERAGE NUMBER OF GAPS IDENTIFIED COMPARED TO NUMBER OF VALIDATED DOCUMENTS

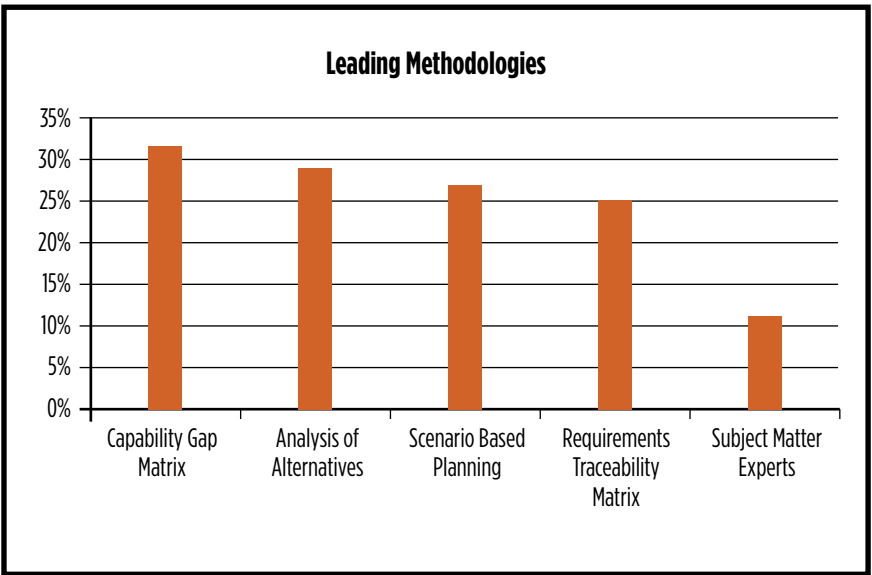


several methodologies so the percentages will not sum to 100 percent. A variety of analytical techniques may be appropriate depending on the type of analysis being conducted. As an example, intelligence-based assessment would likely be an appropriate technique for identifying a strategic capability gap requiring a new weapon system, but not appropriate for identifying the need for a new inventory system for the Defense Commissary Agency.

Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities-Policy

The research team observed at least two interpretations of the Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities-Policy (DOTMLPF-P) analysis within the ICDs. The analysis sometimes took the course where ICDs identified DOTMLPF-P categories of nonmateriel solutions that could satisfy capability gaps, while others took the second interpretation where ICDs considered the DOTMLPF-P implications of their proposed materiel solution. Defense Acquisition University training for DOTMLPF-P distinguishes between these uses and indicates that the ICD should focus on the former approach as the latter is addressed in later stages of the acquisition process (Defense Acquisition University, 2014).

FIGURE 5. TOP METHODOLOGIES USED



We also observed a wide range of quality in these analyses. Many ICDs contained rote statements declaring the insufficiency of these non-materiel approaches to close capability gaps. To paraphrase an example, several ICDs stated that “DOTMLPF solutions were considered..., but adjustments or improvements in these areas will have minimal impact to mission satisfaction.” Though not every capability gap can be met with nonmateriel solutions, such “box check” DOTMLPF-P analyses offer no value to the requirements validation process.

3 In contrast, several analyses reflected a concerted effort to find nonmateriel solutions to supplement the proposed materiel solution. One example of this level of analysis is the Air Force’s Advanced Pilot Training ICD. In its DOTMLPF-P analysis, the Service employed a three-phase process: first, brainstorming and combining possible solutions; second, conducting quantitative analysis on a subset of the best of the proposed solutions; and third, conducting a qualitative assessment of the final list of proposed solutions. Not all of the nonmateriel solutions were deemed feasible or prudent, but several were included as part of the final recommendations. Further explanations of how the Air Force conducted this analysis are found in the ICD and its attachments on KM/DS.

Recommendations and Guidelines

Through the analysis the team observed a variety of interpretations of how to write an ICD. In general, analytical rigor could be stronger. In a fiscally constrained environment, the importance of documenting analysis is magnified, and many ICDs fell short of careful documentation of analysis. Another observation is that most of the ICDs were submitted by the Services and very few by joint sponsors. This is not surprising as individual Services organize, train, and equip their forces; it is expected that capability gaps will continue to be identified by the Services.

Useful Analytical Techniques

Several ICDs utilized subject matter experts (SME) to identify capability gaps and recommend solutions. One way to incorporate SME input into a more rigorous fashion is by employing the Delphi Technique. In this method, the researcher works with 10-15 experts to identify, further define, and determine the importance of an issue in their area of expertise (Linstone & Turoff, 1975). Using the Delphi method when SMEs are available is one way to add analytical rigor to the ICD process.

Though not possible for all ICDs, several documents included a life-cycle cost summary that was effective in communicating the costs of the capability gap. If the proposed solution is expected to reduce some recurring cost, presenting those numbers can make a convincing case to the reader.

In the Appendix to this article, the authors provide a list of additional analytical techniques along with a short description of each. This resource is intended to assist ICD writers and project managers in selecting a methodology or methodologies appropriate for their document or project. References are provided to direct interested readers to source documents with additional descriptions of each methodology.

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Architectural Enhancements

Nearly all existing ICDs present a High-Level Operational Concept Graphic (OV-1) depicting the proposed solution(s). A previous Air Force Institute of Technology researcher identified several additional Department of Defense Architecture Framework (DoDAF) products that could be useful to present within the ICD (Hughes, 2010). The Capability Taxonomy (CV-2), Capability Dependencies (CV-4), Capability to Operational Activities Mapping (CV-6), as well as the Operational Resource Flow Description (OV-2) and Operational Activity Decomposition Tree (OV-5a) are products now required by JCIDS for the ICD.

Hughes also found value in including the Operational Activity Model (OV-5b) and Operational Activity to Systems Function (SV-5). The OV-5b presents capabilities and activities and their relationship among activities,

inputs, and outputs. The SV-5 maps systems back to capabilities or operational activities. Neither is currently recommended in the JCIDS Manual, but could be presented there as optional architecture products.

Characteristics of Model ICDs

Based upon analysis of the data that were examined during the study, several guidelines or best practices emerged. The best written ICDs provided detailed, but relevant analysis without being too wordy. Here, we propose the contents of a model ICD.

The most fundamental building block of an ICD is conformance to JCIDS standards of format and content. The JCIDS Manual presents a logical flow of the document from gap identification to final recommendations. The Concept of Operations should illustrate how the described capability will support the Joint Force Commander. The JCAs or Universal Joint Task List pedigree should be clear, but not overly detailed. Documents that rolled up capability gaps to Tier 2 or Level 2 components seemed more readable than those that traced capabilities to lower levels. A document that acknowledges extant systems is more convincing in establishing a capability gap.

The team believes that a concise ICD may be written with 5–12 gaps identified. Page lengths may vary by ACAT level, with more complex proposed solutions demanding more explanation, but the ideal ICD would be 15–25 pages in length. In short, a well-written ICD will follow the prescribed format, clearly define its necessity to the joint mission, and be presented in a clear and logical manner. Additionally, the ICD should present clear MOEs with minimum and desired values. Good MOEs allow the reader or evaluator to know when the new capability has delivered on its design promises. MOEs are sometimes confused with measures of performance (MOP). Noel Sproles states, “MOEs are concerned with the emergent properties or outcomes of a solution. They take an external view of a solution and as such are different from MOPs, which are concerned with the internal workings of a solution” (Sproles, 2002).

Table 2 compares ICD content required by the *Capabilities-based Assessment (CBA) User's Guide*, the JCIDS manual, and recommendations based on our analysis. As part of the analysis, the team identified those ICDs that implemented and followed the best practices identified by the team. These ICDs, shown in Table 3, are identified in order to

give future ICD writers and functional groups examples of what they can strive toward to make clear and concise documents that are both effective and efficient.

Future Research and Conclusions

Future research could focus on the relationship between the ICD and the program it generates. Can the utility or performance of a program be traced to the description of the initial capability gap and

TABLE 2. COMPARISON OF CBA/ICD CONTENT

CBA User's Guide	JCIDS Manual	Research Team
Purpose	CONOPS/Desired Outcomes	CONOPS
Background/Guidance	Joint Functional Areas	Relationship to Tier 2 JCA/UJTL
Objectives	Description of Required Capability Gaps, Overlaps, Redundancies	Analysis Techniques Used with Description of Scope
Scope	Capability Attributes/Metrics	Prioritized List of 5-12 Capability Gaps
Methodology -Approaches -MOEs -Technological/Policy Opportunities	Relevant Threats/Operational Environment	Clearly Defined MOEs with Threshold and Objective Values
Organization/Governance	Proposals for Non-materiel Solutions	DOTMLPF-P Analysis of Non-Materiel Solutions
Projected Schedule	Final Recommendations	Clear Final Recommendations
Responsibilities		

Note. CBA = Capabilities-Based Assessment; CONOPS = Concept of Operations; DOTMLPF-P = Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities - Policy; ICD = Initial Capabilities Document; JCA = Joint Capabilities Assessment; JCIDS = Joint Capabilities Integration and Development System; MOEs = Measures of Effectiveness; UJTL = Universal Joint Task List.

TABLE 3. SAMPLE OF EXEMPLARY ICDS

Document Name (Control Number)	Year	Noteworthy Items
Data Masked (05-51947485-00)	2005	Layered analytical methods resulted in 100 shortfalls that were further clustered and examined-top 3 presented for further study
Military Operational Medicine (07-65416952-00)	2007	Extensive Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities (DOTMLPF); lots of prioritized tables
Aviation Ground support (07-600735309-00)	2007	Prioritized tables, quantitative threshold values, good DOTMLPF, multiple methods used to determine/rank Nonmateriel Solutions
Initial Capabilities Document for Joint Improvised Explosive Device Defeat (07-66686002-00)	2007	Performed a well-documented, thoughtful DOTMLPF analysis; references three assessments—Joint Staff (J8), Joint Improvised Explosive Device Defeat Task Force baseline, and follow-on; prioritized tables
Biometrics in Support of Identity Management (09-090146111-00)	2008	Detailed analysis including Scenario-Based Planning and Risk Analysis
Advanced Pilot Training (10-99164267-00)	2009	Strong DOTMLPF Analysis; clear explanation of analytical approach included in Appendices
Vessel To Shore Bridging (09-97169105-00)	2009	Gaps have numerous subparts; uses a typical but good example of capability prioritization/mapping matrix (includes Measures of Effectiveness [MOE] and Minimum values)

TABLE 3. SAMPLE OF EXEMPLARY ICDS (CONTINUED)

Document Name (Control Number)	Year	Noteworthy Items
Cross Domain Enterprise (10-112959174-00)	2010	Uses a typical but good example of capability prioritization/mapping matrix (includes MOEs and Minimum values); recommends mix of Materiel and Nonmateriel Solutions
Amphibious Combat Vehicle ICD (11-151956055-00)	2011	Requirements traceable to the Joint Operating Concept vice Universal Joint Task Lists; uses a typical, but good example, of capability prioritization/mapping matrix (includes MOEs and Minimum values); recommends mix of Materiel and Nonmateriel Solutions
Personnel Recovery (12-167465473-00)	2012	Succinct Document; recommends Materiel and Nonmateriel Solutions
Data Masked (12-159990107-00)	2012	Detailed analysis using several techniques; Well-defined MOEs including Threshold and Objective Values

requirement definition? Are there characteristics of an ICD that indicate how well a program will adhere to cost, performance, and schedule expectations?

Since 2002, the JCIDS process has been refined and enhanced. There appears to be a convergence in the formatting and content of many ICD/JCDs since 2008. While the quality of historical ICDs varies, marked improvements to the analysis have been documented since 2008, possibly due to the GAO report from the same year.

Through research of the current methodologies used in ICDs since the inception of the process, the research team has formulated an outline of proposed areas upon which writers and implementers can focus. Future writers may use this outline as well as series of DoD guidelines to provide the Joint community with superior ICDs that achieve their goals in a more efficient manner with minimal processing time.



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APPENDIX

Additional Analytical Techniques to Assist Initial Capabilities Document (ICD) Writers and Project Managers

Method	Source(s)	Explanation	Usage Context(s)
Pre-Capabilities-based Assessment (CBA)			
Scenario-based Planning	Capabilities-based Assessment (CBA) User's Guide, p. 87 (Ringland & Schwartz, 1998) (Hiam, 1990, p. 284)	Technique using scenarios to define/give structure to an otherwise murky strategic future. A type of brainstorming, which may use nominal group technique or another group problem-solving technique. ▪ Assumptions/drivers of change (identify key variables and historical trends) ▪ Develop framework for drivers ▪ Produce initial miniscenarios (vary the type: surprise-free, radical, and in-between) ▪ Reduce to 2 or 3 scenarios ▪ Write scenarios ▪ Identify issues arising (sensitivity analysis with scenarios' impact on key variables)	Mostly pre-CBA; used to build portfolios; however, can be used in a CBA (e.g., to analyze threats, etc.).
Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis	(Helms & Nixon, 2010)	Analyzes internal (strengths/weaknesses) and external (opportunities/threats) factors to help guide corporate strategy development. Useful in a group strategy setting, using nominal group technique, or another group problem-solving technique (like a Group Decision Support System, or GDSS). See also Porter's 5 Forces and Barney's Resource-based View for more specific analyses.	Mostly pre-CBA; used to build portfolios; however, can be used in a CBA (e.g., to analyze threats, etc.). <u>Generally criticized for its lack of depth and rigor.</u>
Porter's 5 Forces Analysis	(Porter, 2008)	Builds on the "threats/opportunities" side of SWOT to explain how market structure, defined by five market forces (threat of entrants, supplier power, buyer power, intensity of rivalry, threat of substitutes) and one additional force (complementors/government/public) drive the content and performance of firms.	Mostly pre-CBA; used to build portfolios; however, can be used in a CBA (e.g., to analyze threats, etc.). <u>Generally criticized for focus on external environment, vice internal.</u>

APPENDIX (Continued)

Method	Source(s)	Explanation	Usage Context(s)
Barney's Resource-based View (RBV)	(Barney, 1991)	Builds on the "strengths/weaknesses" side of SWOT to explain how a firm's internal resources (value [V], rareness [R], nonsubstitutability [NS], imperfect imitability [II]), lead to sustainable competitive advantage (SCA). $SCA = V + R + NS + II$ <u>Must have first three to achieve competitive advantage, and all four to achieve SCA.</u>	Mostly pre-CBA; used to build portfolios; however, can be used in a CBA (e.g., to analyze threats, etc.). <u>Generally criticized for focus on internal environment, vice external.</u>
The Project Management Diamond Approach	(Shenhar & Dvir, 2007)	Uses four quadrants of Technology, Complexity, Novelty, and Pace to define the size, scope, and risk of a systems engineering product/project	Pre-CBA (used to define a product portfolio), CBA/ICD (developing Measures of Effectiveness (MOE), Capabilities Development Document (CDD) (defining system risk).
Market Segmentation Grid	GAO Report No. 07-388, p. 11	A grid which compares four markets (current/new customers in existing segments/customers in new segments/new customer wants and needs) to four offering types (current business/enhancement to current business/new business/new to industry) in order to position portfolio projects into four categories (strike zone/traditional/pushing the envelope/white space opportunity). A method of analyzing business risk that encourages businesses to find the right mixture of categories of projects. Similar to Risk/Rewards Matrix.	Mostly pre-CBA; used to build portfolios; however, can be used in a CBA.
Risk-rewards Matrix	GAO Report No. 07-388, p. 16 (Hiam, 1990, p. 377)	A grid that plots "risks" vs. "rewards" of projects. Similar to Market Segmentation Grid in that it encourages businesses to find the right mixture of categories of projects. The same tool can be used to compare effectiveness to cost in the AoA "Alternatives Comparison" step (particularly useful in showing confidence levels and threshold values). The "GE matrix" version of this maps "business strength" (internal) vs. "industry attractiveness" (external). The circles may be subdivided into market share/total market pies to enhance analysis. <u>Augments SWOT.</u>	Mostly pre-CBA; used to build portfolios; however, can be used in a CBA. Strength is that <u>the confidence level of estimates is captured (by the size of the circles).</u>

Method	Source(s)	Explanation	Usage Context(s)
Nominal Group Technique	(Sink, 1983)	A brainstorming technique that mixes individual and group activities to attempt to increase the amount, diversity, and quality of ideas generated. Many variations, but follows the basic process below: ▪ Individual Brainstorming ▪ Sharing Ideas ▪ Group Brainstorming (divergent) ▪ Group Discussion ▪ Group Brainstorming (convergent) ▪ Voting/ranking	Pre-CBA strategic planning, CBA (developing capabilities/MOE), Analysis of Alternatives (AoA)/ICD/CDD (developing attributes/Key Performance Parameters [KPP]). <u>Technique strong in generating many diverse ideas without arriving at Groupthink. Other group problem-solving techniques may be superior (e.g., GDSS), but at an increased process cost.</u>
Delphi Technique	(Goodman, 1987)	A type of brainstorming that uses experts to a) identify issues in their area of expertise, b) further define issues in their area of expertise, and c) identify the importance of issues in their area of expertise. Generally uses 3-9 experts, and begins with <i>Nominal Group Technique</i>, using future rounds to refine/reduce/prioritize issues.	CBA ICD (capabilities, MOEs), and AoA/CDD (attributes, KPPs). An example of an “expert” systems analysis technique. <u>Careful choice of experts is essential.</u>
CBA/ICD			
Capabilities-based Assessment (CBA)	<i>Capabilities-based Assessment (CBA) User’s Guide</i>	1) Describes capabilities required to perform a mission 2) Identifies gaps in capabilities and associated operational risks 3) Establishes a requirement to address gaps	CBA. Results in an ICD (which not only documents the CBA, but acts as a decision document).
Initial Capabilities Document (ICD)	<i>Capabilities-based Assessment (CBA) User’s Guide</i>	1) Describes/summarizes Concept of Operations (CONOPS) (-1 page explanation of CONOPS) 2) Describes guidance (see <i>Requirements Traceability Matrix</i>) 3) Describes capabilities required (includes MOEs/threshold values) 4) Describes capability gaps (prioritized, if possible) 5) Summarizes relevant threats/operational environment 6) Proposes nonmateriel and materiel solutions (see <i>Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities-Policy [DOTMLPF-P] Analysis</i>) 7) Final recommendation (normally, but not necessarily, a materiel solution)	CBA/ICD. The ICD is a decision document to further explore an enhanced capability (result of a CBA). Cornerstone document in the Joint Capabilities Integration and Development System (JCIDS) process. <u>Listing to the left is not comprehensive.</u>

APPENDIX (Continued)

Method	Source(s)	Explanation	Usage Context(s)
Requirements Traceability Matrix	Air Force Instruction (AFI) 10-601	Also known as “house of quality,” traces system attributes to operational/user/strategic requirements. Multiple levels.	CBA/MOE (developing capabilities/MOEs), AoA/ICD/CDD (developing system attributes/KPPs)
Paired Comparisons	(Blanchard & Fabrycky, 2010, p. 182)	To build a rank-ordered list, each of the options is presented to the decision maker two at a time (instead of all at once). For N criteria to be ranked, $N(N - 1)/2$ pairs must be compared. <u>Assumes transitivity of preferences.</u>	CBA/MOE/ICD (development of criteria). <u>Rank-ordering importance of design parameters/capabilities/gaps.</u>
Porter’s Value Chain Analysis	(Hiam, 1990, p. 415) (Porter, 1980)	1) Select unit of analysis, both for your organization and for competitors 2) Identify primary value-adding activities (direct/indirect/quality assurance) Inbound/outbound logistics, operations, marketing/sales, service 3) Identify support activities (direct/indirect/quality assurance) Procurement, technical development, human resource management, firm infrastructure 4) Identify linkages between value chain activities 5) Study the value chain to identify sources of competitive advantage	Pre-CBA, AoA. Much like a <i>DOTMLPF-P Analysis</i> , the value chain requires a gap analysis, but not just internal (between self and competitors), and not just in isolation (focus is on interactions).
Systems Definition Matrix	(Sage & Armstrong, 2000, p. 98)	Applies general systems theory to define both the SCOPE (needs/objectives/criteria) and BOUNDS (parameters/variables/constraints) of a system (e.g., capability, MOEs, attributes, KPPs). <u>No real analytic technique used to define</u> , although defining the SCOPE and BOUNDS of a system can use many of the methods contained herein.	CBA/ICD (capabilities, MOEs), and AoA/CDD (attributes, KPPs). See also Work/Product Breakdown Structure (WBS/PBS) for a technique to develop the initial listing of attributes.
Input-Output Matrix	(Sage & Armstrong, 2000, p. 102)	Applies general systems theory to define inputs (intended/unintended) and outputs (desired/undesired) and begin a more sophisticated discussion about refining a system, such as: situation, expertise, risk, spillover effects, knowledge, viewpoints, experience, kind of need, frequency, urgency, limits, and tolerances. As shown in Sage, uses a WBS structure, but could also use a PBS structure.	CBA/ICD (capabilities, MOEs), and AoA/CDD (attributes, KPPs).

Method	Source(s)	Explanation	Usage Context(s)
Rapid Application Development (RAD)	(Mackay, Carne, Beynon-Davies, & Tudhope, 2000)	RAD uses short, iterative design cycles to produce working prototypes and systems. A mixture of paper prototypes (e.g., the different Department of Defense Architecture Framework (DoDAF) views, use cases, screen shots), code stubs I menus, and models may all be used. Many types, including: ▪ Joint Analysis and Design (JAD): ½-day sessions placing developers and users together. Developers use the rest of the day to build prototypes. Lasts ~1 week. ▪ eXtreme: exploration consists of users writing story cards (use case), which developers analyze and give estimates to complete. Business then prioritizes the cards by usefulness and developers prioritize by risk. Best mix of cards selected to implement.	<u>Usually used when implementation is more important than documentation;</u> however, the process of idea generation and documentation makes this technique ideal for pre-CBA and CBA activities. Technique may also be used in early systems engineering (SE) to help define systems (assumes that many users do not “know what they want until they see it”).
Use-cases	<i>Capabilities-based Assessment (CBA) User’s Guide</i> , p. 87	A use-case may be as broad as a story outlining how a system would be used in an ideal circumstance (or multiple circumstances), or might be as specific as a Unified Modeling Language (UML)-based diagram outlining a specific system interaction that can be used to generate an engineering prototype. Many ICDs iterate 1–4 possible “scenarios for use,” with the resulting scenarios resembling SE use-cases.	Normally post-CDD; however, technique useful in early SE. See Scenario-based Planning for a similar technique applied to large-scale planning.
Intelligence-based Assessment	Existing ICDs	Used either to further define a capability gap, or to further define the “threats/operational assessment” category, this item usually lists the threat as defined by current intelligence assessments, as well as the reference for the applicable intelligence assessment.	Pre-CBA, CBA, ICD. Analysis type is present in Operations Plan/Concept of Operations Plan (OPLAN/CONPLAN), so it helps trace operational requirements/gaps to those documents.
Work/Product Breakdown Structure (WBS/ PBS)	(Turner & Cochrane, 1993)	May be defined from top-down (decomposition), or bottom-up (engineering). Begin with major items, and continually ask “what comes next,” or “what is this component/objective made of.” Stop when either: 1) you know how to measure (objectives) or 2) a reasonable amount of work (i.e., “work package”). <u>“Decomposition” risk is that not all end items are identified, leading to inaccurate estimate. Engineering risk is in omitting important integration items, or nonproduct-related tasks (i.e., Project Management.)</u>	CBA/MOE (developing criteria), AoA/ICD/ CDD (system definition). Used to decompose requirements or work hierarchically. May then be used for the basis of defining/estimating work, cost, measures of effectiveness, or other decision objectives/ criteria.

APPENDIX (Continued)

Method	Source(s)	Explanation	Usage Context(s)
Measure of Effectiveness (MOE) Definition	(Sproles, 2002, p. 255)	- Request to formulate MOEs - Determine viewpoint - Determine mission - Decide on Critical Operational Issues (COI), i.e., “tasks/categories”) - Draft MOEs (creative/testable/consistent with library/statement) - Evaluate/Revise/Agree on MOEs - Apply MOEs	CBA/ICD. MOEs are normally high-level, and one might expect 10–20 of them in an ICD, whereas a CDD might contain hundreds of KPPs. Modern ICDs will usually contain MOEs as well as threshold values.
Requirements Correlation Table	<i>Manual for the Operation of the JCIDS</i> , 2012, p. B-31; AFI 10-601, p. 37	Summary of all desired capability characteristics listed as <i>threshold/objective</i> values, mapped to their Joint Capability Area (JCA). Three tables: Key Performance Parameters (KPP), Key System Attributes (KSA), Attribute. Each table has a brief explanation of derivation/justification of attributes listed. - KPP: system attributes considered most critical or essential for an effective military capability. Failure to meet KPP threshold may result in program reevaluation/reassessment. - KSA Table (AF-only): Only the most critical system attributes are included and <i>prioritized</i>. - Additional Attribute: Same as KSA, but contains additional items	ICD/CDD. Helps decision makers and acquisition community decide on most important attributes, and the threshold / objective values those items must exhibit. Note that JCAs, listed in the <i>Manual for the Operation of the JCIDS</i> , p. B-B-1, can be used to assist in attribute definition as early as the CBA process, as well as to derive KPPs from JCAs.
Capability Gap Matrix	Existing ICDs	Perhaps the most common table arising since 2008 in ICDs, this table lists (in the following order): Priority, Capstone Concept for Joint Operations (CCJO) Key Characteristics, Capability, JCAs, Parameters/Measures of Effectiveness, and Minimum Value (for Parameters). Answers many key questions, and may be combined with a capability gap matrix. See <i>Requirements Correlation Table and Capability Gap Pairwise Matrix</i> .	CBA, ICD. This table combines capabilities, MOEs, and minimum values. <u>It does not directly address capability gaps (unless gaps are incorporated).</u>

Method	Source(s)	Explanation	Usage Context(s)
Capability Gap Pairwise Matrix	Capabilities-based Assessment (CBA) User's Guide, p. 89; Existing ICDs	A method of prioritizing capability gaps with respect to each other by pairwise comparison (using correlation matrix). Each capability is listed both on the rows and the columns, and compared to others (1.00 is "the same as," while 0.00- .99 is "less than," and 1.01- > is "greater than"). The relative weight of items to each other is multiplicative (with 2.00 being "twice as important as"). Scores are summed across rows (and normed, if desired), and then rank-ordered based on the scores, with a higher score being more important. Note: One variation uses "stoplight" (i.e., Red, Yellow, Green) to highlight the degree to which an attribute (column) represents a "gap" with current key UJTL, JCA, etc. tasks (tuple).	CBA. Technique also useful to rank-order MOEs (ICD) and/or criteria (AoA/CDD). See <i>Pairwise Comparison</i> for a similar technique exploring the same questions (uses transitivity to justify using fewer comparisons). <u>Scores, rankings, and "stoplight" symbols are qualitative measures, assigned at the discretion of the ICD team.</u>
DOTMLPF-P Analysis	<i>Capabilities-based Assessment (CBA) User's Guide; Manual for the Operation of the JCIDS</i>	Any analysis that includes the following factors (and their potential interactions): Doctrine, Organization, Training, Materiel, Leadership Policy and Education, Personnel, Facilities, and Policy. <u>Important to consider in all phases of early systems analysis, including: a) Gap analysis (CBA), b) nonmateriel solution (CBA—most typical use), c) nonmateriel enablers to materiel solution (CBA and/or CDD).</u>	CBA/MOE (developing capabilities/MOEs), AoA/ICD/CDD (developing/rating system Attributes/KPPs). See DOTMLPF-P Matrix.
DOTMLPF-P Matrix	Existing ICDs	A matrix showing capability gaps and/or objectives down tuples and Y/N/P answers to DOTMLPF-P on each column, with a "rationale/comments" column. Y = gap may be resolved without materiel development N = no solution currently exists P = partial solution exists	CBA /ICD/AoA/CDD. <u>This version of the matrix is tailored toward gap analysis, specifically.</u> May have other uses; see DOTMLPF-P Analysis.
Cross-interaction Matrix	(Sage & Armstrong, 2000, p. 110)	A correlation matrix showing the interactions between system objectives (as shown, uses ordinal "+," "0," and "-" to show interactions, but could also use scalar <i>Capability Gap Matrix</i> Measures).	CBA/ICD (capabilities, MOEs), and AoA/CDD (attributes, KPPs).
Frequency/Investment Matrix	(Williamson, 1979)	Recurrent or occasional, but nonspecific market transactions are best handled by classical (market) contracts. The tendency toward recurrent and idiosyncratic transactions tends to favor unified governance. May also explain boundary of firm, vertical integration, and departmentalization (consideration for funding CBA work via contracts).	Used to determine type of contract one might use to purchase different types of services on the market. <u>Uses transaction costs (immeasurable) as theoretical mechanism to explain.</u>

APPENDIX (Continued)

Method	Source(s)	Explanation	Usage Context(s)
AoA/CDD			
Analysis of Alternatives (AoA)	AFI 10-601; AoA Handbook, pp. 14, 31, 33, 45,46,47	The AoA is a process, consisting of four basic sections: 1) Effectiveness Analysis, 2) Cost Analysis, 3) Risk Analysis, and 4) Alternative Comparison. Each of these four items uses techniques such as <i>Decision Evaluation Matrix</i> to evaluate alternatives based on MOEs. MOEs may be mapped to their overarching tasks or desired outcomes. • Effectiveness Analysis: 1) Select Mission Tasks (MT), MoEs, and MoPs, 2) Select threats/ scenarios, 3) Describe alternatives, 4) Determine level of detail, 5) Identify suitable analysis tools/ data sources (consider including sensitivity analysis) • Cost Analysis: 1) sunk, 2) research and development, 3) investment, 4) operating/ support, 5) disposal, 6) baseline extension, 7) prefielding • Risk Analysis: see <i>Risk Analysis</i> • Alternative Comparison: see <i>Decision Evaluation Matrix</i> and <i>Risk-Rewards Matrix</i>. The <i>AoA Handbook</i> shows a <i>Decision Evaluation Matrix</i> with additional columns (for risk and cost).	AoA/ICD (developing and applying MOE to capabilities), CDD (developing and applying criteria to alternatives). <u>The items used to BOUND the AoA are same items used to BOUND the ICD.</u> <u>AoA Handbook gives guidelines for performing the steps, overview of analysis tools, and modeling suggestions.</u> <u>Finally, AoAs need not identify a single solution (in fact, they may identify a suite of solutions that meet certain requirements).</u>
Decision Evaluation Display	(Blanchard & Fabrycky, 2010, p. 187)	Graphical representation of: 1) alternatives (A, B, C); 2) equivalent cost/profit, 3) other criteria (X, Y, Z). Although not strictly a 2-dimensional view, the x-axis is structured according to increasing cost/profit of alternatives, and the y-axis is scaled with relative (ordinal, i.e., less than, equal to, more than) achievement by alternatives of the criteria. (Note: Normally, these would be separate graphs for each criteria, but they are <u>stacked on top of each other to simplify the display, with no implication of relevance of the different position of each criterion on the y-axis [except with reference to itself].</u>)	CBA/MOE (developing criteria), AoA/ICD/ CDD {applying criteria). Organizes information on alternatives and degree of compliance with criteria (including threshold values) while still allowing for decision-maker insight, intuition, and judgment. <u>Not intended to be mathematically applied.</u>

Method	Source(s)	Explanation	Usage Context(s)
Decision Evaluation Matrix	(Blanchard & Fabrycky, 2010, p. 189)	A matrix with alternatives on the x-axis (as a <i>tuple</i>), and three items on the y: • Header #1: a future not under the control of the decision maker (“state of nature”) • Header #2: the probability (<i>p</i>) of that future • Each cell: evaluation (<i>E</i>) measure (positive or negative) of [alternative x future]; may be subjective (i.e., categorical) or objective (e.g., monetary values). Possible decision-making criterion (to select most desirable alternative): • Aspiration level: setting desired <i>min</i> and <i>max</i> levels for each criterion, or for all criteria as a whole • Most probable future: <u>useful if one probability dominates</u> • Expected value (EV): $EV = \sum(E \times p)$ where $\sum p = 1.00$ <u>useful for repetitive environment</u> ~ Laplace: if <i>p</i> unknown for each alternative, divide 1.00 by number of alternatives) ~ Maximin: <i>best</i> alternative given the worst possible outcome ~ Maximax: <i>best</i> alternative given the <i>best</i> possible outcome ~ Minimax (includes “regret”): best outcome – outcome for “<i>a_j</i>”/“<i>s_j</i>”; attempts to calculate opportunity cost of a decision ~ Hurwicz rule: assigns an optimism index from 0-1.0 (<u>assumes linearity</u>)	CBA/MOE (developing criteria). AoA/ CD/ DD (applying criteria). Considers alternatives/ criterion of effectiveness in past/present, but also alternatives/possible future conditions [of use]. <u>Assumes: all viable alternatives considered, all possible futures identified, all futures and [alternatives x futures] are orthogonal, occurrence of specific future is unknown (otherwise, matrix simplifies to a vector of evaluation measures).</u> <u>Limitation: each of these methods yields different results.</u>
Decision Tree	(Kirkwood, 2002)	Calculates an expected value (EV) for each of a number of possible options, exploring what happens if selection leads to success or failure. <u>May include a “none of the above” option.</u> One common use is to include, add together the cost of each of the options with their expected payout to generate the evaluation (<i>E</i>) measure. • $EV = \sum(E \times p)$, where $\sum p = 1.00$ for the outcome of each decision. <u>Most useful for repetitive environment; otherwise, the EV metric has no inherent meaning (although often shown as monetary value, \$).</u>	CBA/CD/AoA/CDD. Amenable to monetary decisions <u>that can be stated in Boolean (success/failure) terms. Options must be orthogonal. May also be used to model multiple, sequential decisions.</u> See <i>Decision Evaluation Matrix</i> for an additional application of this technique.

APPENDIX (Continued)

Method	Source(s)	Explanation	Usage Context(s)
Optimization Modeling/Linear Programming	(Blanchard & Fabrycky, 2010, p. 177)	$E = f(X, Y_d, Y_i)$ $X =$ Design variables (factors that define design optimization space) $Y_d =$ Design-dependent variables (under control of designers) $Y_i =$ Design-independent variables (not under designer-control)	CBA/MOE (developing criteria), AoA/ICD/CDD (applying criteria). Determining effectiveness of a system based on a model of that system including the most relevant variables. Models lack of certainty due to factors not under designers' control. See <i>Decision Evaluation Matrix</i> for an additional application of this technique.
"Scorecard" Matrix	(Sage & Armstrong, 2000, p. 111)	Yet another technique to compare alternatives to criteria, this time with the emphasis on technology maturity alternatives (see <i>Market Segmentation Grid</i>) crossed with the "-ilities"—although any combination thereof with other techniques in this listing could be used.	CBA/ICD (capabilities, MOEs), and AoA/CDD (attributes, KPPs).
Utility (Indifference) Curves	(Brosh, 1985, p. 70)	Having developed a decision tree with monetary outcomes (but not yet assigned probabilities of outcomes), it is possible to query the decision maker as to the amount deemed acceptable as a guaranteed payout instead of accepting the probabilities of payouts represented in the decision tree. Varying the probabilities and re-asking this question allows one to create a utility curve, with the payout on the x-axis and utilities on the y-axis. The "risk-neutral" decision maker's utility curve is negative first derivative (positive, but decreasing), while the "risk-averse" is a positive first derivative (positive, but increasing).	Answers question of decision maker's risk-averse/neutral/seeking nature, i.e., is valuation of marginal utility of money decreasing/constant/increasing? Determines whether to use <i>minimin</i> , <i>minimax</i> , <i>maximax</i> . Paired with <i>Decision Evaluation Matrix</i> to model alternative preference in terms of "utility" vice "monetary."
Weighting	(Blanchard & Fabrycky, 2010, p. 185)	Weights (W) must sum to 1.00 (100%) for each criterion. Ratings (R) based on whatever scalar rating schema one devises (does not work for ordinal/categorical ratings). $Weighted\ Rating = W \times R$ • Tabular display: results indicate how close each alternative comes to the <i>ideal</i>. • Graphical additive: results indicate the overall contribution of the rating in each category to the overall desirability of the alternative.	CBA/MOE (developing criteria), AoA/ICD/CDD (applying criteria). Choosing across a number of design alternatives when categories are not of equal importance (see <i>systematic elimination</i> for another similar method). <u>Caution is advised in developing both criterion and weighting, as well as in interpreting two alternatives that end up rating near each other on the scale.</u>

Method	Source(s)	Explanation	Usage Context(s)																																				
Z-score Transformation	(Daszykowski, Kaczmarek, Vander Heyden, & Walczak, 2007)	For items collected using ratio/continuous data for which an expected value (mean) and dispersion (standard deviation) are known, application of a z-transformation can re-score an item (results in a number between -1.0 and +1.0). Items can then be further transformed by <i>weighting</i> or another technique and be comparable across different items (e.g., "time-to-implement" vs. "distance").	AoA.																																				
National Family Opinion (NFO) Product Analysis	(Hiam, 1990, p. 273)	1) Survey customer attitudes to obtain rankings of importance of product attributes and a rating of the overall product (Likert-type scale: 5-point, -2 to +2). Likert scales are commonly used in surveys to measure attitudes. For example: My current level of job satisfaction is: <table><tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr><tr><td>Extremely</td><td></td><td></td><td></td><td></td><td></td><td>Extremely</td></tr><tr><td>Unsatisfied</td><td></td><td></td><td></td><td></td><td></td><td>Satisfied</td></tr></table> or in the case of the NFO Product Analysis: How well does the product meet the desired attribute (x)? <table><tr><td>-2</td><td>-1</td><td>0</td><td>+1</td><td>+2</td></tr><tr><td>Not nearly</td><td></td><td></td><td></td><td>Far too</td></tr><tr><td>enough of x</td><td></td><td></td><td></td><td>much of x</td></tr></table> 2) Use stepwise linear regression to determine most important attributes to overall ratings (calculate R^2, then "Importance Index": R^2_{ind} / R^2_{tot}). 3) Graph the "importance index" vs. mean ratings for each attribute. Items on upper corners are those worth investing effort into.	1	2	3	4	5	6	7	Extremely						Extremely	Unsatisfied						Satisfied	-2	-1	0	+1	+2	Not nearly				Far too	enough of x				much of x	AoA. A method like this compares the perceived "gap severity" with the "importance" of an attribute in order to assist the researcher in prioritizing the attributes.
1	2	3	4	5	6	7																																	
Extremely						Extremely																																	
Unsatisfied						Satisfied																																	
-2	-1	0	+1	+2																																			
Not nearly				Far too																																			
enough of x				much of x																																			
Systematic Elimination	(Blanchard & Fabrycky, 2010, p. 183)	<u>Do not consider weights, nor trade-offs across alternatives. May use scalar or categorical ratings.</u> • Compare alternatives against each other (norm-referencing: will establish dominance between two options [drop the lower one]). • Compare alternatives against a standard (criterion-referencing: 1) retaining if meets standard for at least one criterion, or 2) retaining if meets standard for all criterion). • Comparing criteria across alternatives (after <i>ranking</i> criterion: 1) choose best alternative, break ties with the second most important criterion, or 2) examine one criterion at a time, comparing the alternatives and eliminate those not meeting minimum standard).	CBA/MOE (developing criteria), AoA/ICD/CDD (applying criteria). Choosing across a number of design alternatives. <u>Outcomes can be specified for all criteria and alternatives.</u> May use to select best option, or to determine which of a number of options meet minimum criteria for further inclusion. See <i>weighting</i> for another similar method.																																				

APPENDIX (Continued)

Method	Source(s)	Explanation	Usage Context(s)
Sahid's Consequences Table	(Hammond, Keeney, & Raiffa, 1998)	Lists alternatives across the columns and key attributes/decision criteria down tuples. The goal of this table is not to combine disparate data types, but rather to search for options that clearly "dominate" other options. The "dominated" options are then eliminated systematically.	AoA. Because it is an initial screening process, it reduces options/simplifies choice; however, <u>ensure the most important attributes are screened first.</u>
Even Swaps	(Hammond, Keeney, & Raiffa, 1998)	A more sophisticated analysis using <i>Sahid's Table</i> , "how much of one attribute are you willing to swap for an increase/decrease in the other?" In this way, attributes of key interest can be made comparable by trading up/down other attributes. <u>This is one form of sensitivity analysis.</u>	AoA. <u>Does not treat alternatives as exclusive; encourages decision maker to look for (not listed) alternatives to satisfy "swapped" items.</u>
Risk Analysis	<i>AoA Handbook</i> , p. 40	Risks are categorized by Severity (S, i.e., consequence) and Probability (p, e.g., likelihood). If each risk is assigned a number from 0.00 - 1.00 for both categories, then a composite risk index can be calculated using: $CR = S \times p$, and a risk matrix can be used to plot the results. Risk may then be avoided, accepted, transferred, and/or mitigated. Some add three columns to a risk table to add how the risk was managed, the resultant risk, and any secondary risks that risk mitigation created.	AoA. Technique uses qualitative assignment of risk values. <u>Normally, risks are assumed orthogonal (however, risk interactions can be modeled with this technique).</u>
Sensitivity Analysis	(Blanchard & Fabrycky, 2010, pp. 589, 614)	A generic category of tools that plots/graphs/calculates the relationship between changing variables, giving an idea of how a modification in one variable affects others. Plotting different alternatives on the same axis gives an idea of the favorability of one option versus the other in the trade space measured (a.k.a. the "breakeven point"). Examples: Pareto chart (a line or bar graph displaying results ordered by frequency of occurrence), scatter plot, cost/year plot.	Primarily AoA/CDD, but can be used in CBA/ICD.
Cost Breakdown Structure (CBS)	(Blanchard & Fabrycky, 2010, p. 577)	Similar to a WBS/PBS, a CBS breaks all costs down, either by product, cost center, or development phase. Blanchard and Fabrycky call this a "functional" breakdown). A typical CBS might include items such as: research and development cost, production/construction cost, operations & maintenance cost, retirement and disposal cost. Many of the cost categories included in a CBS are standardized items in the finance community, and each has estimation technique(s) associated with it. Costs are often captured on a <i>Cost Collection Worksheet</i> .	AoA/CDD. <u>The U.S. military does not normally perform some of the key items included in a CBS; therefore, estimates in these areas may not be reliable (or else the military might contract the cost estimate).</u>

Method	Source(s)	Explanation	Usage Context(s)
Cost Collection Worksheet	(Blanchard & Fabrycky, 2010, p. 586)	Basic mechanism used to gather and report costs generated by a CBS. Much like a WBS, costs are broken down by function and subfunction (and the associated cost categories) in the tuples, while the cost by program year, total (actual), total net present value and % contribution are in columns.	AoA/CDD. Compares programs by cost center/year, or cost profile (since profile by center/year is accessible to viewing).
Parameter-based Costing	(Blanchard & Fabrycky, 2010, p. 581)	One of the four types of cost estimating, parametric analysis, involves determining key parameters that drive cost (historically), then using these parameters to estimate future costs.	AoA/CDD. <u>Only as good as past information and current judgment.</u>
Activity-based Costing	(Blanchard & Fabrycky, 2010, p. 581)	A method directed toward “detailing and assignment of all costs to the activities that cause them to occur,” in an effort to include traceability (for items historically difficult to track; i.e., indirect costs like “overhead”).	AoA/CDD. <u>May be at odds with WBS/PBS methods of tracking costs (because functions like project management spread across multiple cost centers).</u>
Life-cycle Cost Summary	<i>AoA Handbook</i> , p. 37	Breaks out life-cycle costs two ways: 1) by alternative and life-cycle phase, 2) by budget category and life-cycle year (any combination of these is acceptable, based on the requirement).	AoA.
Money Flow Modeling	(Blanchard & Fabrycky, 2010, p. 176)	Considers present equivalent (<i>PE</i>), annual equivalent (<i>AE</i>), or future equivalent (<i>FE</i>) amount, as well as internal rate of return and payback period. $PE, AE, \text{ or } FE = f(F_t, i, n)$ $t = 0, 1, 2, \dots, n$ (salvage value/cost added at end of final year) $F_t = \text{positive or negative money flow at end of year } t$ $i = \text{annual interest rate}$ $n = \text{number of years}$	ICD/AoA/CDD (economic analysis of alternatives). Calculating outlay and payback of a system over its acquisition and utilization. See <i>Decision Evaluation Matrix</i> for an additional application of this technique.



Keywords: *3D Printing, Ground Vehicle Systems, Gaming Environment, Systems Engineering, Tailoring, Unmanned Vehicle Systems*

A Proposed 2025 Ground Systems “Systems Engineering” Process

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The U.S. Army’s mission reflects a strong impetus to provide flexible and adaptable ground vehicles that are rapidly fieldable. Emerging manufacturing technology, such as three-dimensional (3D) printing, is making mass customization possible in commercial industry. If the Army could produce tailored military ground vehicles that incorporate mission-specific tactics, it would outperform generic systems. To produce such systems, a new systems engineering (SE) process should be developed. Virtual environments are central to the proposed SE/2025 process because they provide a sandbox where soldiers and engineers might directly collaborate to codevelop tactics and technologies simultaneously. The authors’ intent is to describe how ground vehicle systems might be developed in 2025 as well as to describe current efforts underway to shape the future.



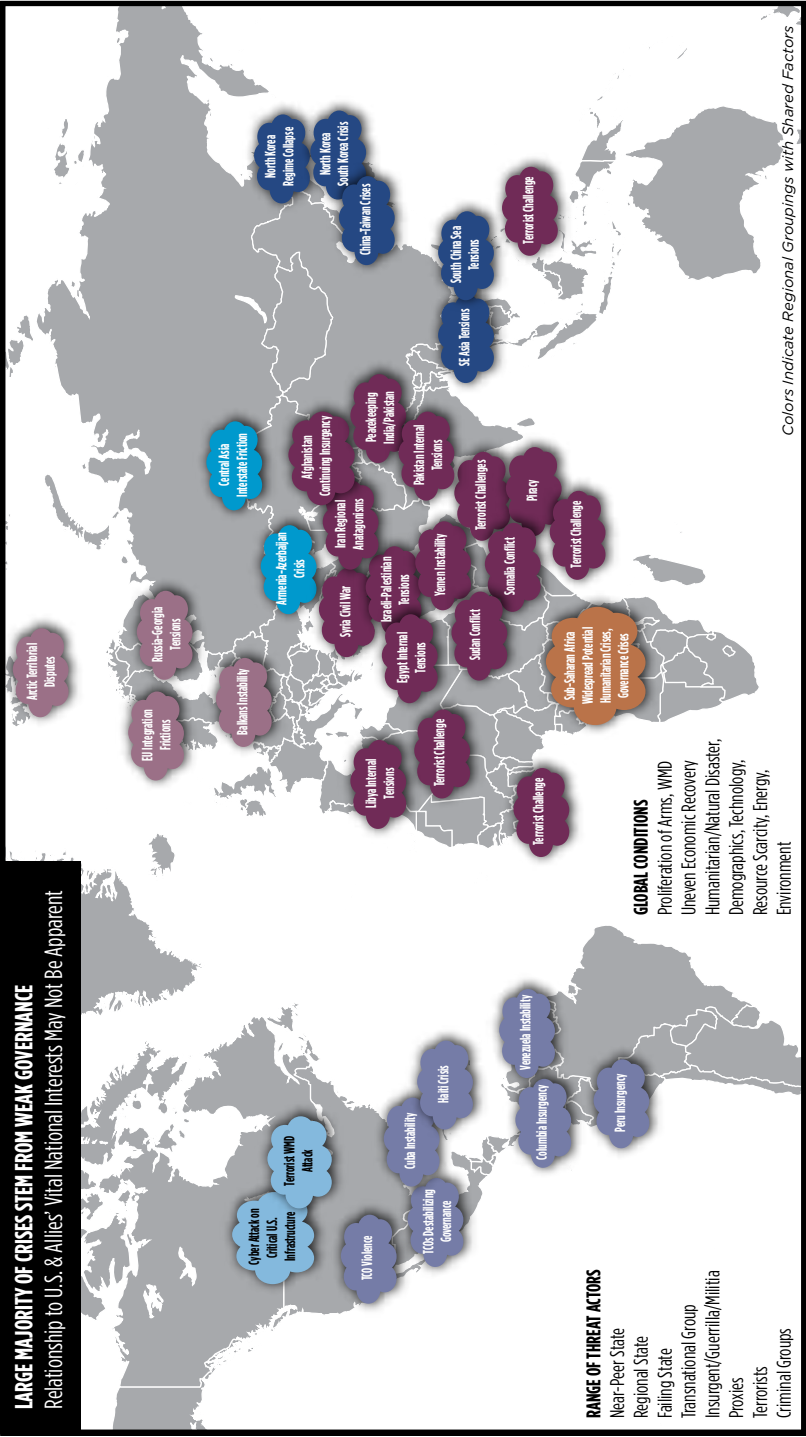
In the past, the United States Army has been able to anticipate capability gaps and needs based on a relatively static threat, but that model has disintegrated over the past two decades (United States Army, 2013). Figure 1 illustrates pictorially the range and complexity of the current defense landscape. Constantly shifting mission requirements will likely remain the norm in the foreseeable future. As such, combatant commanders will need ground vehicles, including robots that are flexible, adaptable, and rapidly deployable. Additionally, some of the most promising future warfighting technologies, such as robotics, computing, and advanced communications, will be readily available for non-State actors and nations to purchase from the global commercial market. To maintain a military advantage, the United States needs to develop a process that enables the lucid and rapid production of mission-tailored platforms that do not rely solely on cutting-edge technology. Just as radar stealth and drones were game changers in the past, the acquisition process itself could become a game-changing technology in the future.

The Department of Defense (DoD) acquisition process transforms warfighter needs into materiel by three separate, but interlinked processes: the Joint Capabilities Integration and Development System; the Planning, Programming, Budgeting and Execution System; and the Defense Acquisition System. According to Chyma (2010), these processes answer four basic questions:

- What is the requirement?
- What is the acquisition strategy?
- What is the cost estimate?
- Is it affordable?

The current process is linear and document-centric, which makes the process of answering these questions in an integrated manner very challenging. According to Boehm (2010), “The weakest link in systems engineering is often the link between what the warfighters need and what the development team thinks they need, together with a shared understanding of the operational environment and associated constraints and dependencies” (p. 20).

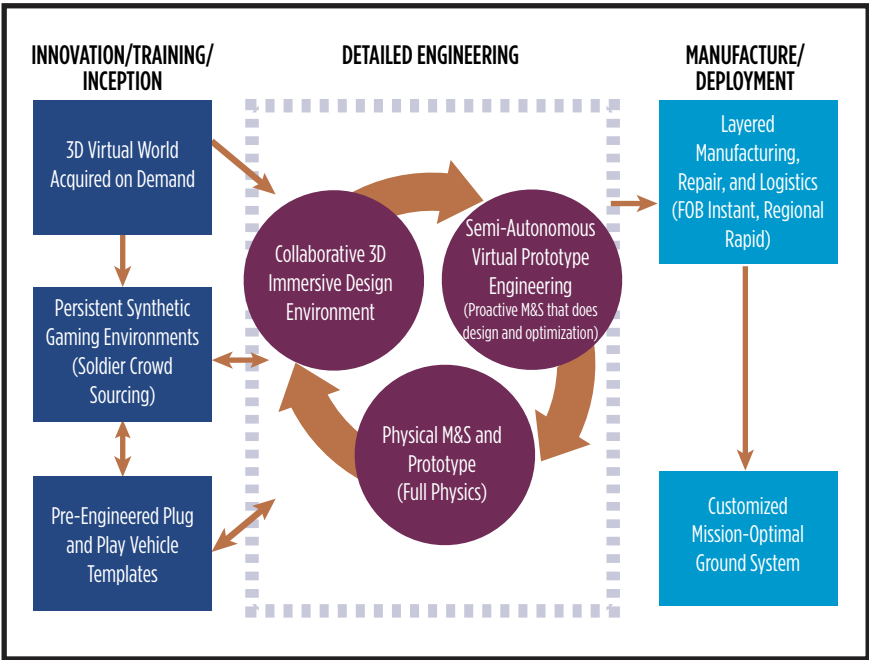
FIGURE 1. GROUND SYSTEMS MUST BE ADAPTABLE TO A WIDE VARIETY OF OPERATIONAL ENVIRONMENTS



Systems Engineering 2025 (SE/2025), as described in this article, explores a possible future process to address shortfalls in the interlinked acquisition processes by using virtual worlds to enable new levels of collaboration and experimentation with changeable tailored platforms. The year 2025 represents a symbolic point in time where rapid manufacturing will start to provide the ability to produce systems effectively. The authors’ intent is to outline how ground systems might be developed in 2025 as well as to describe current efforts underway to shape the future.

Figure 2 shows the SE/2025 process flow. The entry point into the process starts with the Persistent Synthetic Gaming Environments (left center) where thousands of soldiers may “kick the tires” on technologies and customize vehicles. This game-based environment will also provide a discussion group where soldiers can pool their collective expertise and brainstorm solutions. Meanwhile, engineers can observe what is working and program managers can assess the true tactical value of technologies versus cost. Real-time scenarios can be created for experimentation

FIGURE 2. GROUND SYSTEMS SE/2025 “SYSTEMS ENGINEERING” PROCESS.



Note. FOB = Forward Operating Base; M&S = Modeling and Simulation

by using intelligence assets to create instantaneous geo-specific environments as shown in the upper left of Figure 2. To avoid overwhelming users with choices from the infinite combination of vehicle technologies, vehicle templates and capability modules will be evolved within the gaming environments as shown at the lower left of Figure 2. Vehicle templates are preferred configurations of modules and technology that the crowd of soldier-gamers proves to be robust for mission effectiveness. The templates will adapt over time as users share among themselves and piggyback on the best ideas. The overarching theme is that a tailored system will nearly always outperform a standardized system that tries to do everything.

While not explicitly illustrated in Figure 2, a critical feature for the success of SE/2025 is enhanced communication between stakeholders across the acquisition community. Korfiatis & Cloutier (2013) showed the promise of immersive environments (especially gaming environments) to facilitate a deeper understanding of CONOPs (Concept of Operations) by immersing the team in an experiential, first-person environment. To further maximize communications effectiveness, information should be provided at just the right time in a format or dashboard that allows quick interpretation of complex data and that hides irrelevant details. A recent emergence is the employment of tradespace exploration tools by both the Army Whole System Trades Analysis (WSTAT) (Edwards, 2012) and the Marine Corps Framework for Assessment of Cost and Technology (FACT) (Browne, Ender, Yates, & O’Neal, 2012). FACT and WSTAT are both excellent examples of how SE is beginning to provide dashboard information to decision makers. These tools allow highly visual and interactive explorations of the tradespace, which would otherwise be extremely challenging to achieve. Employing modular designs will also help communications because modules are essentially black boxes that will only need to be dealt with at their interfaces.

The final section of SE/2025 in Figure 2 is Manufacture and Deployment. Manufacturing and Logistics will likely become inseparable in the future as localized production and rapid manufacturing have the potential to become the norm. The Army will find itself with new choices as to what is produced stateside, regionally, and at forward operating bases (FOB). True capability-on-demand will be realizable when rapid manufacturing, and plug-and-play modular components enable mass customization. Already, the Henry Ford-era mass production paradigm is eroding within the automotive industry where high levels of customization are increasingly available in the marketplace (White, 2012; Muller, 2010).

Deciding what is produced stateside, regionally, and at FOBs will depend on the portability of manufacturing equipment, nature of modularity, and deployment timeframes. Items that require large amounts of energy, materials, and specialized environments (like clean rooms) will likely be produced stateside. In contrast, some vehicle components might be digitally e-mailed to an FOB and produced expeditionary on site. A large benefit of 3D printing, also known as additive manufacturing, is that it takes a generic base material such as a powdered metal and fuses it layer by layer into a final piece. This means one machine and one base material can produce a quite varied set of components. The need to be rapidly deployable will drive designs toward kitable solutions to minimize the initial-entry airlift weight. Armor kits, for example, can then be applied later. Soldiers may swap modules on and off vehicles in the field—just like assembling Lego toys—to provide a rapid observe, orient, decide, and act loop (Boyd, 1996).

DoD SE Process Versus the Competition

Presently, we are competing against the business models of terrorists and insurgents (and many threat countries) which are “very much agile and open approach. They do not have thick internal R&D [research and development] establishments, and are willing to take knowledge and technologies from anywhere to achieve their goals” (Hood, 2007). Additionally, insurgents have made excellent use of the Internet for collaboration and knowledge sharing. They engage in rapid development and agile systems engineering through real-world application. Army General James Cartwright, former vice chairman of the Joint Chiefs of Staff, as quoted by Kitfield (2013), states, “... if you take the hunt for IED [improvised explosive device] cells, that was a 30-day fight.” The enemy would invent a fuse, U.S. forces would develop a counter to it, and the enemy would respond by inventing another triggering device. “And if it took you longer than 30 days to respond to a change in enemy tactics, your people were dying.” The United



States Army needs to shorten its materiel acquisition observe, orient, decide, and act loop (Boyd, 1996) to keep a decisive advantage over an innovative asymmetric enemy.

The current DoD process is a linear, requirements-first system in the translation of user needs into materiel solutions (Boehm, 2010). Due to the length of the existing process, decisions made and available technologies that were relevant at the beginning of a program may be obsolete by the end of the program. To quote the Chinese-authored *Unrestricted Warfare*, which discusses how developing countries might counter the United States, “Customizing weapons systems to tactics which are still being explored and studied is like preparing food for a great banquet without knowing who is coming, where the slightest error can lead one far astray” (Liang & Xiangsui, 1999).

Liang & Xiangsui (1999) further explore the fact that the United States generates a vast amount of technology on which it has been unable to capitalize, pointing out that:

...proposing a new concept of weapons does not require relying on the springboard of new technology, it just demands lucid and incisive thinking. However, this is not a strong point of the Americans, who are slaves to technology in their thinking. The Americans invariably halt their thinking at the boundary where technology has not yet reached. (p. 24)

Development of the first crowdsourced military vehicle, the Flypmode, by the Defense Advanced Research Projects Agency (DARPA) and Local Motors gives a glimpse of the potential for SE/2025. Jay Rogers, founder of Local Motors, points out conflicts are won not by spending tons of time and billions of dollars, but “They win it because they figured out what was going to beat the enemy, and they built that” (Boyle, 2011). Rogers went on to say:

Maybe we did not do the same development that [the contractor] did, to make sure the strut on the vehicle lasts a million miles. But if it saves a life, and it lasts for a whole conflict, haven’t we done a better thing?

President Barack Obama was shown the Flypmode vehicle, which only took 4 months to produce (Boyle, 2011), and enthusiastically pointed out:

Not only could this change the way the government uses your tax dollars—think about it, instead of having a 10-year lead time to develop a piece of equipment, if we were able to collapse the pace of which that manufacturing takes place, that would save taxpayers billions of dollars—but it also could get technology out to the theater faster, which could save lives.

Persistent Synthetic Gaming Environments (Soldier Crowdsourcing)

The use of video games is not new to the Army. In 1981, General Donn A. Starry, then-commander of the U.S. Army Training and Doctrine Command, was struck by what he saw in the video game arcades (Trachtman, 1981):

I see a lot of people in those arcades learning something, and they're all volunteers, and they're paying a quarter to learn whatever it is they learn from these machines. I don't know what they learn, but I'm convinced they learn something, and that the Army needs to exploit it. (p. 56)

SE/2025 proposes to tap into thousands of soldiers, who already play video games in their spare time.

The Army Capabilities Integration Center (ARCIC) has begun an experiment called Early Synthetic Prototyping to create a persistent gaming environment to answer the following question:

How does the Army develop and implement a process and a set of tools that enables soldiers to assess emerging technologies in a synthetic environment to provide relevant feedback that informs science and technology research, doctrine, organization, and training development?

Past game-based experiments were not persistent and were limited in participation to a relatively small user base. The target of the ARCIC investigation is to involve upwards of a thousand soldiers in the gaming, which is crowdsourcing. However, open research questions remain unanswered about this methodology, including:

- Can we draw (explicitly and/or implicitly) useful feedback from soldiers about future technology capabilities using a game environment as a concrete experience?
- Are the results of analysis from soldier feedback significantly different from the results of analysis from traditional experimentation?
- How do we begin to allow soldiers an active role in the design of platforms?

Research is presently being conducted by the authors to answer these questions.

The fundamental purpose of creating a persistent gaming environment for SE is to generate a sandbox for testing out new tactics in conjunction with science and technology (S&T) simultaneously. Dr. Peter Singer, director of the Brookings Institution 21st Century Defense Initiative (Unmanned Systems, 2010), observes that “knowing that having the right doctrine can be the difference between winning and losing wars, between committing America to the 21st century version of the Maginot Line vs. the Blitzkrieg.” SE/2025 has the goal of generating 21st century blitzkrieg by directly allowing soldiers to experiment with doctrine directly. Soldiers can then feed experiential insights and measurable data back to engineers and decision makers. Conversely, the art



of the possible for cost, timing, and technology can be provided back to the soldiers. The speed of feedback produced in a gaming environment suggests the potential for engineers, program offices, and soldiers to codevelop systems. Gaming environments might even allow an assessment of the battlefield value of S&T investments prior to committing research dollars to actually develop the technology. The final benefit of using synthetic environments is that soldiers will more readily adopt new equipment if they have already used it in a virtual environment. It is not uncommon for new equipment to sit at the FOB because soldiers simply are not comfortable and familiar with it.



To develop robust templates of the most effective vehicle configurations, many iterations of the same scenarios should be performed due to the stochastic nature of decisions made during a battle (Weber, 2012). A slight deviation in timing or difference in course-of-action could vary the battle outcome greatly so stochastics are important. Another critical element to maximize the benefit of these environments is to provide a discussion forum for users to exchange tips and tricks, and to learn by replaying winning and losing scenarios. Collaboration among players will ensure maximum leapfrogging of ideas—known as crowd accelerated innovation (Anderson, 2010).

Figure 3 shows how a persistent gaming environment will engage the Army DOTmLPF-P (Doctrine, Organization, Training, materiel, Leadership and Education, Personnel, Facilities –Policy) communities. The environment should have several specific features: First, it should provide a sandbox where soldiers may build and modify ground systems (and scenarios) as they see fit. Second, the physics fidelity should be modifiable to allow engineers to tailor the game with applicable real-world physics as appropriate. Third, it should be template- or module-centric to avoid overwhelming users with too many combinations and choices so they can only focus on relevant details. Fourth, there must be a discussion and sharing area that allows replays and piggybacking on ideas.

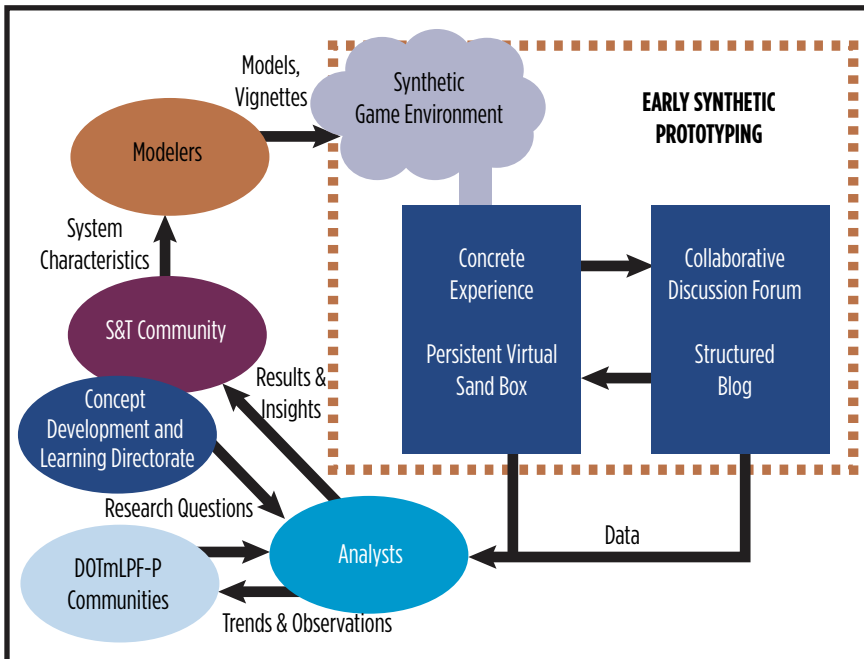
3D Virtual World Acquired on Demand

The spectrum of future operations covers a variety of known and unknown threats, and variable reaction timelines. It is now possible to capture, in real-time, a battle scenario that may be input into a gaming environment or passed on to engineers for the development of mission-specific ground systems. Planners for the raid on Osama bin Laden's

Abbottabad, Pakistan Compound used satellite imagery from the National Geospatial-Intelligence Agency to create models of the compound prior to the actual attack. The models were used to allow the Joint Special Operations Command to create mission simulators for the pilots who flew the helicopters to practice virtually ahead of time (Ambinder, 2011; Harris, 2011). This rapid construction of 3D scenarios will continue to evolve and blur the line between simulations and reality.

Either satellite imagery or air-/ground-collected imagery may be used instantly to construct realistic scenes. Depending on the application, various sensor modalities may be employed. DARPA and Space and Naval Warfare Systems Command (SPAWAR) have both made progress on a number of projects that help to make instant scenarios available. The DARPA RealWorld Project (Intific, n.d.) has a goal of creating high-definition scenes in under 30 minutes. SPAWAR’s UrbEM Project (Nguyen et al., 2009) aims to develop, mature, and demonstrate technologies that will provide rich 3D models of complex urban environments from the ground perspective, mainly using sensors normally found on unmanned ground vehicles. UrbEM has investigated the following technologies

FIGURE 3. CONCEPT OF THE PERSISTENT GAMING ENVIRONMENT



that may be used to develop scenarios: structure-from-motion, multi-view stereo, laser scanning fused with color image data, spatial phase video, and registration software/algorithms. An example of an UrbEM experiment is shown in Figure 4 where multiple views are automatically combined to create a 3D model. Similar effects may be achieved where video frames are continuously acquired. The Microsoft Photosynth project (Photosynth, n.d.) demonstrated the ability to create 3D geometry from a collection of online pictures, which is stunning considering it requires a computer to combine multiple views, lens, lighting, and even the inclusion of people in photographs. With Photosynth, it is possible simply to use Web-based photo repositories such as Google Images or Flickr to create 3D models of objects autonomously.

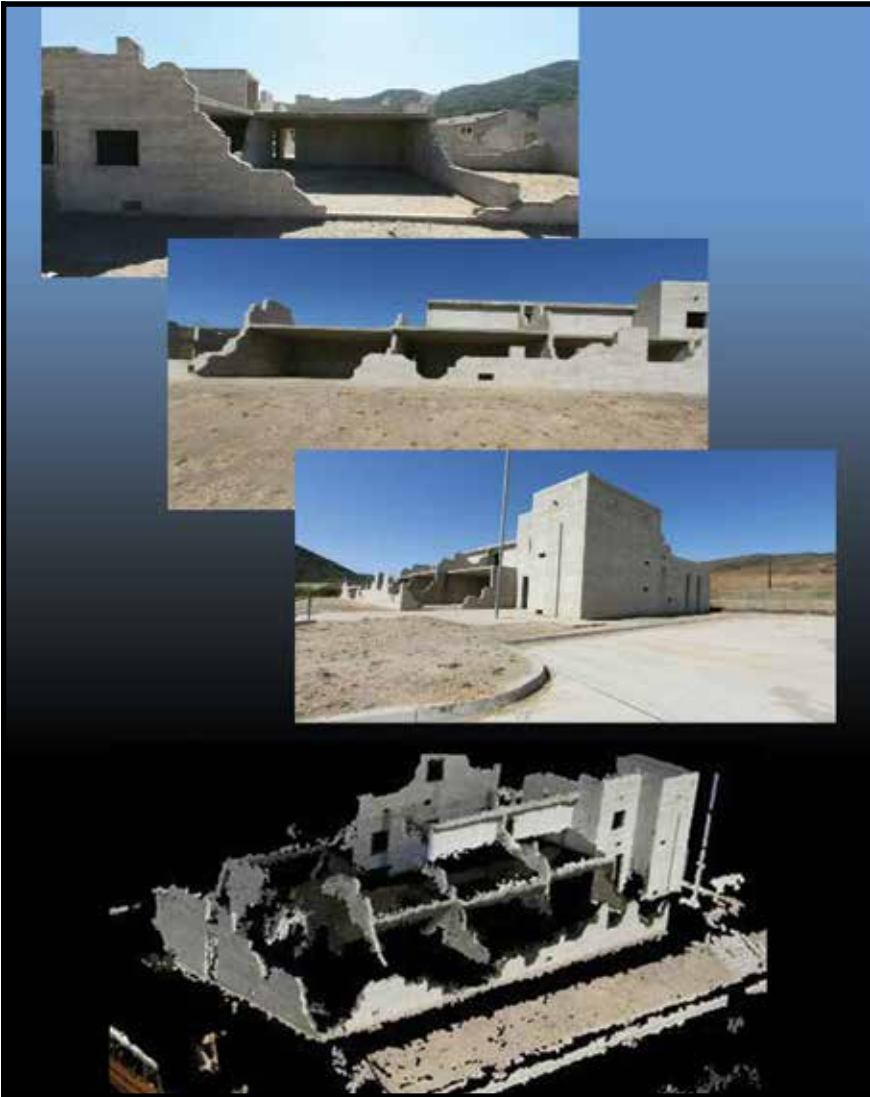
Preengineered Plug-and-Play Vehicle Templates

A template in the context of future vehicle design is an assembly of modules that is a doctrinal preference for a successful outcome. Templates are key to the rapid fielding of different solutions based on terrain, enemy, mission, or other considerations. Imagine a case where there will be a sustained operation requiring the capture of insurgents. Users should be able to select preengineered vehicle templates to try out in advance to see what works best. Once they find that a robot or tank works well, they can tailor the template vehicle to their tastes and preferences. Having a generic starting template is important in case an event occurs that requires an immediate response, allowing no time to customize vehicles beyond what is captured already in the template. This is also important for experimenting in the gaming environment so players have base vehicles with which to play in the virtual environment without starting from scratch. The development of templates encourages innovative evolution of designs within the gaming environment by allowing easy modifications. A distinct combat advantage is to be gained from tailoring because it will confound the enemy's ability to exploit a common vulnerability—the Achilles' heel might always change.

Templates, along with modularity, are critical to avoid decision paralysis in the face of too many options. Information overload directly reduces the human ability to make smart, creative, and successful decisions (Begley, 2011). As promising vehicle configurations evolve from the persistent gaming environment, these can be tied to classes-of-use cases for a vehicle that may be deployed. These configurations can then be progressively tailored as more information about a conflict becomes known or the greater the probability of a certain type of event occurs, as

shown in Figure 5. Individual commanders will be able to customize the base templates as needed for specific missions—be it in the real world or virtual world. This evolving design methodology is supported by having

FIGURE 4. RECONSTRUCTIONS OF 3D MODELS: STRUCTURE AT CAMP PENDLETON MILITARY OPERATIONS ON URBAN TERRAIN COMPOUND



Note. Multiple images allow on-the-fly reconstructions from a series of photographs as part of the UrbEM project. Adapted from Nguyen et al. (2009).

discussion forums and replay capabilities for soldiers to discuss what options are most desirable and to share first-person virtual operational experiences with other stakeholders.

Detailed Engineering

Detailed engineering starts with Semiautonomous Virtual Prototype Engineering (Figure 2). Virtual Prototype denotes the fact that physics-based models have already become accurate and multidisciplinary enough that they should be considered digital (or virtual) prototypes. Semiautonomous implies that future modeling and simulation (M&S) will be more proactive than current computer aided design (CAD) since some design work can be done collaboratively with computers. Conventional M&S such as computational fluid dynamics, finite element analysis (FEA), and other computer aided engineering methods are traditionally reactive and simply provide an engineer with an assessment of performance; the engineer must manually fix the design and rerun the model. For example, consider the design of some structural part: Right now, an engineer creates a design in CAD, runs an FEA analysis and, based on the results, repetitively tweaks the design until the part functions as intended. In the future, the engineer will merely describe the use-case of the part (and constraints) to the computer and, using M&S, the computer will autonomously optimize the part. In 1982, Gunn estimated that “only 20% of the parts initially thought to require new designs actually need them; 40% could be built from an existing design; and 40% could be created by modifying an existing design” (Gunn, 1982). For this reason, a number of universities are already working on autonomous part search methodology (Iyer, Jayanti, Lou, Kalyanaraman, & Ramani, 2005).

The future SE Detailed Engineering process will be based on pervasive prototyping. IDEO, designers of Apple’s first mouse, the Gripper toothbrush for Oral-B, and the Palm V point out that “if a picture is worth a thousand words, a good prototype is worth a thousand pictures” (Kelley & Littman, 2001). Prototyping can be virtual (all within a computer), physical, or a combination of the two such as hardware-in-the-loop simulations. Decisions made during detailed design must be captured with ubiquitous knowledge management. Knowledge is expensive to generate and ignorance is even more expensive.

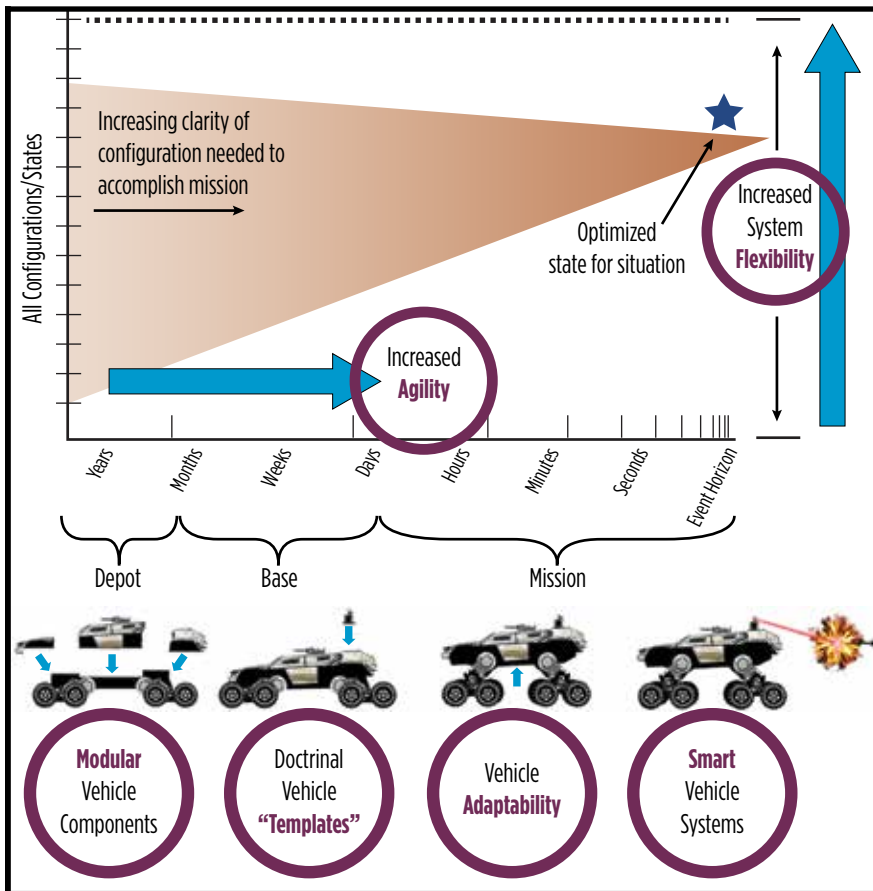
Physical prototyping supplements pure M&S (virtual prototyping) by validating assumptions and identifying unknown interactions. In particular, subsystem-level prototypes can be combined with modeling

to enable hardware-in-the-loop simulations and man-in-the-loop simulations. The act of building something in itself is incredibly informative. Systems integration laboratories (SILs) also fall into the category and test the integrated function of multiple components. SILs are critical because SE fails most frequently at the interfaces. Examples of a physical simulation are shown in Figures 6 and 7.

Layered Manufacturing, Repair, and Logistics

The future force might be substantially redefined by new options presented via rapid manufacturing, and particularly additive manufacturing. Per Wikipedia (Rapid Manufacturing, n.d.), “Rapid manufacturing is a

FIGURE 5. TEMPLATES OF MODULAR VEHICLES AND PLAN FOR MANUFACTURING & LOGISTICS



Note. Such templates and plans will become inseparably coupled in the future.

technique for manufacturing solid objects by the sequential delivery of energy and/or material to specified points in space to produce that part.” 3D printing reduces the number of separate machines necessary to create a part by transforming powdered or liquid raw materials layer by layer into a final piece. Additionally, additive manufacturing allows the elimination of welding, brackets, and flanges when the piece can be produced as a whole. Conventional machining processes remove material, which creates waste, where additive manufacturing only places material where needed. Finally, additive manufacturing may also be used to make repairs. General Electric has demonstrated an ability to repair worn parts by using a precision spray technique to add material to an existing part (General Electric, 2013).

A new ability to produce parts locally may substantially change procurement and repair logistics. Future logistics (notionally illustrated in Figure 8) must optimize the movement of materials and manufacturing equipment to provide maximum flexibility and minimal cost. Items that require large amounts of energy, materials, and specialized environments will likely be produced stateside. Some items may be manufactured at the FOB using technologies such as 3D printing. The Navy explored the notion of ships becoming floating factories in a Proceedings Article (Cheney-Peters & Hipple, 2013), possibly even harvesting resources from

FIGURE 6. US ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER (TARDEC)’S RIDE MOTION SIMULATOR (RMS)



Note. TARDEC’s RMS is an example of a man-in-the-loop physical simulation.

the surrounding seas or ashore. Due to the intrinsic complexity of customized platforms, it will be critical to use information technology to form an effective manufacturing and logistics strategy.

Army Captain Elsmo provides a simplistic storyline example (Elsmo, 1999):

In reality, a ground system will probably have multiple components coming from a variety of locations. Assemblies and subassemblies may be created anywhere in the logistics and manufacturing chain. This gives a very new meaning to what the life cycle of a product and its constituent modules may become.

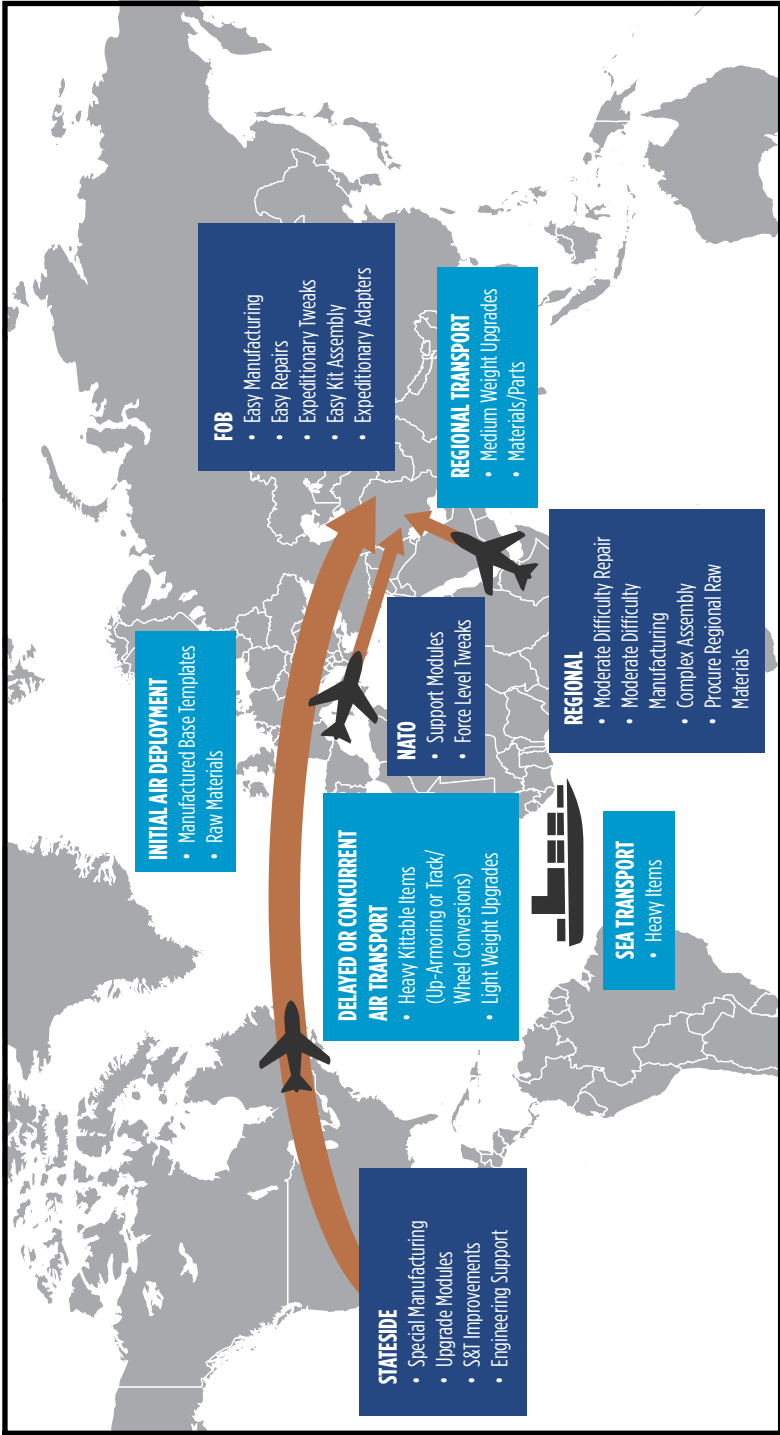
The layered manufacturing/logistics process is tied directly to the gaming environment and detailed engineering process. Figure 5 shows how modules and developed templates for ground systems evolve in lock step with manufacturing and logistics. As more information develops about the potential materiel need, more definition of the design is provided. Once a system has been fielded, modules allow a vehicle to be adapted by changing out these modules. Examples include kitable armor, swapping out radios, upgrading sensor packs, or retuning engine control modules. Further, the vehicle itself will be smart. An example of a smart vehicle is one that senses a cargo load and then automatically reprograms its stability control and antilock braking to accommodate the load.

FIGURE 7. US ARMY TARDEC’S N-POST SHAKER



Note. TARDEC’s N-post shaker is a hardware-in-the-loop simulation.

FIGURE 8. NOTIONAL FUTURE LAYERED MANUFACTURING/REPAIR/LOGISTICS



Note. With the onset of Future Layered Manufacturing/Repair/Logistics, the movement of materials and manufacturing equipment is optimized to provide maximum flexibility and minimal cost.

The notion of local manufacturing is not entirely new to the Army. The U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) had fielded a mobile parts hospital in the past, which was the automotive equivalent to the mobile army surgical hospital unit, providing treatment to a vehicle so its crew is protected and could finish the mission (Williams, 2004). The Rapid Equipping Force began fielding expeditionary lab mobile units in 2013, which include 3D printers, computer-assisted milling machines, and laser, plasma, and water cutters, along with common tools like saws and welding gear (Hill, 2013). The industry is fast approaching a point where even static structures such as buildings may be 3D printed (University of Southern California, n.d.). Logistics must also modernize to take advantage of these new production technologies. Boeing has already used 3D printing to make more than 22,000 parts used on civilian and military aircraft flying today (The Future of Military Logistics, 2012).

Due to changes in manufacturing and logistics, the defense industry could start to shift away from the historical big contract methodology where large defense contractors are awarded a contract to develop an entire vehicle based on requirements documents that may exceed 300+ pages. In the world of commercial automotive, the lines have already started to blur as to what the brand name of a vehicle means. Engines come from one manufacturer, bodies another, and electronics another. Looking further into the future, the manufacture of a future ground vehicle may become a very layered manufacturing and logistics process. The role for contractors in such a future may be to develop modules and subsystems that plug-and-play with vehicles. Additionally, contractors might supply manufacturing equipment and maintain the logistics base that will enable mass customization. Such a shift would have an impact on the planning and budgeting process, which is focused on platforms in contrast to modules.

Conclusions

The complex nature of future global conditions requires ground vehicles that are adaptable, flexible, smart, and rapidly deployable. The very nature of this type of vehicle requires an agile SE process that anticipates many scenarios in advance. Using persistent synthetic gaming environments may help develop vehicle templates that consider tactics and technology concurrently. Templates will provide the most robust mission (and cost) effectiveness while still allowing for tailoring. Rapid manufacturing and nonstatic mission requirements are quickly making one-size-fits-all military

ground vehicles an obsolete concept. Logistics may be transformed into a deeply interlinked manufacturing/repair/logistics process with localized production and assembly of many parts or modules. Readers should consider whether the next great technology breakthrough for the Army might be an agile systems engineering process that is infused with crowdsourced soldier input, concise communication of information, and proactive M&S tools.

Author Biographies



Dr. Robert E. Smith is a researcher in the U.S. Army TARDEC's Modeling and Simulation Group (Analytics). He has over 15 years of experience in computer-aided engineering. His career experience includes experience at Ford Motor Company, Whirlpool Corporation, and General Dynamics Land Systems. He holds a PhD in Mechanical Engineering from Michigan Technological University. Dr. Smith is Defense Acquisition Workforce Improvement Act Level Level III certified in Systems Planning, Research, Development and Engineering—Science and Technology Management.

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LTC Brian D. Vogt, USA, served in several leadership positions, including simulations analyst for the Systems Engineering Core program at Fort Leavenworth, KS. He commanded a tank company and headquarters company during two tours in Baghdad, Iraq. He is a graduate of the Armor Officer Basic Course and Advanced Course, Combined Arms Services Staff School, Command and General Staff College, and the Naval Postgraduate School where he earned an MS in Modeling, Virtual Environments, and Simulations. LTC Vogt currently serves at Fort Eustis, VA, as an FA57 Simulation Operations Officer.

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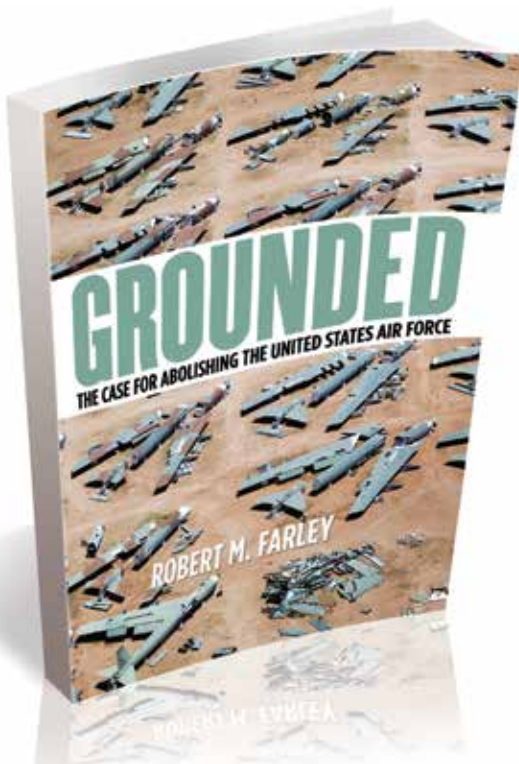
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Featured Book

Grounded: The Case for Abolishing the United States Air Force

Author(s):

Robert M. Farley

Publisher:

The University Press of Kentucky,
Lexington

Copyright Date: 2014

ISBN:

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978-0813144979 (ePub)

Hard/Softcover:

Hardcover, 264 pages

Reviewed by:

Aleisha R. Jenkins-Bey,
Assistant Editor, *Defense ARJ*

Review:

University of Kentucky Professor Robert M. Farley has written a very controversial account of why he believes the assets of the U.S. Air Force should be broken down and dispersed among the other military services, namely the army and navy, removing the need for an independent air force. Professor Farley includes a proposition for a new structure of reorganization for the future of the nation's airpower, which would largely change the focus of the military services. This review provides an objective analysis of the book, *Grounded: The Case for Abolishing the United States Air Force*.

On one hand, the author does a good job of presenting his case using several instances in the history of the U.S. Air Force where it was not able to fulfill part of the initial intent of its independence, which was the ability to win wars from the air with very little loss of life and with better cost efficiency. Professor Farley additionally does an outstanding job of enlightening readers on how often and how many new aircraft are designed to do a specific job, then are deemed obsolete due to ever-evolving technology or are grounded for technical issues. Along with a few characteristics of the U.S. Air Force that create political and military problems for the United States, he effectively lists four proposed principles of reorganization for the removal of the U.S. Air Force's independence. Also to the author's credit, he acknowledges the importance of military aviators and the courage of members of the U.S. Air Force, reiterating that *Grounded* "should be understood as part of the opening gambit for a restructuring of U.S. military institutions."

On the other hand, perhaps not all bases were covered in the consideration of the revamping of the military services, which proposes to remove the independence of just one of the Services, but would create great debate within the acquisition community. The question posed by Professor Farley that seemed to jump out as a basic concern is: "Does giving an air force independence solve more problems than it creates?" However, because our independent air force has now existed since 1947, should not the question be: "Does *removing* the independence of an air force solve more problems than it creates?" Professor Farley does not discuss exactly by what means the nation will save money should the U.S. Air Force be abolished, although his plan addresses cost efficiency. Following his plan for reorganization, and taking into account his four principles, it seems that in dividing all of the

U.S. Air Force's assets—including aircraft, weapons, personnel, bases, and missions, all mentioned by Professor Farley—the Department of Defense, the nation, and the military services would lose not just money, but decades of knowledge and expertise possessed by current members of the U.S. Air Force. Understandably, many airmen would either not want to join one of the other Services or would be unable to retain their prior specialties in the army or navy. He does not discuss the issues of training personnel or the cost and availability of supplies and uniforms. There would likely need to be a shift of responsibilities for existing units in the army and navy to provide ample air defense during this restructuring—also not discussed. Another important consideration would be the loss of a seat for the U.S. Air Force on the Joint Chiefs of Staff, in which the Service chiefs ensure the personnel readiness, policy, planning, and training of their respective military services. However, once again, readers should consider the book an “opening gambit” for restructuring, not the full plan.

After several years of perfecting his argument, Professor Farley's dispersal of U.S. Air Force assets seems well laid out between the army and navy for a new kind of air domination. His argument is supported with detailed evidence. Defense acquisition professionals can benefit from Professor Farley's discussion of the Clausewitz approach and his comparison of the existence of the U.S. Air Force to that of the Royal Air Force, the aerial warfare branch of the British Armed Forces, which is also the oldest independent air force in the world; and the Luftwaffe, the aerial warfare branch of the German Wehrmacht during World War II. However, his work fails to recognize the limited gains and insurmountable losses that would result from the removal of the U.S. Air Force's independence, and thus does not answer the question of whether giving the U.S. Air Force independence, or taking it, would solve more problems than it creates. It will be interesting to see how the rest of this long-running argument plays out in regard to defense acquisition.

Aleisha R. Jenkins-Bey is the assistant editor of the *Defense Acquisition Research Journal*. Prior to her current position, she was the lead editor in Military OneSource's Arlington office. She has served as a commissioned officer in the Air Defense Artillery branch of the U.S. Army.

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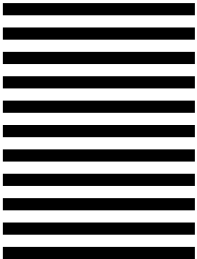
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