Affordability Analysis for DARPA Programs

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In recent years, an affordability analysis has become important for understanding the investments and the payoffs for all types of projects. Competing claims on a shrinking defense budget means that not every idea, no matter how technically sound, can be developed. The Defense Advanced Research Projects Agency (DARPA) undertakes high-risk, high-payoff endeavors that involve advanced technologies. There are special challenges in conducting an affordability analysis for such advanced concepts; the traditional methods of cost and benefit estimation may not be applicable or may have to be modified to fit the needs of the analysis. APL conducted affordability analyses for DARPA projects in three areas: affordable rapid response missiles, flexible fabrication of titanium, and gun-launched satellite systems. The analysis methods included a blend of interval cost estimation and life-cycle cost/benefit analysis. (Keywords: Affordability analysis, Engineering economic analysis, Hypersonics, Laser-forming technique, Low-cost space access.)

INTRODUCTION

An assessment of affordability is a key factor in analyzing proposed weapon and sensor systems and has become exceedingly important to DoD programs. Since the end of the Cold War, there is no longer a galvanizing threat where system performance is *sine qua non*. Declining defense budgets and an increasingly prohibitive cost of supporting a separate defense industrial base have forced DoD programs to consider the economics of system development, production, and deployment as equal to technical performance. APL established a dedicated operations research capability within the Joint Warfare Analysis Department with the objective of conducting affordability analyses as part of technical tasks. The tasks performed include three efforts sponsored by the Defense Advanced Research Projects Agency (DARPA). The analyses and techniques applied in these tasks is the subject of this article.

Affordability analysis is an integral part of the system engineering approach. Closely coupled to understanding technical issues, it seeks to use a common set of methods. Analysis can focus on the subsystem, system, and mission levels and is performed for the entire program life cycle. Typical products of an affordability analysis include cost-effectiveness analyses, risk analyses, and total ownership cost estimates. An affordability analysis synthesizes information from three basic areas: mission analysis, technical analysis, and cost analysis. Mission analysis covers the operational environments and operating concepts (e.g., "What is the system supposed to do?" and "How is the system going to do it?"). From technical analysis comes a functional work breakdown structure (the system description) and system performance models (describing the system's essential performance). Cost analysis provides cost breakdown structures (relating cost elements to the system description) and cost estimating models (relating cost data to the system's elements and performance).

No single formula precisely defines an "affordable system." As a micro-concept, an affordable system is procured when needed within a budget, operated at a desired performance level, and maintained and supported within an allocated life-cycle budget. As a macro-concept, affordable systems are constrained by top-line budgets, require timing for competing uses of resources, and must contend with the dimension of inflexibility in near-term budgets, although long-term considerations may make many programs justifiable.

Difficulties of conducting affordability analyses are magnified for innovative concepts or systems that push the state of the art. New technologies may be in early stages of development; costs and/or performances are subject to great uncertainty. New management concepts, fabrication concepts, and production processes may promise great cost savings, but lack of historical data requires analysts to carefully consider how benefits are justified and quantified. The systems discussed in this article contain all these factors. For more fully developed systems, analyses of this type are normally conducted as part of a detailed, formal analysis of alternatives. The systems discussed here are either too preliminary or too conceptual for such a full approach.

Although affordability is often equated with a low acquisition cost, that is not the only consideration. For a system to be affordable it must address multiple cost considerations, including those of total operating costs, viable funding profiles, and supportable development burdens. The system's performance must be expressed quantitatively so that it may be combined with schedule and cost data into one or more relevant metrics. These measures of effectiveness (MOEs) are developed to measure affordability in meaningful terms.

For an advanced concept or system, the development and calculation of the MOEs are more difficult. Common characteristics that affect an affordability analysis for these types of systems are as follows:

- Existence often only as a conceptual design
- Difficulty in forecasting costs from existing data
- Necessity to make reasonable assumptions regarding mission, investment, inventory, logistics, and life-cycle issues, often based on sparse data or hazy assumptions regarding operations
- Proposed MOEs require equal applicability to existing systems

For affordability analyses of advanced systems, two major themes govern: interval cost estimation and life-cycle cost analysis. In early stages of development, costs cannot be accurately captured by single (point) estimates; their stochastic nature, usually characterized by a probability distribution for the purposes of affordability analysis, will lead to a range (or interval) covering nominal, pessimistic, and optimistic estimates. A system's true costs and benefits are more rigorously assessed by performing a life-cycle cost analysis that examines the costs and benefits over its entire life (cradle to grave).

APL's affordability studies performed for DARPA illustrate the two themes of interval cost estimation and life-cycle cost analysis. The Affordable Rapid Response Missile Demonstrator (ARRMD) study is an example of the generation of an interval cost estimate. The studies performed for the Flexible Fabrication of Titanium Program and the Light Gas Guns for Satellite Launch Program illustrate system life-cycle analyses. In each task, affordability analyses were conducted concurrently with technical assessments and contributed to the overall technical assessment by identifying regions of operations that met affordable constraints.

INTERVAL COST ESTIMATE

Process Overview

The first part of any affordability analysis is generation of a useful cost estimate interval with associated probabilities. Cost estimates can come from a variety of sources[1] but usually are based either on detailed engineering buildups or on regression equations relating historical cost data to physical characteristics such as weight, range, volume, horsepower, or circuit complexity. Exact characteristics used to determine applicable cost estimating relationships depend greatly upon the system under study. Often, these estimates are adjusted for technical complexity and concept maturity. Estimates can also be formed from combinations of engineering estimates at varying levels of resolution and cost estimating relationships. Usually, more advanced technologies have greater cost uncertainty. Uncertainty is captured and quantified in a systematic, traceable manner by using a stochastic model (Fig. 1).

The first step is to develop a system's cost breakdown structure to appropriate levels of detail. Structures should be defined sufficiently to enable the generation of reasonable estimates, striking a proper balance between detail and aggregation.

The next step is to develop a probability distribution for each element in the structure. These distributions are not usually known but must be formulated either by engineering buildup or parametric estimation.

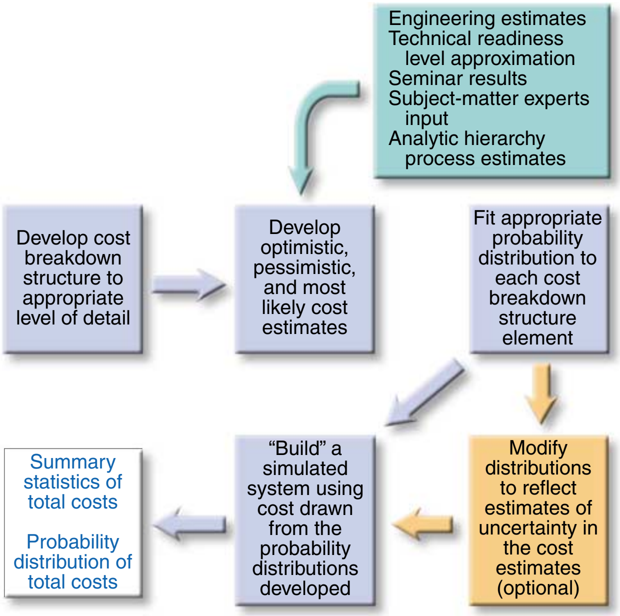

Figure 1. Cost modeling process. (Blue, indicates main path; orange, optional elements; green, data sources.)

Ideally, distributions should be based on engineering estimates, with prices and probabilities for various contingencies estimated by engineers and cost analysts. If details of this type are unavailable, other methods can be used. One such method is called a PERT cost approach.[2] This approach fits a beta distribution of the appropriate parameters, based on three costs for each element: most likely, optimistic, and pessimistic.[3] The technique involves equating cost estimates to minimum, mean, and maximum values of a beta probability distribution and then solving for distribution parameters that fit the points, in a manner similar to the task-time estimate for a traditional PERT analysis of project completion times.[4] Most likely, optimistic, and pessimistic costs could also be linked to technological maturity assessments such as the NASA Technological Readiness Level,[5] with a distribution becoming more skewed toward cost growth as the Technological Readiness Level drops. The advantage of these two methods is that they do not require large quantities of data; only three estimates for each element are needed.

A single total system cost is obtained by randomly selecting an estimate for each subsystem's cost, using appropriate subsystem cost distributions. The process is repeated many times (typically, several thousand estimates of overall total system cost are desired to characterize the analysis); the results are the basis for a statistical summary of the total system cost.

The method accounts for cost uncertainty based on the distributions and parameters developed. However, it does not account for the possibility of error in the determination of optimistic, pessimistic, and most likely costs. For example, an engineer may estimate that there is a 20% chance that a particular cost estimate (optimistic, pessimistic, or most likely) is inaccurate by a given percentage. This uncertainty can also be included in a model. By chaining these uncertainties, a better estimate of system variance is captured.

ARRMD Project

DARPA's ARRMD Project is an example of interval cost estimation. The project's goal is to demonstrate a hypersonic cruise missile with an average unit flyaway price (AUFP) of $200,000 per missile when ordered in production quantities. The project is divided into several phases. Phase I was an initial design competition between two concepts: the Waverider concept using a hypersonic technology engine variant (called HYTECH) and a more traditional cylindrical missile using the dual-combustion ramjet engine concept. The Boeing Corporation's Phantom Works developed both concepts. In 1999, DARPA decided to develop the Waverider concept for Phase II, which will culminate in flight demonstrations of a prototype missile. The formidable technical issues associated with ARRMD were described in a previous *Technical Digest* article[6]; we concentrate here on the affordability and cost risk analysis.

Boeing developed a work breakdown structure of up to 70 individual subsystem elements contained in each concept. Some elements are characterized as percentages of other elements or as sums stated without further breakout, but the majority of elements have an associated cost. Each element has a booked cost (considered the most likely cost). Descriptions of elements contain associated cost risks (high-end estimates termed "cost threats") or potential cost savings. Adding all cost threats yields the pessimistic price, and adding all the potential cost savings yields the optimistic price. The integrated product teams working on the missile design provide the threat and savings estimates. These estimates permit the interval cost estimate to be generated with a minimum of additional information demanded from engineers and integrated product teams. Typical results from these types of calculations are shown in Fig. 2.

The analysis tool for these affordability analyses started as a Microsoft Excel 97 workbook. A series of Visual Basic for Applications (VBA) modules was developed as more detailed modeling was added, and, finally, a commercial "add-in" program, @RISK, was used to provide probability distributions. The resulting combined tool has an interface that is both familiar and comfortable to project managers, sponsors, and others. VBA modules facilitate traceability and error checking, and use of @RISK allows rapid model development.

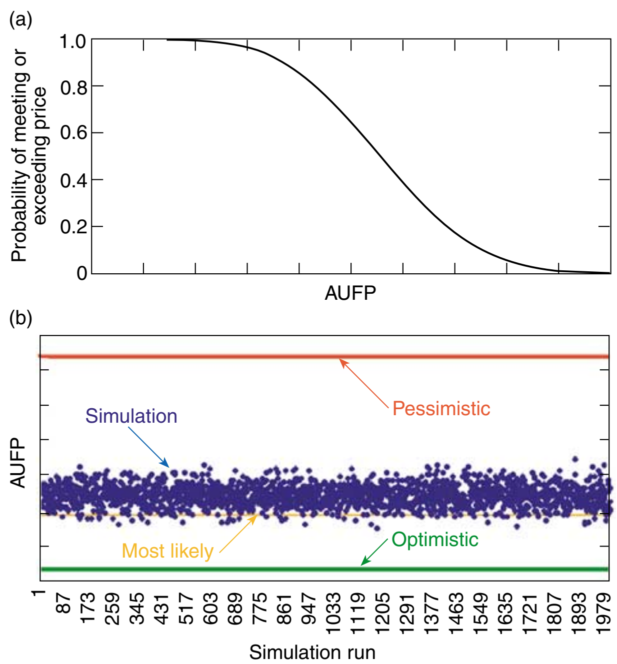

Figure 2. Cost estimate generation. (a) Average unit flyaway price (AUFP); (b) cost simulation results.

APL's participation in the affordability analysis portion of this project has included full participation as the government representative on the Affordability Integrated Product Team. Through interval cost estimates, DARPA has received continuing insight into the cost risk and uncertainty of the ARRMD Project.

SYSTEM LIFE-CYCLE ANALYSIS

Process Overview

The second type of analysis, system life-cycle analysis, requires details of the costs and capabilities for a concept or system over its entire life cycle—from initial research and development through disposal. A series of values representing thresholds for affordability is defined in terms of specified MOEs, and a series of performance constraints is imposed. System performance for achieving the affordability thresholds is calculated and compared with existing or proposed systems.

Two basic approaches are used. One approach defines an affordability target using a selected cost metric (e.g., unit cost, life-cycle cost) and examines obtainable performance under those cost constraints. Design to cost and cost as an independent variable are examples of this approach. The second approach defines required performance and examines the cost-effectiveness of options in achieving that performance. The ARRMD study, described earlier, is an example of the first approach: the $200,000 AUFP was fixed, and the comparison was based on the best performing system that meets that price. Analyses for the Flexible Fabrication of Titanium Program and for the Light Gas Guns for Satellite Launch Program are examples of the second approach: a fixed capability is desired, and the affordability of various systems that meet those goals is examined. The system for laser-forming titanium parts was the prototype for this type of analysis, and the technique was extended in the other analysis.

Flexible Fabrication of Titanium Program

In 1995, APL was awarded a contract to lead the Flexible Fabrication of Titanium Program. The program's goal was to contribute to a revitalization of the national titanium industry by developing, verifying, and commercializing a new process that economically and rapidly fabricated three-dimensional titanium objects from low-cost precursor materials. The technical approach was to build titanium structures to a "near shape" in one step using a high-powered carbon dioxide laser that fused titanium powder in an inert atmosphere. This technology was ultimately transferred to the defense and commercial sectors.[7]

Titanium is a metal widely used in the aerospace industry because of its high strength and relative lightness. Large components such as aircraft bulkheads (Fig. 3) are expensive. Their fabrication requires long lead times because their manufacturing proceeds from large billets that are forged and machined over several cycles; most of the original billet is discarded. It is common for a manufacturer to buy as much as 15 kg of raw material to fly 1 kg of finished product. In developing the laser-forming technique, APL not only led the technical development of the process but also was responsible for an evaluation of the potential affordability of producing titanium parts by laser forming. The economic analysis was based on experimentally determined operating parameters. Its results supplied

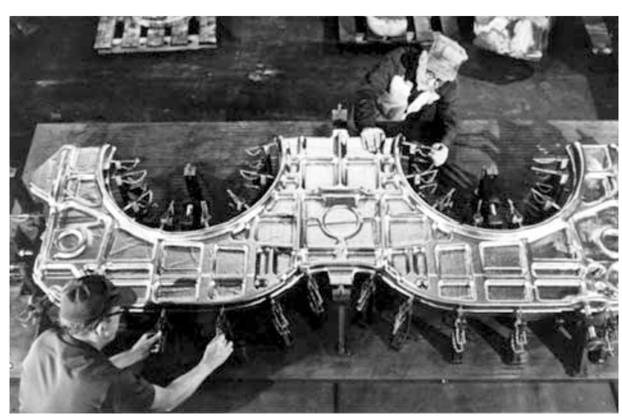

Figure 3. Aircraft titanium bulkhead.

direct feedback to guide technical development by identifying important driving parameters that would make a fabrication facility using this technology viable.

Initial analyses looked at the life cycle of a manufacturing facility. Figure 4 illustrates a top-level work element structure that describes major activities associated with acquisition, operations, and decommissioning. To focus analysis on the manufacturing problem, an aircraft titanium bulkhead was used as a study product. Table 1 lists the operating parameters and selected processing parameters. Initial study showed that the manufacture of one bulkhead would cost approximately \$200,000 and take about 47 days (≈\$1400/kg of finished product, a favorable result compared with the approximate \$6600/kg, 9-month cycle time for forged bulkheads). Illustrated in Table 1 are the effects of a ±25% perturbation of parameter values that helped to identify some of the driving parameters of the process. For example, the most influential operating parameters in achieving the nominal \$1400/kg cost of the finished product were the number of work shifts used, capital cost of the facility, and service life of the facility. Processing parameters that contributed the greatest influence were laser speed, fusing rate of the material, and up time of the facility.

The initial analysis was expanded to examine the investment potential by constructing a balance sheet and an income statement over a 20-year period for a laser-forming business. Typical assumptions of this analysis include the following: costs and types of required labor, production parameters for a mixture of two product types (to be marketed at different prices), costs of consumable materials, costs for facility development and maintenance, and overhead costs for developing, marketing, and delivering products. The analysis assumes that three laser machines are used independently to manufacture the product line; the machines are brought into production, one at a time, over a 5-year period. Their useful (sellable) product increases as the manufacturing experience matures. Other typical expenses of a profit-making business are included in the analysis. A balance sheet analysis for the first 5 years of operation for a typical case shows that payback is very quick—within 2 years—and produces increasing dividends (or retained earnings, depending on the investment philosophy of the operation). The approach of combining a technical engineering analysis with financial analysis income and balance sheets was further refined to include the statistical variations of parameters as described in the following example.

Table 1. Perturbations in cost analysis of the flexible fabrication of a titanium bulkhead (±25% of nominal).

Parameters	Cost/kg delta
Operating	
Capital cost	**±\$154**
Service life	**+\$145 to −\$86**
Interest rate	±\$51
Work shifts	**+\$430 to −\$20**
Engineer cost	±\$42
Technician cost	±\$51
Process electricity	±\$13
Raw material	±\$7
Equipment maint.	±\$57
Industrial rent	±\$4
Factory floor space	±\$2
Processing	
Float gas rate	±\$2
On-target gas rate	±\$9
Laser power	±\$13
Laser conv. efficiency	+\$15 to −\$9
Gas	±\$13
Laser speed	**+\$416 to −\$249**
Up time	**+\$333 to −\$99**
Fusing rate	**±\$330**

Note: Bold indicates greatest influence on cost.

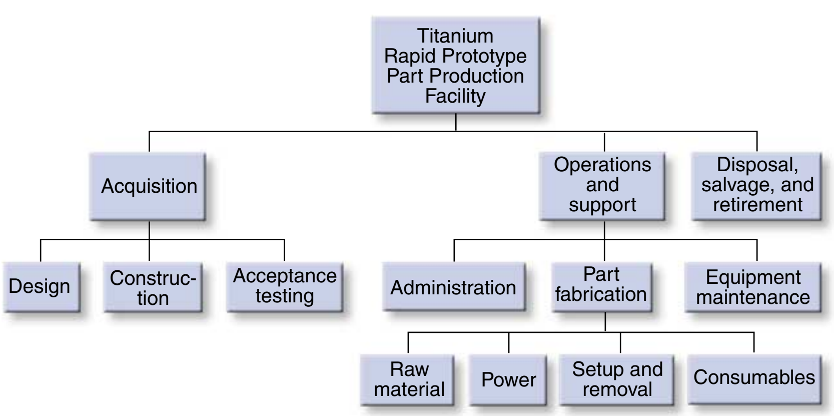

Figure 4. Work element structure.

Light Gas Guns for Satellite Launch Program

A second life-cycle cost analysis was performed on the Light Gas Guns for Satellite Launch Program. An extension to the cash flow methodology was used to assess the feasibility of using a light gas gun as a means of getting small payloads into low-Earth orbit (LEO). Although the physical characteristics of such a launch system vary with specific design details, the typical launcher design studied has a tube length of approximately 700 m and a tube diameter of 1.5 m.

The launcher would be built at a 22° inclination along the slope of a mountain. A projectile with a sabot is placed in the breech, and hydrogen gas at a pressure of 680 atm and a temperature of 1500 K is introduced behind the projectile. A series of side chambers injects the hydrogen gas in stages as the projectile passes. Fast-acting valves at the muzzle limit the loss of hydrogen to approximately 5% of the total in any given shot. The muzzle velocity varies between 4 and 7 km/s, and the gravity (*g*) load varies from 3,500 to 10,000 longitudinal *g* at launch. At a specified trajectory point, the projectile's rocket motor fires, providing the final velocity needed to place the payload in LEO.

In the first phase of the study, several designs were examined; a more detailed engineering and affordability analysis was performed on one variant. Study results, along with a more detailed description of the launch system, appeared in a previous issue of the *Technical Digest*.[8] The initial study found favorable technical and economic factors for a system capable of putting a 100-kg satellite into LEO.

DARPA asked APL to lead a follow-up study. The participants included John Hunter Associates, Lawrence Livermore National Laboratories, Microcosm, Inc., and The Morris-Knudsen Company. The last two organizations provided vehicle costing and launcher construction costing, respectively.

Several gun launcher variants were examined for their technical feasibility and affordability. An additional task examined the use of a small 100-kg unmanned "microshuttle" as a feasible payload. The microshuttle's mission was to rendezvous and dock autonomously with an existing, larger satellite and facilitate repairs by attaching a new electronic module to the satellite. The larger satellite would be part of a 24-unit constellation designed and built to allow on-orbit servicing. Issues of *g* hardening, structure, power, propulsion, and other aspects of spacecraft design were investigated. As a result, a solid preliminary design was available before the affordability analysis was begun.

Four different launcher guns and vehicle combinations were examined. Systems were referenced by the magnitude of their muzzle velocities (4, 5, 6, or 7 km/s). Each system was capable of placing a 100-kg payload into LEO. Affordability analyses focused on determining the conditions under which any system could be competitive and economically feasible.

Three different models were developed to accomplish the analysis. First was a deterministic cash flow model (the operating cost model), which represented all cash inflows and expenditures from the research and development phase, through initial low rate operation, to full operation for a period of 20 years. This model served as a basis for the second operating cost model: a stochastic cost model that permits many of the key operating parameters to be varied, thereby facilitating uncertainty and sensitivity analyses. Third, a stochastic satellite constellation model was developed. The model studied the microshuttle's impact on maintaining a 24-unit constellation during the 20-year design lifetime. Figure 5 shows the relationships among these models and their major parameters. Essential model parameters were as follows:

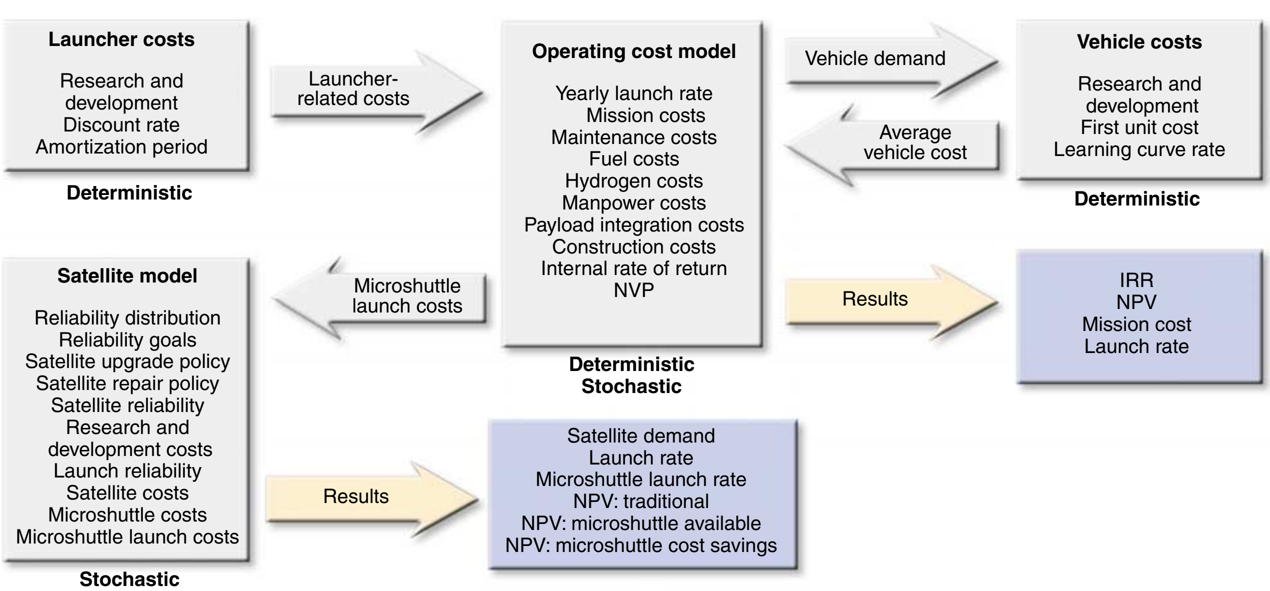

Figure 5. Affordability modeling process (IRR = internal rate of return, NPV = net present value).

- Amortization period: 15 years (results were found to be relatively insensitive to varying the period from 5 to 20 years).
- Discount rate: 8%.
- Fuel costs: (accounted for the costs of heating the hydrogen prior to launch) remained constant.
- Hydrogen: initial fill plus 5% loss per launch.
- Internal rate of return (IRR): (rate of return of all the cash flows, discounted for time) analogous to rate of return on a certificate of deposit or mutual fund.
- Launch cost: cost charged to the customer to put the payload (assumed at 220 lbm) into space did not include the cost of the payload.
- Launch vehicle costs: provided as a first unit cost and a learning curve rate of 90%; average vehicle costs were then calculated based on lot size and were used as an input to the cash flow model.
- Maintenance: estimated as a fixed cost per year plus a linear function of the launch rate.
- Net present value (NPV): current value of all the cash flows in the project, discounted for time.
- Payload integration costs: costs of integrating the satellite with our launch vehicle; calculated as a percentage of the total launch cost.
- Launcher and launch vehicle research and development costs: launcher costs were obtained from former Strategic Defense Initiative Organization studies and were scaled and time corrected; vehicle costs were obtained from NASA models and scaled after comparing those models' estimate of research and development cost for the microshuttle with an APL in-house estimate.
- Yearly launch rate: 3 years of construction were assumed, and a low initial launch rate of either half the yearly launch rate or 50, whichever was lower, in year 4; rate varied from 5 to 300 per year.

(IRR and NPV are described in more detail in the boxed insert.)

The stochastic model permitted certain key parameters to vary according to a uniform distribution within specified limits. A uniform distribution was chosen when there was no compelling reason for another distribution (the Laplace criterion—in the absence of specific knowledge, all feasible outcomes are considered equally likely). The uniformly distributed parameters were launch rate, launch cost, construction cost, research and development costs, and average vehicle cost. Several combinations of fixed and variable parameters were analyzed. Microcosm, Inc., provided an independent review of the generated launch vehicle costs. The Morris-Knudsen Company provided an independent estimate of launcher construction costs. Reviews and estimates for construction costs and vehicle costs helped define limits for those parameters in the sensitivity analysis.

AFFORDABILITY METRICS AND CONCEPTS

We used several standard financial metrics as our measure of effectiveness (MOE) for affordability. This is a quick review of the financial measures and concepts discussed in the article. A more complete review of internal rate of return (IRR) and net present value (NPV) can be found in Ref. 9. Reference 1 contains an excellent discussion of learning curves.

NPV is a metric that quantifies the value of an income stream (which can contain either positive or negative cash flows in each period) over a period of time, taking the interest rate into account. Mathematically, this is defined as

$$\mathrm{NPV} = \sum_{t=0}^{n} F_t (1+i)^{-t} \ ,$$

where t = time period in years, n = number of years, F_t = net cash flow in year t, and i = interest rate per period.

IRR is a measure of profitability. It is the interest rate that, when applied to a stream of cash flows, causes the NPV to be zero. IRR is analogous to the return on a mutual fund or certificate of deposit. Mathematically, it is defined as the interest rate i^* such that

$$0 = \sum_{t=0}^{n} F_t (1+i^*)^{-t} \ .$$

All other terms are as defined previously for NPV. NPV and IRR were both used as parameters and as MOEs in the analysis.

The learning curve or progress function is a means of quantifying how familiarity and experience with the completion of a product leads to greater efficiency and cost reduction in production. Learning curves are frequently expressed as percentages. An 85% learning curve implies that a cost reduction of 15% occurs when the number of articles is doubled. The fourth unit produced would cost 85% of the cost of the second unit, the eighth unit would cost 85% of the fourth unit, and so forth. Mathematically, the learning curve relationship is defined by the following equation:

$$Y_n = Y_1 n^b \ ,$$

where n = unit number and Y_n = cost of unit number n. The exponent b is defined by

$$b = \ln(m)/\ln(2),$$

where m is the learning curve rate expressed as a decimal. The learning curve rate and initial unit cost of the launch vehicle were used as parameters in the analysis.

The economic viability of the light gas gun launch system hinges on the magnitudes of market size, unsubsidized research and development cost, and the vehicle cost. All of these items are very uncertain. Other costs had smaller regions of uncertainty but could vary within a factor of 2. For a light gas gun launcher system to be competitive (that is, to charge 30% of the cost that would be charged using Pegasus for launching equivalent payloads) and profitable (that is, to have an overall IRR of 30%, a level that may be attractive to venture capitalists), the minimum launch rate must be between 50 and 100 launches per year, and the maximum average launch vehicle cost (less the satellite and vehicle integration costs) must range between $1 and 1.5 million per vehicle. The economics generally favored higher muzzle velocities, except when research and development was heavily subsidized, as illustrated in Figs. 6 and 7.

The satellite model was designed to capture the effect of having an on-orbit servicing capability. The baseline case considered the cost of maintaining the constellation over a 20-year life under two philosophies: replacing satellites as their consumables are exhausted or replacing satellites when they suffer an equipment failure. An extended case, with a microshuttle to repair damaged electronics, was modeled, and cost savings that would be incurred if such a system were available were calculated. Key parameters for this model were as follows:

- Consumables: constellation satellites had a 10-year supply of consumables; satellites were replaced when consumables were exhausted, except for one scenario that allowed the microshuttle to replenish the consumables.
- Microshuttle costs: developed by the APL Space Department, based on their engineering analysis of the design.

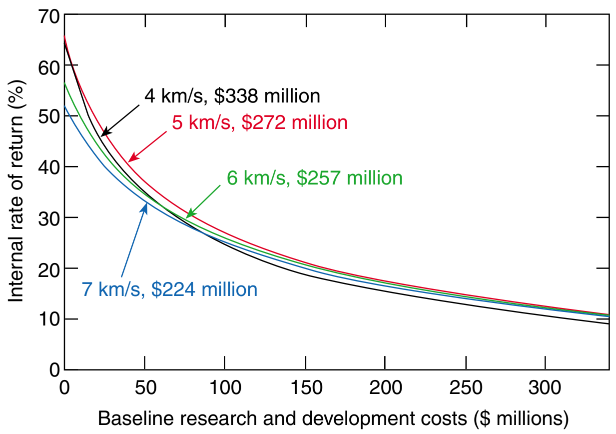

Figure 6. Effect of research and development costs. Launch rate = 50; launch cost = $2 million.

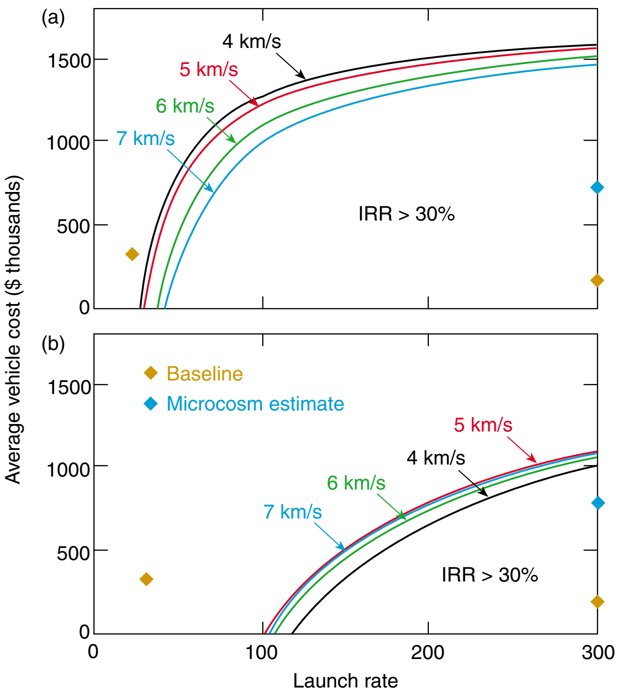

Figure 7. Effect of launch vehicle cost. Morris-Knudsen Company construction cost estimates; launch cost = $2 million; curves show 30% IRR; area under curves shows IRR > 30%. (a) No research and development; (b) baseline research and development.

- Microshuttle launch costs: varied parametrically between $2 and 7 million per launch, reflecting cases ranging from low-cost gun launch to current costs for a Pegasus launch.
- Number of satellites: 24, which were all assumed to be on-station at the start of the analysis; any satellite that malfunctioned was immediately repaired or replaced; no on-orbit spares were assumed.
- Microshuttle research and development costs: (as estimated by the Space Department) were included as initial expenses in cases where the microshuttle was used.
- Satellite costs: assumed that satellites that were designed so that they could be serviced would have a 10% cost increase.
- Satellite reliability: model fits an exponential disposition (constant failure rate) through a stated reliability goal (we used 85% reliability at 10 years); satellite lifetimes were then drawn from these distributions.
- Satellite repairability: in the baseline case we assumed that all failures required a replacement satellite; in the microshuttle case we assumed that 80% of the failures resulted in a stable satellite, rendering the satellite repairable; the other 20% of the failures required that the satellite be replaced.
- Satellite upgrade policy: in the baseline case we assumed that there were no upgrades unless a satellite

was replaced; in one excursion we allocated one microshuttle launch per satellite every 3 years to upgrade the satellite.

The analysis model was again written in Microsoft Excel 97, using @RISK for stochastic elements. In the model, cost savings are calculated using the microshuttle on a yearly basis for the entire constellation lifetime. The NPV of the discounted yearly cost saving was calculated and used as the primary MOE (see the boxed insert). As a result of the analysis, it was determined that there is no real advantage to using the microshuttle: even at the lowest launch costs, the probability of significant cost savings is small (Fig. 8a). The high reliability of the satellite requires few repair launches, and most satellites are replaced because consumables are exhausted. This result suggested another case for analysis.

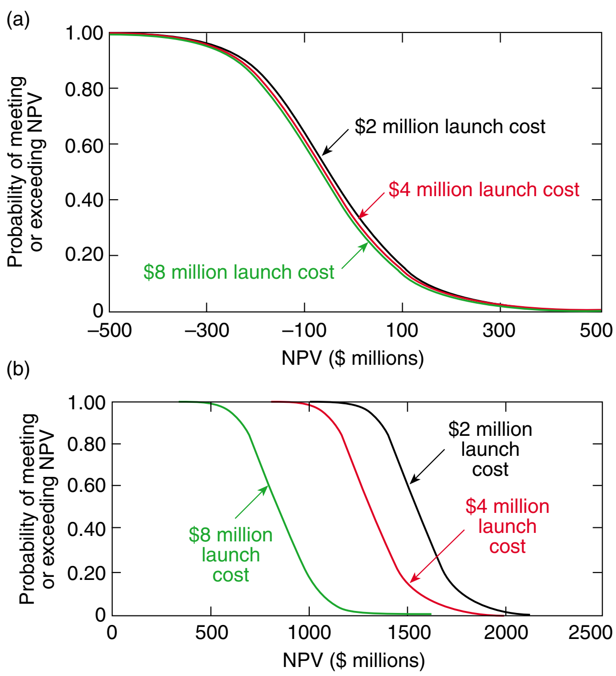

Figure 8. Microshuttle financial analysis: (a) baseline and (b) lower-cost, lower-reliability satellites. Number of realizations = 3000 (NPV = net present value).

The high-reliability baseline case was compared to one in which the satellites were half as reliable (75% reliability at 5 years) and cost three-quarters as much as baseline satellites. The microshuttle was permitted to upgrade every satellite at 3-year intervals and to replenish consumables when fuel was exhausted. This concept incorporated on-orbit servicing as an integral part of the system reliability design. This latter concept showed potentially significant cost savings over the lifetime of the systems (Fig. 8b).

CONCLUSION

Techniques used in an affordability analysis of three DARPA programs were drawn from engineering economics and financial analysis. For a relevant analysis, these techniques must be combined with a good technical understanding of system performance. The methodologies and processes developed are robust and easily adaptable to a wide variety of projects and systems in many different stages of design maturity. However, the greatest strength of this type of affordability analysis is its ability to provide decision makers with useful information during the earliest studies of advanced concepts.

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