



"The optimization model developed has made substantial contributions to the long term effectiveness of our organization."

Dennis Garegnani  
Published in Interfaces

## Best Practice:

- Prescriptive analytics for investment strategy.

## Decision Support System:

- Risk management - selection of high-value projects to maximize company performance.

## Project Portfolio Optimization:

- Risk analytics, multi-attribute utility theory and chance constrained programming.

# Lockheed Martin Space Systems Company Optimizes Infrastructure Project-Portfolio Selection

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Lockheed Martin Space Systems Company spends millions of dollars on the maintenance and modernization of its infrastructure each year. Projects often involve investments that cannot be justified purely in terms of net present value or other classical investment-evaluation methods. The options are also restricted because funds that are not spent within a given time frame must be relinquished. Furthermore, some projects may be delayed and the unplanned carryover of their costs moved into the next fiscal year; this causes the postponement or cancellation of other unrelated projects because of in-budget transfers. In this paper, we used multiattribute utility theory and chance-constrained programming to optimize the selection of infrastructure projects. Our solution ensured the selection of high-value projects to maximize the company's performance. These selections were subject to the constraints that a portfolio did not exceed the available budget and that the carryover of the unspent funds to the next fiscal year did not exceed predetermined limits. We used Microsoft Excel to ensure broad accessibility, transparency, user interaction, improved data collection and asset management, and ease-of-use by managers.

*Key words:* capital rationing; chance-constrained programming; multiattribute utility theory; budgetary carryover; spreadsheet applications.

*History:* This paper was refereed.

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Lockheed Martin Space Systems Company, based in Denver, Colorado, is located on a 5,500-acre facility with 37 major buildings—most constructed prior to 1970. Each major building contains a multitude of systems, all exhibiting various degrees of wear and tear. The Facility Operations and Services (FO&S) Department at Lockheed Martin is responsible for choosing a portfolio of projects to improve the condition of the site. Allocating capital to the maintenance and modernization of the facility infrastructure and office space is a nontrivial task given the size of the facility. Previously, FO&S selected projects based on the judgment of decision makers within the department and qualitative input from various stakeholders. This lengthy process often involved stressful negotiations, but produced suboptimal decisions. Lockheed Martin needed a robust analytical method for optimizing its project selection. Therefore, we developed a decision-support system based on multiattribute utility theory and chance-constrained programming.

We used multiattribute theory to clarify and measure the department's objective and quantify the potential contribution of each project to that objective. We addressed the risks and constraints inherent in capital-rationing problems explicitly via chance-constrained programming. We used a spreadsheet program to develop, solve, and present our model. This ensured broad accessibility and transparency, improved data collection and asset management, and ease-of-use by managers. Using this tool, FO&S achieved a substantial improvement in the value of Lockheed Martin's infrastructure.

## Problem Description

During the fourth quarter of each year, Lockheed Martin allocates more than \$10 million in capital funds to FO&S, which maintains a list of approximately 300 potential projects. Broadly speaking, these projects are in one of three categories: *construction*,

installation, or purchase. Although FO&S's overall capital allocation is fixed and should not be overspent, some small overruns are usually tolerated. It selects a project portfolio in the third quarter of each year; during the fourth quarter of that year, it spends its available budget on those projects. The budget must be spent within the fiscal year in which it is allocated because unspent money cannot be carried over and added to the budgets of subsequent fiscal years.

Implementation of an analytical approach in project selection was long overdue. Historically, FO&S decision makers (10 to 15 managers, project managers, engineers, and planners) spent an inordinate amount of time, effort, and emotion each year on capital-project-portfolio selection and funding, making their selections based on their personal knowledge of the facility. There were myriad considerations, such as complying with local and federal law, modernizing office environments, minimizing the risk the facility might pose to aerospace products manufactured and tested on site, maintaining the infrastructure in working condition, and ensuring the facilities are properly configured to support the pursuit of new business. Given the diverse areas of expertise of the decision makers and their levels of familiarity with each project, they often expressed widely varying opinions, and spent substantial time and money negotiating. Because there was no quantitative and objective way to measure a project's value, each project necessitated a debate each year. However, because of the sheer numbers of available projects, the decision makers lacked the time to debate each project's value thoroughly. Therefore, they selected a small subset of seemingly important projects and debated their significance until they reached a consensus. This consensus might result in the portfolio that best benefited the company; however, it might just as easily be the one that allowed the debate to end.

Another drawback of the previous practice was that it considered only a particular project's importance to the company and its estimated cost. It did not consider the timing of cash flows or the uncertainty in timing and magnitude of cash flows. Unless a project was a multiyear endeavor, questions about its duration were usually not asked. High-valued projects were often selected because they were perceived as important; however, they typically introduced unexpected fiscal uncertainty. If these projects

were completed later than planned, they could cause substantial disruption in financial-planning cycles. During the portfolio-selection process, schedule and budget uncertainty were not addressed; consequently, the predictive power of the FO&S's planning was limited.

Replacing the previous practice with an analytical, computer-based approach would allow the department to significantly reduce the time and effort invested in portfolio selection, improve the value of selected portfolios, and minimize the budget overruns.

## Related Literature

The central issue in capital-rationing problems is the allocation of limited financial resources among alternative projects with the aim of achieving the maximum profit over time. Generally, the projects are weighted in comparison to each other using net present value (NPV), present value ratios, or incremental analysis of alternatives. The decision maker then chooses a project portfolio that maximizes expected return on investment while adhering to the capital-budget constraint. When the choice between project alternatives is subject to intertemporal budget constraints, a mathematical programming technique is needed. Ordinary linear programming is a commonly used technique if investment projects involve no risk. In other cases, such as random cash flows or uncertain future budgets, one needs a stochastic programming technique, such as probability distribution analysis, two-stage stochastic programming, or chance-constrained programming (CCP).

All these approaches require a monetary valuation of each project. For situations where no monetary valuation is available, multiattribute decision theory has been utilized to suggest a relative value of each project. When the attributes involve some degree of uncertainty, a technique called *fuzzy multiattribute utility theory* can be used (Sealey 1978, Keeney and Raiffa 1993).

CCP is the most widely used technique in uncertain conditions. It admits random data variations and permits constraint violations up to specified probability limits. The levels are based on the decision maker's risk aversion. Using CCP, the constraints are

first stated in probabilistic terms. Then, they are transformed into their deterministic equivalents such that they can be solved by linear programming.

Charnes and Cooper (1959, 1963) introduced chance-constrained formulation of stochastic programs. In a classic book, Vajda (1972) provided an excellent introduction to the formulation as well as various interpretations. Naslund (1966) produced the earliest work on CCP use in capital-rationing problems. Kelle (1987), Sarper (1993), and Gurgur and Luxhoj (2003) provided an extensive review of stochastic investment planning.

## The Model

We developed a decision-support system for Lockheed Martin in three stages. In the first stage, we used multiattribute utility theory to quantify the value of each project to the company. We defined the attributes that are most critical to the maintenance and modernization of the infrastructure, and then combined these attributes into a utility function using the *swing-weighting* technique. To implement this technique, we first described all attributes by their worst and best levels; we then ranked the attributes based on how much the department would like to change them on a scale ranging from worst to best. Then, we assigned a 100-point difference to an attribute selected as the first choice for improvement (i.e., worst), and assigned a 0-point difference to an attribute that showed no difference if it moved from worst to best. We expressed all other differences as percentages of 100. For example, 50 percent means that the value improvement resulting from moving from worst to best is half the value of the 100-point attribute. Finally, we normalized the raw weights using a scale of 0–100.

In the second stage, we used financial data on projects implemented during the previous five years, and followed a Bayesian approach to update management's estimates on the mean and variance of each project's spending. We then constructed a chance constraint to ensure that the choice of portfolios stays within the budget plus a small tolerance for overrun with at least a predetermined probability. In the third stage, we estimated the risk of unplanned carryover for each project using the mean and variance of the investment cost, as well as the mean and variance of

project duration. We added this carryover constraint to the model.

We explain these steps in more detail below.

## Project Valuation

Infrastructure improvements are usually in a different class than "textbook" investments. Textbook investments lend themselves easily to time-value-of-money analysis; they can be prioritized based on NPV, benefit-cost ratio, or other common economic analyses using easily accessible data that reflects estimated cash flows both to and from the project in question. Infrastructure projects might support many profit-generating efforts, but they do not directly generate profits to the company. Thus, the estimated costs of such projects might be very predictable, while the expected monetary return is hardly quantifiable.

FO&S undertakes projects that support the on-site manufacturing of products intended for space travel and have wide-ranging technical complexity. Although we can estimate the cost of most infrastructure projects accurately, calculating the return from these projects is usually impossible. Therefore, we used multiattribute utility theory to quantify the value of each project. First, we determined the attributes that are most important to decision makers. We then identified these attributes—regulatory, modernization, risk, infrastructure, and business—through extensive conversations with the director of the department and with many of the employees directly involved in selecting the projects that had been undertaken in the past.

The *regulatory* attribute focused on the facility's compliance with federal and state government regulations. Specific levels within the regulatory attribute were defined such that each available project was scored according to how well it helped the company attain or maintain regulatory compliance. The *modernization* attribute scored projects on how well they positioned the facility to meet business and employee needs. The *risk* attribute rated the risk that the facility itself posed to flight hardware. For example, a satellite might risk water damage from old pipes adjacent to a clean room in which it is stored. The *infrastructure* attribute dealt specifically with the deterioration

of the various building systems. A high score indicated that the project would remedy a currently failing system; a low score indicated that the project would reduce the probability of future failure. Finally, the *business* attribute signified whether a project supported the winning of contracts that the company classified as “must win.”

We combined these attributes into a utility function and used it to calculate a relative value of each project in lieu of a straightforward NPV calculation. We developed an additive utility function based on the foundation of mutual preferential independence—i.e., scores in any one of the attributes were assumed to have no effect on the scores of other attributes for a given project. Given the philosophical separation between the attributes, we believe mutual preferential independence to be an accurate assessment. The swing-weighting technique tied the attribute and their respective scales together into a single measure of the value of each project (Winterfeldt and Edwards 1986). It is considered technically more robust than simply setting the relative importance of criteria (Quaddus et al. 1992).

To implement this technique, we asked the department director to imagine a situation in which FO&S faces a hypothetical project described by the worst consequences on all attributes. The director was then asked to assess which attribute should be changed from its worst level to its best level, which attribute should be changed next, and so on until a complete rank order of these attributes was established. The resulting ranks (in decreasing order of importance) were: regulatory, risk, infrastructure, business, and modernization.

We assigned a rate of 100 to regulatory. The director was then asked to assign rates between zero and 100 to the remaining attributes, with the rates ordered identically to the ranks. We divided each attribute’s rate by the sum of the rates of all five attributes to find the weight of each attribute. The sum of the attribute weights was equal to one and each weight was represented by a number between zero and one.

We found that the regulatory concerns, which had a weight of 0.303, were paramount. Risk was second in importance with a weight of 0.273, followed by infrastructure (0.182), business (0.152), and modernization (0.091). After scoring each available project on

all the attributes, we calculated each project’s utility as the sum of the project’s scores, respective to each attribute, times the weight of that attribute.

## Budget Constraint

Before we constructed the budget constraint, we used a Bayesian approach to update management’s estimates on the mean and variance of each project’s spending. Based on the financial data on projects implemented during the previous five years, we split the project list into three philosophical categories: *construction*, *installation*, and *purchase*. Construction examples include construction of a new building or clean room. Installation projects comprise those in which a large piece of equipment is to be installed, such as infrastructure or connections for a new autoclave or vacuum oven. The third category, which is rarer, encompasses the purchase of an asset, such as a new dump truck or snowplow.

We divided the project list into three groups based on the budget allocated to each project. The cutoff levels were set with the intent of dividing the list into three groups of approximately equal size. The first group included projects budgeted up to \$20,000, the second group between \$20,000 and \$100,000, and the third group more than \$100,000.

There were nine groups of projects created by the three budget classes within the three categories. Table 1 shows the percentage errors between the actual spend and baseline budget (as a percent of baseline budget) for 2001 through 2005, inclusive.

A positive mean indicates that the projects overspent their budgets, on average; a negative mean shows a tendency toward spending less than their allotted budgets (e.g., construction projects with a

Baseline budget range	Construction (%)		Installation (%)		Purchase (%)	
	MPE	Standard deviation	MPE	Standard deviation	MPE	Standard deviation
\$0–\$19,999	83	175	59	135	–12	231
\$20,000–\$99,999	48	130	–2	76	62	94
\$100,000–\$1,500,000	–8	65	–20	57	39	100

**Table 1: The data illustrate the mean percent error (MPE) and standard deviation of errors in predicting project spending during 2001–2005, on average.**

budget of less than \$20,000 tend to cost 83 percent more than the original estimate). Each project's estimated budget was corrected by the mean percent error (MPE) for its group. The budget-cost variance was recalculated by multiplying the estimated budget by the variance of prediction error to quantify the uncertainty of each available project.

Based on the updated figures for the mean and variance of each project's budget, we constructed a chance constraint for the choice of portfolios such that the probability of staying within the budget plus a small tolerance for overrun was kept above a specific risk level. The department director specified that risk level as a 95 percent probability of staying within budget.

### Unplanned-Carryover Constraint for the Portfolio

When a project that was intended for completion in a given year takes longer than expected, the money spent to fund the project in subsequent years is called *unplanned carryover*. Carryover is important because it represents a financial obligation that must be covered in the future. Unlike planned carryover, which is a natural byproduct of multiyear projects, unplanned-carryover obligations restrict the decision maker's freedom in the future because the carryover must be funded in subsequent years; however, future-year capital budgets will probably not be increased to cover the obligation. Thus, other future projects might have to be cancelled or postponed to fund the unplanned carryover. Project deselection can be painful when customers outside of FO&S have planned their operations based on an earlier promise by FO&S to implement specific projects. Therefore, the department is keenly interested in limiting exposure to unplanned carryover.

Formulating an unplanned-carryover constraint requires predicting the timing of each dollar spent on each project. Because the department had never kept such historical data, we developed an approximation method. We assumed a triangular distribution for the duration of each project; the department specified three distribution parameters—the shortest-possible duration, the most-likely duration, and the longest-possible duration. We could then compare these durations to the time available to implement projects in

the next fiscal year and use the past data to update the parameters.

To predict the unplanned carryover, we assumed that the spend rate of a project is constant and is equal to total (expected) cost over the (expected) length of that project. We calculated the expected unplanned carryover by finding the mean value of the portion of the triangular distribution beyond the end of the year and multiplying it by the spend rate. The variance of unplanned carryover for each project was calculated similarly using the variance of the portion of the triangular distribution extending beyond the end of the fiscal year. The appendix shows a detailed account of the calculations. The risk level for the aggregate unplanned-carryover constraint was specified as 95 percent.

### Spreadsheet Implementation

We used Microsoft Excel to develop our model, solve the optimization problem, and present the results. The optimization was implemented using Premium Solver rather than the free add-in Solver because the number of decision variables (i.e., projects) usually exceeds 200 in a typical fiscal year. The model we used in the current period had 267 binary decision variables and two constraints. Its run time was 95.2 seconds on a 2.4 Ghz computer with 2,048 MB RAM. As expected, the run time was sensitive to the number of decision variables and increased exponentially as we added more projects. For example, the run time was nine minutes and 23 seconds for a 500-project model.

Numerous software packages, including the popular LINDO, GAMS, and Xpress-MP, are dedicated to solving mathematical programs. We selected Microsoft Excel for various reasons as we will explain in detail below.

Our decision-support system consists of six worksheets. Figure 1 shows the *Portfolio Selection* worksheet of the Excel file.

On this screen, the user enters all relevant information about the project characteristics, such as project type, cost, and duration, and utility scores for each attribute. The amount of budget available for the current year, tolerance limits for total budget spending, and budgetary carryover are additional input variables. After executing Premium Solver, the user can

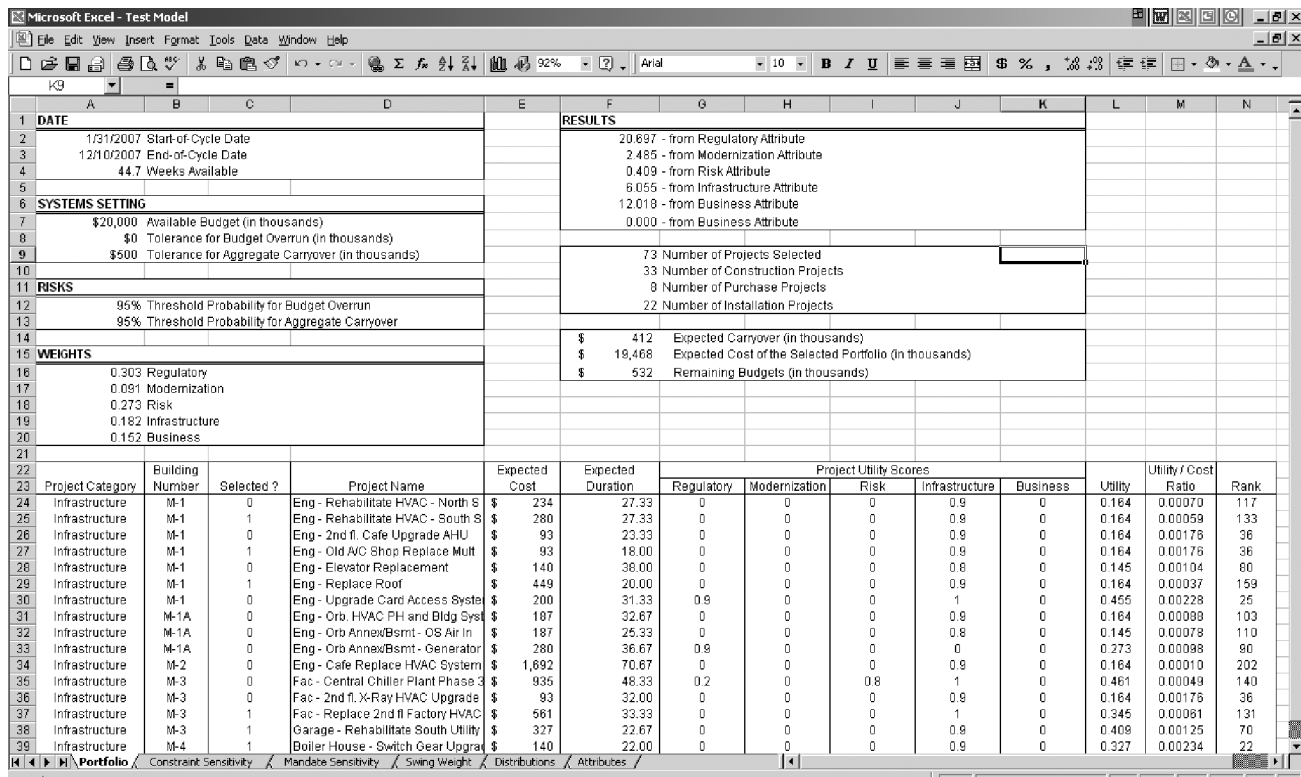


Figure 1: The user enters all relevant information about the project into the Portfolio Selection worksheet. Microsoft product screen shot reprinted with permission from Microsoft Corporation.

view model outputs (e.g., project portfolio selected, estimated figures for total spending, and budgetary carryover) on this screen.

In the second and third worksheets, the user performs sensitivity analyses to observe how the portfolio changes in response to changes in the list of mandated projects or risk levels (Figure 2) in budget overrun and unplanned carryover.

During our tests, management found these tools useful to facilitate discussions within the department (e.g., which projects should be excluded when management mandates a specific project, which projects are sensitive to what type of risks, and which projects are likely to be dropped as the risk level increases).

The remaining three worksheets, which are designed to remain write-protected, contain system parameters critical to the execution of the optimization model. *Attributes* and *Swing-Weight* worksheets explain the attributes and the calculation of attribute weights in the objective function, respectively. The

*Distributions* worksheet keeps financial data on projects that were implemented in the previous five years. Based on the project type entered in the first worksheet, management's estimates on the mean and variance of each project's spending are updated following a Bayesian approach. In the *Portfolio Selection* worksheet, these updated figures are used to construct chance constraints for the budget spent and budgetary carryover.

### Benefits to Lockheed Martin: Model Results

We constructed and verified the model in 2006; however, we delayed its full implementation until 2007 because of time constraints. The capital plan of recommended projects must be submitted by the end of the third quarter of the year. By the time that we finalized the model, the deadline for the 2006 fiscal year had passed; therefore, the department submitted its

SENSITIVITY ANALYSIS											
Sensitivity to Budget Overrun Probability Threshold						Sensitivity to Carryover Probability Threshold					
PROB (OR< \$200k)	95%	90%	85%	80%	75%	95%	95%	95%	95%	95%	95%
PROB (CO< \$200k)	95%	95%	95%	95%	95%	95%	90%	85%	80%	75%	
Project No	Selected?	Selected?	Selected?	Selected?	Selected?	Selected?	Selected?	Selected?	Selected?	Selected?	Selected?
1	1	1	1	1	1	1	1	1	1	1	0
2	1	1	1	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0	0
4	1	1	1	1	1	1	1	1	1	1	1
5	0	0	1	1	1	1	1	1	1	1	1
6	1	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0
14	1	0	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1
17	1	0	1	0	0	0	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1
21	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0

Figure 2: The user can observe how the portfolio changes in response to risk levels. Microsoft product screen shot reprinted with permission from Microsoft Corporation.

capital plan using its traditional business approach, and used our model for project selection in 2007. This sequence of events proved invaluable in testing the effectiveness of our model and understanding its benefits to the company. We knew which projects the department had selected in 2006 using the traditional approach. Because our model test run was also completed during that time, we were able to compare our portfolio recommendations with the department’s actual selection.

The numerical results showed that our optimization tool improved the project-selection process in three areas:

- Better use of available budget;
- Reduction in carryover risk;
- Increase in overall utility to the department.

**Better Use of Available Budget**

Figure 3 illustrates whether the portfolio selected by the department meets or exceeds the available budget.

On the x-axis, we ordered these projects in descending priority according to the utility-to-cost ratios of projects. The horizontal line represents the spend level expected using a 95 percent probability. It is easy to see that the department carefully selected a portfolio that would not cause current-year budget overruns.

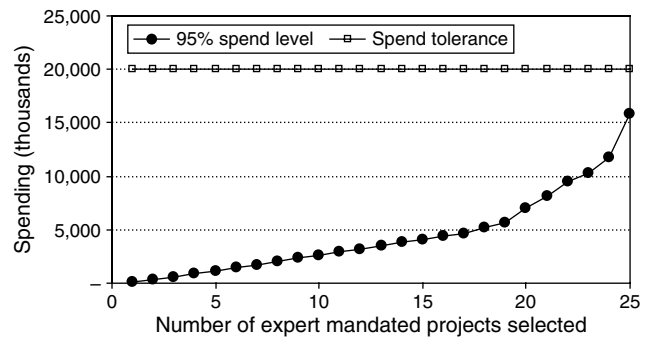


Figure 3: The project portfolio selected by the experts in 2006 adheres to budget constraints.

The predicted spend-level line approaches, but does not cross, the tolerance of a \$20 million budget. One reason for this cautious approach was that the department was unable to quantify the risk involved in project spending. Because the probability of exceeding the budget was not measured, the department set a safety margin arbitrarily. Therefore, the predicted spending on the selected portfolio was approximately \$16 million—only 80 percent of the available budget was used. Our portfolio, on the other hand, would have used more than 97 percent of the budget and specified that the budget constraint would be satisfied with at least a 95 percent probability.

**Reducing the Carryover Risk**

The unplanned-carryover constraint also required improvement. The previous approach did not consider the timing of cash flows or the uncertainty in timing and magnitude of cash flows.

As Figure 4 shows, when the traditional approach was used, a violation of the unplanned-carryover constraint would occur after selecting the 18th project in the portfolio; the unplanned carryover reached \$502,000, which was above the \$500,000 limit. When the experts chose their entire list of 25 projects, they increased the unplanned-carryover level substantially.

The department was not surprised that a significant level of unplanned carryover was associated with the expert-chosen portfolio. For many years, the capital-allocation decisions had been made based on budgetary information alone. Although the budget constraint was rarely violated, the department had a history of experiencing unplanned carryover

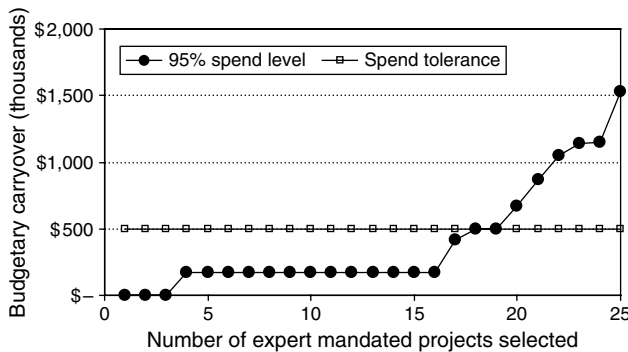


Figure 4: The portfolio selected by the experts in 2006 violates the budgetary carryover constraint.

	Utility from experts' selection (without carryover constraint)	Utility from experts' selection (with carryover constraint)	Utility from our model
Regulatory	1.858	0.909	2.485
Modernization	0.331	0.255	0.409
Risk	8.133	2.045	6.055
Infrastructure	14.150	2.855	12.018
Business	0.000	0.000	0.000

Table 2: The model improves every attribute of the department's performance.

at the end of the year when it became clear that some projects were unlikely to be completed in time. The project managers had to apply a great deal of pressure to themselves, their project teams, and their subcontractors as they scrambled to limit unplanned carryover. Implementation of our model reduced the likelihood of unplanned carryover to a predetermined limit such that the department acquired the capability to control the unplanned-carryover risk.

**Increase in Overall Utility to the Department**

We can draw an interesting comparison between the utility scores of the expert-mandated and model-recommended portfolios. Because the experts' portfolios violate the carryover constraint, for a meaningful comparison, we forced the mandated portfolio to comply with the constraint by removing projects with low utility-to-cost ratios from the bottom of the mandate list until the unplanned-carryover constraint was met. Table 2 shows the individual attribute scores for each portfolio.

Our model has improved the department's performance in all attributes other than business because all 2006 projects had a zero score in the business attribute, i.e., there were no high-value projects that supported the winning of contracts that were classified as *must win*. Thus, our model's project selection provides a Pareto improvement over the experts' selection (Table 2).

**Benefits to Lockheed Martin: Business Practice**

In addition to the tangible benefits described above, our analytic approach also benefited the department by changing the way that the decision makers handled the capital-allocation problem.

First, we established a quantitative and objective method to measure a project's value. This reduced the time and effort spent on discussions and negotiations. Historically, more than 20 managers, engineers, and planners attended three to five negotiations meetings each year; thus, considerable time was saved. Using objective criteria in project selection also reduced intradepartment tension and stress.

Second, we highlighted the importance of keeping historical data on previously implemented projects to make inferences about the performances of future projects. In our model, we updated management's estimates on the mean and variance of each project's spending because the department kept data on actual spending for the previous five years. Unfortunately, the department had never kept historical data on project duration or the timing of each dollar spent on each project. Improved data storage and management improved the department's control over carry-over risk.

Third, our model clearly specified those infrastructure projects that management mandated or excluded. Some of the projects had to be implemented whether they produced a high utility or not; these were projects begun in previous fiscal years that had to be finished, or projects that executives had mandated for implementation. We added a mandate column to our spreadsheet so that projects could be forced into the selected portfolio. In addition, it might have been necessary to disallow some projects if the decision makers realized that strategic business initiatives underway across the site would render the proposed project irrelevant soon after implementation. Thus, we added an exclude column for that purpose.

## Lessons for Spreadsheets in OR

While implementing our model at Lockheed Martin and during subsequent interactions with decision makers and other users, we observed that using spreadsheets to construct, solve, and present our analytical model was one of the reasons management received it well. Specific features of spreadsheets helped the transition process; we believe that a better understanding of these features could provide valuable lessons for OR practitioners:

- **Ease of use:** Many people do not have training in specialized optimization packages; however, they

are somewhat familiar with the basic workings of spreadsheets. Their previous knowledge allows them to understand the model more rapidly.

- **Access to software:** Spreadsheets are among the most widely available and used software programs in the corporate world. One can open a spreadsheet program on a desktop without installing specialized software.

- **Transparency:** When an analytical model is built on a spreadsheet program, it is relatively easy to disclose and share its inner workings. Spreadsheets help users to clearly understand how the model works and how to easily update its parameters.

- **User interaction (development phase):** With a specialized software package, the end user specifies needs, but remains inactive as the model is built. With spreadsheets, the end user can be an active participant in the model development. By involving the department's decision makers in the modeling phase, we were able to revise and reconceptualize the business problem and explore different alternatives.

- **User interaction (implementation phase):** Building the model using a spreadsheet format allows decision makers to experiment with project inputs (i.e., cost, duration, and attributes) and observe how the model output changes. After we determined the optimal portfolio of projects and presented the results to the decision makers, they tested different risk levels to determine which projects were sensitive to which kinds of risks. They also chose their own project portfolio and saw the corresponding outputs and utility scores.

- **Trust:** Project-portfolio selection is a naturally contentious issue. Disclosing and sharing the inner workings of the model through a spreadsheet program was very helpful in building the recipients' trust in the model. They might choose not to analyze the model itself; however, because they have their own copy of the model, they are more likely to trust its intent. Because they can view the underlying calculations within the spreadsheet while considering the data required of them, they become more comfortable with the model's basic operations. Using a spreadsheet program helped to remove skepticism about the model's objectivity and level of sophistication. Had the model been created in a less-common programming environment than MS Excel, it could not have

been shared to the same extent; distrust would have resulted.

- Management of spreadsheet assets: Although a typical spreadsheet program requires considerable time to design, test, and verify, management of spreadsheet programs attracts less attention than other types of computer programs (Grossman 2002). It is possible that some features of spreadsheets (e.g., ease of use or transparency) work against them, and they are perceived as low-cost replacements. Our experience was more encouraging. We believe that the close interaction we had with the end users during the development phase was important in that it raised the users' perceived value of the model. Having invested significant time on the spreadsheet, the decision makers had a better understanding of its power and paid attention to its maintenance. The department clearly stated that this spreadsheet program was not the personal property of its designer; it was the property of the company. We were asked to prepare documentation about our Excel file, to explain the inner workings of the model, and to provide other information pertinent to its operation. Thus, if the modeler changed positions or left the company, the model could be easily transferred to his or her successor without loss of critical information.

- Data collection: The department's list of potential projects was stored in Excel well before the model's development; therefore, importing the list of projects with their associated, expected costs was fairly easy. But the real benefit came during the data-collection phase. We copied the model's Excel file and sent it to the decision makers with a written explanation of the data and data specifications needed, which each decision maker then supplied independently by e-mail. This saved considerable time over the previous process in which the modeler met with each person and entered data directly into the model. A precautionary action should be taken, however, to protect input spreadsheets so that only the requested data is entered. Users of the input form may unknowingly foil the modeler if they enter data in a format that differs from the expected format (e.g., k-dollars versus dollars) or if they make formatting changes, which the modeler does not notice (e.g., hiding rows), to the spreadsheet.

## Appendix

### Project Valuation

Table A.1 shows the definition of the final set of attributes, weights, and respective scales. Each available project was rated on all attributes. The total project utility was then calculated as the sum of each of the project's rates, respective to each attribute, times the weight of that attribute (Winterfeldt and Edwards 1986).

### Summary of the Mathematical Model

$$\begin{aligned} & \max_{X_1, \dots, X_N} \sum_{i=1}^N X_i U_i \\ & \text{s.t. } \sum_{i=1}^N X_i E[C_i] + \Phi^{-1}(\alpha_B) \sqrt{\text{Var}\left(\sum_{i=1}^N X_i C_i\right)} \leq B + T_B \\ & \hspace{20em} \text{(budget constraint),} \\ & \sum_{i=1}^N X_i E[O_i] + \Phi^{-1}(\alpha_{CO}) \sqrt{\text{Var}\left(\sum_{i=1}^N X_i O_i\right)} \leq T_O \\ & \hspace{20em} \text{(carryover constraint),} \\ & E_i \geq X_i \geq M_i \quad \text{for } i=1, \dots, N \\ & \hspace{20em} \text{(mandates and exclusions).} \end{aligned} \tag{1}$$

The model formulation is outlined below along with definitions of notation used.

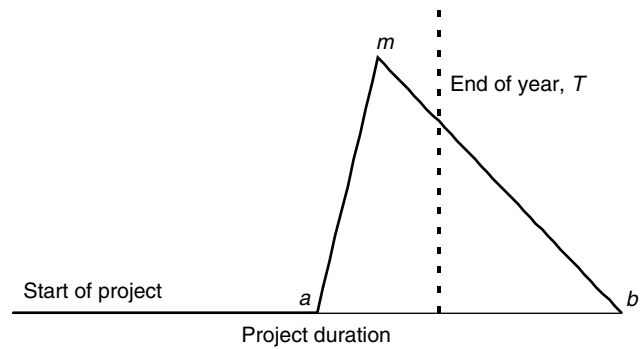
- $N$ : number of available projects.
- $X_i$ : binary decision variable for project inclusion into the portfolio.
- $U_i$ : utility of project  $i$ .
- $C_i$ : random variable representing capital expenditure for project  $i$  during the year.
- $O_i$ : random variable representing budget carryover for project  $i$ .
- $B$ : available capital budget.
- $T_B$ : value of the total budgetary overrun that could be tolerated.
- $T_O$ : value of the total budgetary carryover that could be tolerated.
- $\alpha_B$ : risk level that the company is willing to accept for budget constraint.
- $\alpha_{CO}$ : risk level that the company is willing to accept for the aggregate carryover.

Attributes and Respective Scales	Rate
<b>Regulatory (weight = 0.303)</b>	
Life safety and health situation (current conditions pose exposure risk to personnel)	1.0
Situation noncompliant with regulatory guidelines (NOV from EMD or safety)	0.9
Current condition requires compliance within next 24-month period	0.8
New or pending regulatory obligation	0.7
Best management practice	0.2
No regulatory implication	0
<b>Risk (weight = 0.273)</b>	
Current conditions pose immediate risk of damaging flight hardware	1.0
Current conditions pose immediate risk of damaging program support equipment	0.9
Current conditions pose risk of damaging building infrastructure and/or equipment	0.8
Current conditions pose a potential risk to program assets	0.6
Situation not related to risk	0
<b>Infrastructure (weight = 0.182)</b>	
FICA category 5: System in failure and regular impacts to user requiring workaround	1.0
FICA category 4: System not able to perform to design or high service-request rate	0.9
FICA category 3: System age greater than expected life or significant to high service-request rate	0.8
FICA category 2: System age greater than 50 percent of functional life, or moderate service-request rate	0.5
FICA category 1: System age less than 50 percent of functional life, minimal service-request rate	0.1
FICA category 0: System age less than 25 percent of functional life, no user concerns	0
<b>Business (weight = 0.152)</b>	
Corporate focus program	1.0
Not related to new business pursuit	0
<b>Modernization (weight = 0.091)</b>	
Building code violations	1.0
Current conditions fail to support program mission objectives	0.9
Use and occupancy criteria (allowable vs. unallowable)	0.8
Space categorized as "red space"	0.5
Space categorized as "yellow space"	0.4
Updates existing building finishes	0.1
No relation to modernization	0

**Table A.1: The table data illustrate the attributes, their weights, and the scales that we used in the study. FICA stands for "Facilities Infrastructure Condition Assessment," a quantitative method of evaluating the general condition of buildings and systems in the facility. "Corporate Focus Program" is a term used for business that the company considers "must-win."**

$M_i$ : binary variable, which equals one if project  $i$  is mandated by the department, zero otherwise.

$E_i$ : binary variable, which equals zero if project  $i$  is excluded by the department, one otherwise.



**Figure A.1: We use a triangular distribution to predict the carryover length of a project.**

$\Phi$ : cumulative distribution function for the normal distribution.

### Unplanned-Carryover Constraint

If a project’s duration extends beyond the end of the year, the amount of money spent in the next year is defined as unplanned carryover. Figure A.1 illustrates the concept of predicting the amount of unplanned carryover based on the duration of a project.

We assume a triangular probability distribution for the duration of the project, where  $a$  indicates the shortest possible duration of a project,  $m$  is the most likely duration (the mode of the distribution),  $b$  is the longest possible duration, and  $T$  is the end of the year.

We assumed that the spend rate from the start of a project to its completion is constant and is equal to total (expected) cost over the (expected) length of the project. Then, we could predict the expected value of unplanned carryover by finding the mean value of the portion of the triangular distribution beyond the end of the year, and multiplying that difference by the spend rate:

$$E(O) = \frac{E(C)}{E(D)} [E(D | D > T) - T]$$

$$= \frac{E(C)}{E(D)} \left[ \int_T^\infty \frac{x f_D(x)}{P(D > T)} dx - T \right], \quad (2)$$

$$\text{Var}(O) = \frac{E(C)^2}{E(D)^2} [E(D | D > T) - T] - E(O)^2$$

$$= \frac{E(C)^2}{E(D)^2} \int_T^\infty \frac{x^2 f_D(x)}{P(D > T)} - E(O)^2, \quad (3)$$

where  $E(D | D > T)$  is the expected duration given that the duration exceeds the end of the year,  $f_D(x)$  is

the probability density function for a triangular distribution, and  $P(D > T)$  is the probability that the duration exceeds the time remaining in the fiscal year.

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Dennis Garegnani, Director of FO&S, Lockheed Martin Space Systems, Denver, Colorado 80201, writes: “The optimization model developed for our team has made substantial contributions to the long-term effectiveness of our organization. Up until now, capital allocation decisions had been made largely based on qualitative, tacit knowledge held by various decision makers within the department and through a painstaking and argumentative review process.

Adding this quantitative aspect to our investment strategy has undoubtedly benefited the department over the long term and in some immediate ways as well.

“The most fundamental improvement is the definition of attributes that align to departmental objectives and measuring each project according to them. The department’s decision makers must now examine how well each project contributes to our goals instead of choosing the projects they are most impressed with personally. The strong link that has now been formed between our business strategy and our investment strategy has reinforced the effectiveness of the department and built a stronger, more positive relationship and mutual respect between the facilities team and the central finance team.

“Making portfolio decisions taking estimated project durations into account provides another dimension of improvement. Up until now, we had acknowledged that very lengthy projects should be budgeted into several years but many projects with some likelihood of taking longer than a year were assumed to be single-year projects if there were any probability of finishing in a single year. Describing the uncertainty inherent in the duration provides our decision makers with detail necessary for the meticulous analysis necessary in effective control of our financial performance.

“Having the model at our disposal has already added another level of credibility to the department among its peers. Organization of past financial performance data to predict and control future financial performance has long been needed and the model has addressed this issue as well. Watching the correction and evolution of the model to match our needs has been extraordinarily constructive for the entire department. Simply put, the optimization model has been a huge success and directly affects our productivity and ability to deliver positive results. It has already been recognized as a best practice.”