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A Real Options Valuation Model is developed to recommend how to valuate 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 defendable 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 & Bhargav, 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 (2004) 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.

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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 dis-mounted 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 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.

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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 Measure	Weight	LBR Value	LBR Score	FO Value	FO Score	FLIR Value	FLIR 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**		**6.42**		**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
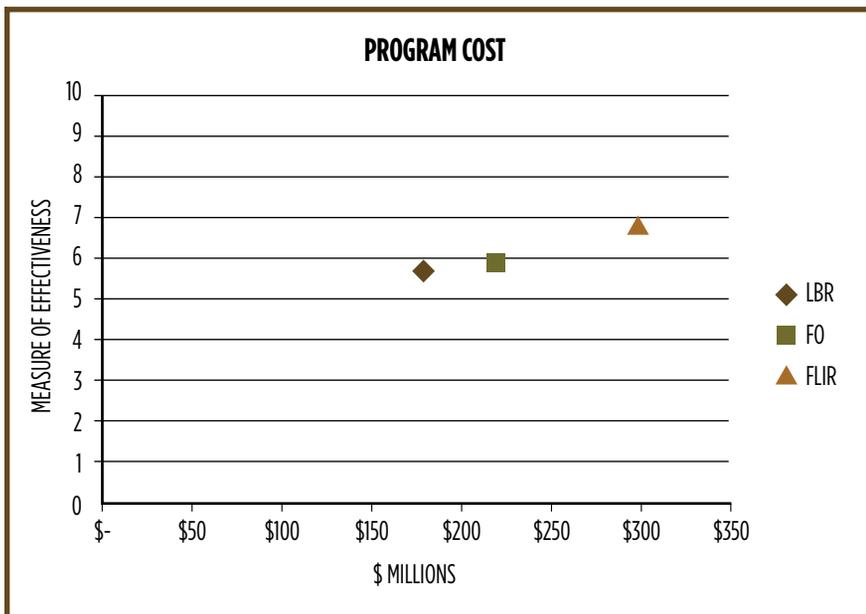
in seeing what specifically they are getting for their investment. In addition, because the MOE is a combination of different metrics that are not necessarily interchangeable, it would not make sense to simply calculate the ratio of MOE to cost. Instead, the marginal analysis defines the trade-off space, 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 success[2] 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).

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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 ($M)	180	220	300
Probability of failure	0.4	0.5	0.6
Cost to fix	*50*	*70*	*90*
Total cost to implement given failure ($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**

(1)

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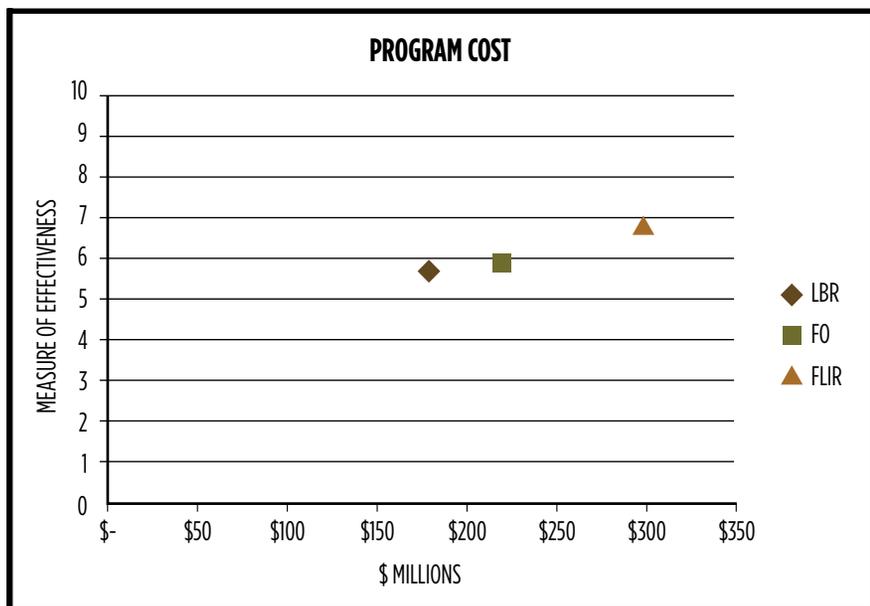
Table 1 and can proceed with the project if we prefer that option (based on the cost versus effectiveness analysis presented in the previous section). If the development fails, we terminate the project and there is no further cost. The value of the option is given by the difference between the expected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

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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 intial 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

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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.