CHANCE-CONSTRAINED MULTIATTRIBUTE CAPITAL ALLOCATION OPTIMIZATION FOR LOCKHEED MARTIN FACILITIES

by

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ABSTRACT

Every manager with spending authority faces a problem similar to this: invest a limited amount of capital in projects to be implemented in a limited amount of time to position the company as competitively as possible. Quite often, the manager is responsible for annual budgets that must be spent within a given timeframe or relinquished. When the manager invests in projects of uncertain duration, some projects inevitably finish in later years than those in which they were funded. Funding for the completion of the late projects must then be provided by canceling or postponing projects that were planned for that year. Consequently, the manager desires not only to predict how much each project will cost, but when its costs will occur.

Managers also commonly face choices between "strategic" investments—or those that cannot be justified purely in terms of classical investment evaluation methods. This paper presents a quantitative approach to optimize project selection under these real-world circumstances. Multiattribute utility theory is employed to ensure high-value portfolios were selected and chance-constrained programming techniques ensured the financial performance of the model's recommended portfolio. Microsoft ® Excel is used to implement the approach to support broad accessibility by managers without training in management sciences and operations research or access to specialized optimization packages. A clear advantage of using spreadsheet software is its transparency, allowing users a clear understanding of how the model works, and how the model parameters can be easily updated on request.

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CHAPTER 1

INTRODUCTION

Lockheed Martin Space Systems Company in Denver, Colorado is located on a 5,500 acre facility containing 37 major buildings—most constructed prior to 1970. Each major building is comprised of a multitude of systems, all exhibiting various degrees of wear and tear. Allocating capital to the maintenance and modernization of the facility infrastructure and office space is a non-trivial task.

The Facility Operations & Services (FO&S) organization within Space Systems Company in Denver has historically chosen a portfolio of projects aimed at improving the condition of the site based on the judgment of decision makers within the department and qualitative input from various stakeholders. This process is lengthy, stressful, and could produce suboptimal investment decisions. A robust analytical method for optimizing investment decisions like these could not only increase the value of Lockheed Martin's infrastructure, but aid many managers in similar situations.

During the fourth quarter of each year, Lockheed Martin Space Systems Company allocates more than ten million dollars in capital funds to Facilities Operations & Services to undertake their mission of maintaining and improving the site infrastructure and working environments. FO&S maintains a list of up to three hundred projects that it would implement in pursuit of this goal if it had limitless funds. However, their capital is constrained and so it must be allocated only to a small subset of these projects. Primary goals of the projects are to sustain regulatory compliance of the facility with local and federal law, minimize risk the facility might pose to aerospace products manufactured and tested on site, and maintain the infrastructure in working condition. These projects often also modernize facility office environments and ensure the facilities are properly configured to support the pursuit of new business.

The capital budget of FO&S is subject to policies similar to those found in many companies. The total dollar amount is treated as if it were static and is definitely not to be overspent, although small percentage overruns are tolerated. The budget must also be spent within the fiscal year it is allocated for. Unspent money cannot be *"carried over"* and added to budgets of subsequent fiscal years. Therefore, managers in FO&S are keenly interested not only in predicting the total amount of expenditure during the year, but in the timing of those expenditures as well.

Various methodologies exist in the scholarly and practical literature to handle capital allocation problems. Deterministic approaches employ integer programming to maximize portfolio net present value subject to a budget constraint. There are mixed-integer programming applications which are aimed at maximizing net present value of considered projects subject to a typical budget constraint. In these applications, the business settings have all deterministic inputs (Charnes and Cooper (1959)). The

Markowitz approach brings probability theory to the analysis in the interest of maximizing portfolio return on investment subject to risk constraints while correlating returns (Albright and Winston (2005) and Markowitz (1952)). There are advanced methods of stochastic programming that handle uncertainties in costs and revenues in predictions of net present values (Gurgur and Luxhoj (2003)). All of these approaches require a monetary valuation of each project. For situations where no monetary valuation is available, multiattribute decision theory is greatly utilized to suggest a relative value of each project (Clemen and Reilly (2001), Dean Ting, et al. (1999), Gogus and Boucher (1998), and Keeney and Raiffa (1993)). The aforementioned approaches have been reconfigured in a multitude of combinations to deal with different investment decisions, but none have dealt with the situation where annual budgets must be relinquished if not spent. The model developed in this thesis fills that gap.

Implementation of an analytical approach to infrastructure capital allocation is long overdue. Historically, managers of FO&S have spent a great deal of time, effort, and emotion each year on capital project portfolio selection and funding. These influence costs may have been justified if the effort produced truly optimal portfolios—but they likely did not. By adopting an analytical, computer-based approach to capital rationing, the department stands to greatly reduce the effort invested in portfolio selection while greatly improving the value of their selected portfolios.

Each year, the department's decision makers (ten to fifteen managers, project managers, engineers, and planners) spend weeks identifying, investigating, and presenting arguments for potential capital projects based on their personal knowledge of the facility. Each decision maker makes well-founded assertions about the value of their projects, but since there was no quantitative, objective way to measure the worth of the project—each project would require a debate every year. There are wide differences of opinion in the group of decision makers given their diverse areas of expertise and levels of familiarity with each project. Substantial time and money are spent each year in the debate. Defining objective measures of project value greatly reduces the amount of emotion and time spent in deliberation. Keeping a record of projects' objective measures of worth means projects don't have to be debated year after year. The model developed in this thesis has the potential to save hundreds of man hours per year by quantifying each project's value and optimizing capital allocation.

The sheer numbers of available projects usually mean that the experts lack the time to debate the value of every project every year, so they select a small subset of projects that seem important and debate their significance until a consensus is reached on which projects are to be implemented. This consensus may result in the portfolio that benefited the company the best, but it might just as easily be the portfolio that allows the debate to end. Keeping quantitative measures of value of the projects in a spreadsheet year after year and capitalizing on the speed of computer modeling means that every project will be considered every year and that each year's portfolio should be very close to the one that best benefits the company's and department's goals.

The incumbent approach to capital rationing considers only how important a particular project is and how much it is estimated to cost. It does not account for the timing of cash flows or the uncertainty in timing and magnitude of the cash flows. Questions about the duration of the project are usually not asked unless the project is a multi-year endeavor. Large projects are often selected because they are perceived as important and affordable. However, these large projects also introduce unexpected fiscal uncertainty. If these types of projects finish later than planned, they can cause substantial disruption in financial planning cycles. Since schedule and budget uncertainty were not addressed during portfolio selection in the past, the predictive power of the FO&S's planning was somewhat limited. The model developed in this thesis aims to account for that uncertainty, and it produces portfolio recommendations that comply much better with the wishes of the decision makers of remaining within the financial bounds set by company policy.

Aside from the benefits of modeling, merely answering basic questions about the uncertainty in a project's schedule brings decision makers an increasingly tangible understanding of the relationship between each project and the department's financial performance. Data on each project's duration is recorded and kept for future portfolio selection efforts. Therefore, duplication of effort to estimate project schedules year over year is eliminated.

Coupling sophisticated modeling techniques with an increased awareness of project characteristics will bring substantial benefits to the organization.

CHAPTER 2

LITERATURE REVIEW

A myriad of techniques have been developed to move capital rationing decisions beyond the purely politicized selection process where managers battle one another for funding for their preferred projects. These techniques range from very simple ranking methods to more sophisticated optimization models. An overview of these techniques follows.

The simplest analytical method for selecting a project portfolio is to rank all the available projects, sort them by rank, then go down the list funding projects until the budget is exhausted. The projects can be ranked according to any relevant scale. These scales could be as subjective as reflecting manager's preference or as objective as expected net present value (Gabriel, Ordóñez, and Faria (2006)).

Some relevant scales for ranking projects in terms of economic return include return on investment, payback period, expected value, and valuing projects according to the capital asset pricing model (Archer and Ghasemzadeh (1999)).

Many companies employ basic rate of return calculations to determine the acceptability of capital projects in hopes of maximizing the economic return of their portfolio. In the simplest form, capital funding is not constrained and projects that return more than the company's financial cost of capital are approved. When the capital is limited, projects must be compared using the company's opportunity cost of capital, or the return the company could make if other available projects were implemented. Sometimes companies set a "hurdle rate" or an arbitrary rate of return that projects must expect in order for them to be adopted (Stermole and Stermole (2000)).

Rate of return calculations carry a host of caveats with them, limiting their effectiveness as tools for portfolio selection. For instance, two projects of dissimilar scale in both cost and return could have identical internal rates of return (IRR), but entail very different implications for the company in terms of affordability. There may also be multiple rates of return for a given project if the cash flows vary substantially over time. On balance, IRR should be avoided as a project selection criteria (Brealey, Myers, and Allen (2006)).

Selecting projects using their expected net present values (NPV) eliminates most of the shortcomings of the IRR method. Projects with positive NPV generate an economic return and are considered acceptable. When developing a portfolio using NPV, projects are ranked by their profitability index—or the ratio of the NPV to the project's cost (Stermole and Stermole (2000)). The projects are then sorted by profitability index and "cherry picked" from the top until all the available funds are committed.

The cherry-picking technique of ranking projects and selecting them from the top until the money runs out rarely produces the best possible portfolios since a single, highly ranked project may edge out a combination of lower ranked projects that would together have made a better portfolio (Gabriel, Ordóñez, and Faria (2006)).

The process of cherry-picking also breaks down in situations involving more than a single budget constraint. One other common constraint is that the budget must be expended by a certain date. There may also be several fiscal periods over which portfolios must be optimized. Some projects may be mutually exclusive or the projects may require constrained non-monetary resources. In real-world situations of any degree of complexity, an analytical-based optimization that takes "multi-period" planning into account must be undertaken (Brealey, Myers, and Allen (2006)).

When ranking projects by economic measures is impossible, the projects can be valued by qualitative measures. Basic qualitative approaches include scoring projects according to alignment with the company's strategic objectives, checklists validating essential project characteristics, and stage-gate reviews checking project viability throughout the lifecycle (Cooper, Edgett, and Kleinschmidt (2000)).

Government decision makers nearly always have to choose between alternatives that cannot be quantified in terms of economic return. They must spend real dollars to increase the well-being of their constituents. Well-being does not readily translate into dollars. In fact, well-being is often defined by several attributes (Keeney and Raiffa (1993)). Several multiattribute decision making strategies are available for cases where more than one measure is used to compare the "goodness", or utility, of different options. These strategies fall under the broader term of multiattribute utility theory.

In cases where there are relatively few options to choose between, the analytical hierarchy process, or AHP, is appropriate. This method evaluates each option with a pairwise comparison between the other options. AHP is one of the foundational multicriteria decision making techniques, but it can be cumbersome in situations where many options must be compared (Winston (2004)).

The goal programming approach is used in situations where the scales measuring performance extend beyond the ideal. Several of these scales can be defined and weighted relative to each other to reflect the decision maker's preferences. Specific goals are chosen along each of those scales and portfolios are chosen according to how little their scores differ from the goals (Sealey (1978)).

Quality Function Deployment (QFD) is another approach within multiattribute utility theory that has been used to optimize capital rationing decisions. QFD was developed several decades ago and is heavily used in the Japanese automotive industry to ensure their cars satisfy their customers better than competitors' cars. QFD is singularly appropriate for situations where decision makers need to link customer wants with design requirements, there are substantial interrelationships between attributes or requirements, and where competitor performance is important and can be quantified (Partovi (1999)).

All of the approaches so far assume that the decision makers know the project outcomes and constraints with certainty. Future costs and benefits of a single project are hard to predict. Predicting portfolio outcomes are even less intuitive. Harry Markowitz developed a method for handling uncertainty in investment portfolios in the 1950's and later received the Nobel Prize in economics for his work. His approach is to quantify the variation in past returns on a number of available stocks and correlate the returns between the same stocks. Given that data, he could choose a portfolio that maximized the expected return while holding the uncertainty to a constant acceptable level or vice versa: hold the expected return constant and choose the portfolio that would minimize the uncertainty in return (Winston (2004)).

A primary contribution of Markowitz' (1952) work is to discredit the idea that inherently uncertain quantities (such as future returns or future costs) should be treated as their expected value to ease analysis. If portfolio selections are made assuming project costs or durations at their mean or expected values, the likelihood of cost overruns or schedule delays is very high. An alternate strategy might be to assume the worst case for project costs and durations, but then very little of the budget will be committed and the value added to the company will be much less than otherwise possible (Gabriel, Ordóñez, and Faria (2006)).

One way of coping with the uncertainty inherent in portfolio selection is to choose a portfolio, describe the uncertainties mathematically, and perform a Monte Carlo simulation to see the range of outcomes the portfolio might produce. The Monte Carlo simulation draws random numbers from the uncertainties described with probability distributions over many iterations, producing its own probability distribution of the possible outcomes. This is called a descriptive method because it describes the range of potential outcomes, but does not recommend a course of action. The classical application of this technique is to describe the uncertainties in cash flows from investment portfolios and perform discounted cash flow analysis (Clemen and Reilly (2001) and Hertz (1964)).

As opposed to the descriptive methods that describe possible outcomes, prescriptive methods recommend a course of action. Some of the prescriptive methods that deal with uncertainty are fuzzy multiattribute utility theory and chance-constrained programming.

When a portfolio is selected to optimize across multiple attributes, but the attributes involve some degree of uncertainty, a technique called fuzzy multiattribute utility theory may be employed (Dean Ting, et al. (1999) and Gogus and Boucher (1998)). The term "fuzzy" means that attributes can be defined using probability distributions instead of constant values. This technique allows the decision maker to handle situations where the attributes are difficult to predict because of limited availability of data or uncertainty from outside factors.

Chance-constrained programming allows a model to recommend courses of action to decision makers maintaining limited probabilities that the problem's constraints will be violated (Gurgur and Luxhoj (2003)). To do this, the constraints are first stated in probabilistic terms. For example, we might want the ideal portfolio that maintains a ninety-five percent probability of costing less than the available budget. Once constraints like these are stated as probabilistic equations, the equations are transformed into their deterministic equivalents so they can be dealt with by computer optimization (Charnes and Cooper (1963)).

The techniques outlined above have been used successfully in industry and government for decades. H. W. Jackman gives an example from the Ontario Hospital Services Commission (Jackman (1973)). The government agency allocated capital funds to a wide array of projects aimed at satisfying multiple goals. Their goal was to optimize their hospital infrastructure through well-planned capital investment. There was competition within the hospital system for these funds and the goals were more numerous and more strategic in nature than what could be addressed with a single, straightforward metric like expected NPV. The modelers in this case took a deterministic goal programming approach where potential investments were valued based on how well they reached multiple goals derived by the commission. The investments were also penalized for straying too far beyond the goals.

James J. Chrisman, et al. (1989), in their work "A Multiobjective Linear Programming Methodology for Public Sector Tax Planning", optimized several tax rates for the city of Peoria, Illinois. They developed their model iteratively with the decision maker, correcting each time for unexpectedly unrealistic recommendations produced by the earlier versions of the model. Their goals were to find a tax structure that simultaneously minimized taxes on low-income taxpayers, discouraged businesses and consumers from leaving the city for more favorable sales tax, keep city tax revenues from decreasing, and minimizing the gasoline tax.

Dean Ting, et al. (1999) present a multiattribute utility theoretical approach to minimize the cost of a metallurgical process for United Technologies and Pratt &

Whitney. Their choice of attributes reflected the major cost drivers in the process. Experts in the process were consulted to determine the correct ranges for each attribute and the relationships between them.

Gabriel et al. (2006) minimized portfolio cost and maximized the utility of a portfolio funded by an unnamed U.S. Government agency using multiattribute utility theory in concert with chance-constrained programming . They treated portfolio cost and portfolio utility (or rank) as separate attributes to be optimized, then applied a chance-constraint to limit the likelihood the selected projects would overrun their funding level. They were able to correlate the financial performance of past projects, and so utilized a covariance matrix similar to Markowitz' (1952). They also used the analytical hierarchy process (AHP) to rank their projects (Winston (2004)).

While these historical techniques have informed many important financial decisions, an unaddressed gap remains. None of the aforementioned approaches combine the ability to optimize a portfolio selection based on qualitative criteria while limiting budget overruns and dealing with budgets that must be relinquished at year-end. The model presented here does.

CHAPTER 3

MODEL DEVELOPMENT

3.1 Project Valuation

With rare exception, infrastructure improvements exist in a different class from "textbook" investments. Textbook investments lend themselves well to time value of money analysis and can be prioritized based on net present value, benefit cost ratio, or other common economic analyses. These economic analyses are enabled by readily accessible data reflecting estimated cash flows both to and from the project in question. Infrastructure, though, may support many profit-generating efforts without directly profiting the company. So the estimated costs of the project may be very predictable, while the expected monetary return is hardly quantifiable.

FO&S undertakes projects of a wide range of technical complexity in support of on-site manufacture of products intended for space travel, but an extreme example to demonstrate the unquantifiable nature of return on investment might be a simple restroom refurbishment project. The construction industry has developed fairly reliable techniques for estimating the costs of projects like these. Those restrooms will undoubtedly improve the working environment of profit-generating employees for years to come. However, Lockheed Martin Space Systems Company earns its income primarily through building and selling technology that will be deployed in space. This type of technology can take many months to build, test, and launch. The company generally receives payment after its products reach their destination in space and begin operation. Sometimes the company is paid for reaching intermediate milestones in the design and production process. In either case, the restrooms play a relatively minor role in enabling the final profit. The new restrooms enable a small portion of the total profit. Calculating return on investment for the restroom project is impossible. In fact, calculating return from most infrastructure projects is impossible. FO&S needs an approach for quantifying the relative value of one available project as compared to another.

Multiattribute utility theory provides this approach. Ascertaining the attributes of worthwhile facility projects was the first step toward a project valuation strategy. These attributes were identified through extensive conversations with the director of the department and with many of the employees directly involved in selecting which available projects had been undertaken in the past.

After several iterations developing the attributes, the final set was agreed upon. The final list of attributes is 1: Regulatory; 2: Modernization; 3: Risk; 4: Infrastructure; and 5: Business.

A quantitative scale is defined within each attribute to allow each available project to be scored on each of the attributes according to how well the project addressed the facility need described by that attribute. A project that mitigates the most serious possible need defined in the attribute is scored a "one" on the scale for that attribute. A project that does not address a need described by the attribute is scored a "zero" on that attribute. The scale within each attribute allows scores between zero and one when a project addressed the type of facility need described by the attribute, but to a lesser extent than those that scored a "one".

Qualitative divisions are defined within each scale, and the department's director assigned relative scores to each division of the scale. These attributes and their respective scales are combined into a utility function and used to calculate a relative value of each project in lieu of a straightforward net present value calculation.

The Regulatory attribute focuses on the facility's compliance to federal and state government regulations. Divisions within the regulatory attribute scale are defined so that each available project is scored according to how well it helps the company attain, or remain in, regulatory compliance. These divisions range from very serious: the project remedies a problem currently posing safety hazards to employees; to less urgent: the project could be implemented to reduce the risk of potential future regulatory violations; to the lowest level where the project is completely unrelated to regulatory concerns.

The Modernization attribute scores projects on how well they position the facility to fill the needs of the business and the employees. The modernization criteria range again from the very serious: a project is needed so the facility can support mission objectives; through the less serious: the project beautifies the facility, but does not enable critical operations.

The Risk attribute involved the risk posed to flight hardware by the facility itself. For example, a satellite might be at risk of water damage from old pipes adjacent to a clean room it is stored in. A high score meant that a serious risk could be mitigated by implementing the project in question while a low score meant little or no risk would be mitigated.

The Infrastructure attribute deals specifically with the wear and tear of the various building systems on the site. A high score means the project could remedy a system currently in failure, while lower scores are given for projects that reduced probabilities of future failures.

The Business attribute is very narrowly defined to highly value projects that support the winning of contracts the company classified as "must win".

Tables 1 through 5 show the scales within each attribute.

Table 1: Regulatory Attribute Scale

REGULATORY	Rate
Life Safety and Health Situation (Current conditions pose exposure risk to personnel)	1.0
Situation Non-Compliant with Regulatory Guidelines (NOV from EMD or Safety)	0.9
Current Condition Requires Compliance within Next 24-Month Period	0.8
New/Pending Regulatory Obligation	0.7
Best Management Practice	0.2
No Regulatory Implication	0

Table 2: Risk Attribute Scale

RISK	Rate
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

Table 3: Infrastructure Attribute Scale

INFRASTRUCTURE	Rate
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, or Repeat user impacts, delays or down time.	0.9
FICA Category 3: System age greater than expected life or Significant to High service request rate, or impact to user, a situation requiring a workaround, down time incidence, noted employee morale	0.8
FICA Category 2: System age greater than 50% of functional life, or Moderate service request rate, Occasional user concerns	0.5
FICA Category 1: System age less than 50% of functional life, Minimal service request rate, none to occasional user concerns	0.1
FICA Category 0: System age less than 25% of functional life, no user concerns	0

(Note: FICA stands for "Facilities Infrastructure Condition Assessment", a quantitative method of evaluating the general condition of buildings and systems in the facility.)

Table 4: Business Attribute Scale

BUSINESS	Rate
Corporate Focus Program	1.0
Not Related to New Business Pursuit	0

Note: “Corporate Focus Program” is a term used for business that the company considers “Must-Win”

Table 5: Modernization Attribute Scale

MODERNIZATION	Rate
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 at "Red Space"	0.5
Space Categorized as "Yellow Space"	0.4
Updates Existing Building Finishes	0.1
No Relation to Modernization	0

After each attribute was fully developed, an additive utility function was developed based on the foundation of mutual preferential independence—meaning scores in any one of the attributes are assumed to have no effect on the scores in any other attribute for a single project. Given the philosophical separation between the attributes, mutual preferential independence is probably an accurate assessment. And since the utility function is additive in nature, the "swing-weighting" technique could be used to tie the attribute and their respective scales together into a single measure of the value of each project (Clemen and Reilly (2001)). To implement this technique, a hypothetical project that caused no improvement in any one of the attributes is used as a worst-case baseline against which to compare the relative values of the other attributes. Then a hypothetical project that caused maximum improvement in all attributes simultaneously is defined as the upper end of the range of utilities.

The director of the department was led through a systematic ranking of hypothetical projects, each causing maximum utility in a single attribute and zero utility in the remaining attributes. The director then ranked the hypothetical projects, one for each attribute, scoring the worst-case baseline project as zero and the project that scored at the top of the attribute he most favored as one hundred. He provided scores between zero and one hundred for each of the intermediate hypothetical projects to indicate the relative importance of each attribute. Each hypothetical project's score is divided by the sum of their scores and the resulting number is the weight of the attribute represented by each respective project having a maximum improvement with that attribute and no improvement in any other attribute. The sum of the attribute weights is necessarily equal to one and each weight is represented by a number between zero and one. Table 6 shows how these projects were compared. The approach is adapted from Clemen & Reilly (2001).

Detailing the application of the swing-weighting technique used to develop Table 6, the first step is to define the worst possible project as one that scored at the bottom of each attribute's scale. This is designated as the Benchmark, and ranked the lowest, or 6th of all the options. The hypothetical projects scoring the best in one attribute and the worst in all the others were ranked by the department's director in terms of benefit to the company. The resulting ranks were first: Regulatory; second: Risk; third: Infrastructure; fourth: Business; and fifth: Modernization.

These rankings mean that the most influential attribute is "Regulatory"—so Regulatory is assigned a rate on the other end of the scale from the worst case benchmark. Regulatory is assigned a rate of 100 and the benchmark is assigned zero. The director was then asked to assign rates between zero and one hundred to the remaining attributes, with the rates ordered identically to the ranks. The ranks then indicate the importance of each attribute relative to the others and the rates indicated by how much.

Finalizing the attribute weights to be used in the utility function, the rates were added and each rate is divided by the sum. This quantity is the attribute weight. This is mathematically represented as shown in equation (1):

$$Weight_i = \frac{Rate_i}{\sum_{i=1}^{5} Rate_i} \tag{1}$$

The results in Table 6 show that regulatory concerns were paramount, with a weight of 0.303. Risk was second in importance with a weight of 0.273. The remaining attributes of Infrastructure, Business, and Modernization had weights of 0.182, 0.152, and 0.091, respectively. With the attribute weights calculated, the utility function can be developed.

To make use of the utility function, each available project is rated on all of the attributes. Each project's utility is then calculated as the sum of the project's rates respective to each attribute times the weight of that attribute (Chrisman, et al. (1989)). This calculation is performed as shown in (2).

$$\text{Project Utility} = \sum_{i=1}^{5} r_i w_i \tag{2}$$

where,

r : project's score on attribute i

w: weight of attribute i

Integration of the utility function into the model is shown mathematically in the Appendix section titled "Summary of Mathematical Model."

Table 6: Swing-Weight Results

	Consequence to Compare							
Attribute Swung from Worst to Best	Regulatory	Modernization	Risk	Infrastructure	Business	Rank	Rate	Weight
(Benchmark)	Worst	Worst	Worst	Worst	Worst	6	0	-
Regulatory	**Best**	Worst	Worst	Worst	Worst	1	100	0.303
Modernization	Worst	**Best**	Worst	Worst	Worst	5	30	0.091
Risk	Worst	Worst	**Best**	Worst	Worst	2	90	0.273
Infrastructure	Worst	Worst	Worst	**Best**	Worst	3	60	0.182
Business	Worst	Worst	Worst	Worst	**Best**	4	50	0.152

3.2 Budget Constraint

The director of FO&S is held personally responsible for keeping annual capital expenditures at or below the amount allotted to the department. This hasn't always been easy or successful. But there is no doubt this is the most important constraint for the model.

The model needed a way to predict the financial performance of each project that could be selected for implementation during the next fiscal year. The goal was to compare past project's budgets with what was actually spent during the year. Once the performance history of the department could be quantified, it could be predicted.

The Capital Planning department (which dispenses the capital to each department every year) keeps a great deal of financial data for each project funded with capital money. The capital planners were more than cooperative in granting access to their past data and helping to interpret it.

After scrutinizing the data, it became clear that the data kept after 2001 was the most relevant to determining how FO&S performed financially on their projects in the past. Prior year's data lacked certain details needed to classify the projects, so the model is based on performance data through 2005.

Following reduction of the data by eliminating other years, the remaining data had to be reduced to only what was relevant to the FO&S organization. The data was reduced to its final sample size of six hundred and twenty five previously-implemented projects. So the sample size was adequate, but each project resembled all the others. An acknowledgement of the variety of projects was needed.

To provide differentiation between projects and enable more realistic modeling, the project list is split into three philosophical categories: construction, installation, and purchase. Given the differences in scopes, each category of project would entail very different degrees of uncertainty in their costs. A project qualified as "construction" if the main idea behind the project was just that—construction. Examples might include building a new building or clean room. Construction projects are the most complex of the three types. Installation projects consisted primarily of those where a large piece of equipment was to be installed. These would include efforts like installing the necessary infrastructure and connections for a new autoclave or vacuum oven. Installation projects are less complex than construction projects, but more than purchase projects. Purchase projects are less common than the others, and encompass those projects that were strictly the purchase of an asset. These purchases might be a new dump truck or snow plow. The narrow scopes of purchase projects mean they are the least complex.

After dividing the project list into the aforementioned categories, the list was then divided into thirds again, but this time using the level of the budget allocated to the project. The delineations between levels were set with the intent of dividing the list into three groups of roughly equal size. This was accomplished by setting the most inexpensive level at zero through twenty thousand dollars. The next group is comprised of projects budgeted between twenty thousand and one hundred thousand dollars. The final group includes projects budgeted for between one hundred thousand and one and a half million dollars.

The intersection between delineations of project type and cost categories defines nine groups of projects. Analyzing the data, each project's financial performance was quantified by comparing the final amount spent on the project during the year to the amount budgeted. The difference between the two amounts was calculated as a percent of the budget. With this "percent error" calculated for each project, the calculated data was organized into histograms—one for each of the groups. Mean percent error and variance percent error were calculated for each group. In the model, the mean and variance could then be used to quantify the risk involved in selecting any of the projects on the list, depending upon which of the nine groups that project fell into. Each project's estimated budget was corrected by the mean percent error for its group and its variance was calculated by multiplying the estimated budget by the variance percent error in order to quantify the uncertainty of each available project in the model. The percent errors between final spend and baseline budget (as a percent of baseline budget) for 2001 through 2005, inclusive, are shown in Table 7. A positive mean indicates those projects overspent their budgets on average and a negative mean shows a tendency towards spending less than their allotted budgets.

Table 7: Past Project Performance Statistics

	CONSTRUCTION		INSTALLATION		PURCHASE	
Baseline Budget Range	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
\$0 - \$20,000	83%	175%	59%	135%	-12%	231%
\$20,000 - \$99,999	48%	130%	-2%	76%	62%	94%
\$99,999 - \$1,500,000	-8%	65%	-20%	57%	39%	100%

The numbers in Table 7 are summary statistics based on (3):

$$\text{Percent Error} = \frac{\text{Final Spend - Baseline Budget}}{\text{Baseline Budget}} \times 100 \tag{3}$$

Predicting the performance of individual projects allows the model to calculate the predicted performance of any selected portfolio. The central limit theorem allows the calculation of the overall portfolio mean cost and variance (Hayter (1996)). The mean of each selected project's cost distribution was added to calculate the expected cost of the portfolio. The variance of each selected project's cost distribution was added to find the variance of the portfolio. These calculations enable the use of a chance constraint limiting portfolio choices by the risk of budget overrun they would cause. The constraint is stated: limit the choice of portfolios such that the probability of spending within the budget plus a small tolerance for overrun is kept above a probability also specified by the decision maker. In operation, the director of the department specified he wanted at least a ninety-five percent probability of staying within budget—with zero tolerance for overrun.

Mathematically, the probability of spending within the budget is found by adding the expected cost of the portfolio to the inverse of the standard normal deviate corresponding to the specified probability times the square root of the sum of the selected project variances (Gurgur and Luxhoj (2003)).

The chance constraint employed to ensure a high probability of remaining within the budget overrun tolerance is stated generally as shown in (4) (Gurgur and Luxhoj (2003)):

$$P\left(\sum_{i=1}^{L} X_i C_i \le B + T_B\right) \ge \alpha_B\,,\ X \in \{0,1\} \tag{4}$$

where,

L: total length of the list of projects available for implementation

X_i: binary decision variable for project inclusion into the portfolio

C_i: total capital expenditure for project i during the year

B: total capital budget the department will receive for the year

T_B: dollar value of the overrun that could be tolerated

α_B: probability the budget overrun will be less than the tolerance T

The deterministic equivalent of (4) is necessary for implementation in the spreadsheet and is formulated as (5) (Gurgur and Luxhoj (2003)):

$$\sum_{i=1}^{L} X_i E[C_i] + \Phi^{-1}(\alpha_B)\sqrt{Var\left(\sum_{i=1}^{L} X_i C_i\right)} \le B + T_B \tag{5}$$

3.3 Unplanned Carryover Constraint

After satisfying the constraint of staying within the annual budget, the department's next concern is to spend the allotted money when it plans to spend it. Spending the money in the fiscal year for which it is allotted is not as important as spending less money than the budget—but it is still a major concern. The dynamics of the capital cycle cause this focus.

If a project starts one year and finishes the next, the amount of money spent on the project during the second year is called carryover. Carryover is important because it represents a financial obligation that must be covered in the future. Carryover obligations restrict the freedom of the decision maker in the future because carryover must be funded in subsequent years, but future years' capital budgets will probably not expand to cover the obligation.

If a project is planned as a multi-year project the carryover is expected and referred to as "planned carryover". Planned carryover is a natural byproduct of large-scale projects and easily anticipated and dealt with. The real problem occurs when projects that were planned to finish in one year take longer than expected and do not complete until later years. Money spent on a project in years subsequent to its planned completion is called "unplanned carryover."

Unplanned carryover is objectionable because it invalidates prior planning and commitments. Each year's project portfolio is selected and funded months before the beginning of the year it will be implemented in. As a result, many of the previous year's projects will still be in progress while the next portfolio is being selected. Finish dates of currently active projects cannot be known with certainty before the project is actually complete, so the portfolio is selected without knowledge of the magnitude of unplanned carryover. If a project's completion accidentally slips into the year after it was planned to complete, the remaining project costs must be met out of the following year's budget—which was not funded to accommodate this unplanned carryover. This means that projects that were previously allocated money for the following year may have to be cancelled or postponed to fund the unplanned carryover.

This de-selection of projects is difficult and potentially embarrassing because effort must be expended a second time to plan and authorize projects under the new budget constraint. (The budget level is the same, but there is less room to maneuver within it due to the unplanned obligation). Project de-selection can be downright painful when customers outside FO&S were planning their operations based on FO&S' earlier promise to implement certain projects which were in the original portfolio but must now be postponed for later years because an unrelated project finished unexpectedly late. Hence, the department is keenly interested in limiting exposure to unplanned carryover.

Formulating an unplanned carryover constraint required more development than the budget constraint, because while the department has always tried to limit their unplanned carryover, they have never kept historical data on their performance to that goal. An alternative strategy had to be devised.

Some way of predicting the timing of each dollar spent on each project had to be devised in order to forecast and constrain the overall amount of unplanned carryover. But since there was no data, and the range of projects varied so widely, a general theory had to be employed.

This general theory started with the very basic ideas that each project started at zero dollars spent and completed with all of its dollars spent. Lacking data by which a mathematical equation could have been formulated showing the spend rate from start to finish of the project, a very broad assumption was made that the cumulative dollars spent were linear between zero at project start and spent to the total expected level at project completion.

At the time this model was created, the department was beginning to collect data on schedule performance of their various projects, but there was not yet enough data to form theories with any real predictive power. So implementers of each proposed project were asked to specify a triangular distribution of potential durations for the projects. They would enter three data points for each project: the shortest possible duration, the most likely duration, and the longest possible duration. These durations could then be compared to the amount of time available for implementing projects in the next fiscal year.

If there were any probability of the project duration exceeding the amount of time available in the year, the model would predict some degree of unplanned carryover. Given the assumption that cumulative spend on each project was linear from start to finish, the expected degree of unplanned carryover could be predicted by finding the mean value of the portion of the triangular distribution extending past the end of the year, subtracting the amount of time in the year, and multiplying that difference by the spend rate. The spend rate was equal to the slope of the line extending from zero dollars spent at the start of the project to the expected total dollars spent at the end of the project.

Figure 1 illustrates the concept of predicting the amount of unplanned carryover based on the duration of the project and diagrammatically shows the assumption that project spend rates are linear over their lifecycles. If a project's duration extends beyond the end of the year, the amount of money spent in the next year is the carryover.

In formulating the mathematical basis for predicting carryover, the foundational issue is the relationship between the distribution of possible project durations and the time available in the year in which to implement the project. The relationship between the triangular distribution of a project's possible durations and the time between the decision to implement and the end of the year is shown in Figure 2.

The unplanned carryover variance for each project was calculated similarly in that the portion of the expected cost of the project falling after the end of the fiscal year was multiplied by the variance of the portion of the triangular distribution extending beyond the end of the fiscal year.

Figure 1: Carryover Linearity Assumption

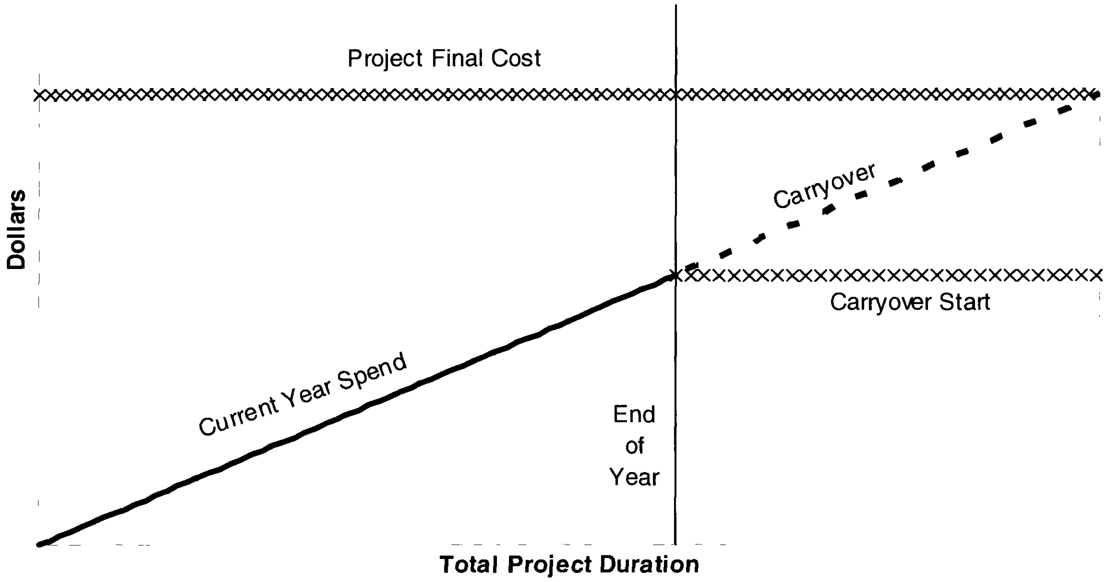

Figure 2: Relationship between Project Duration and End of Year

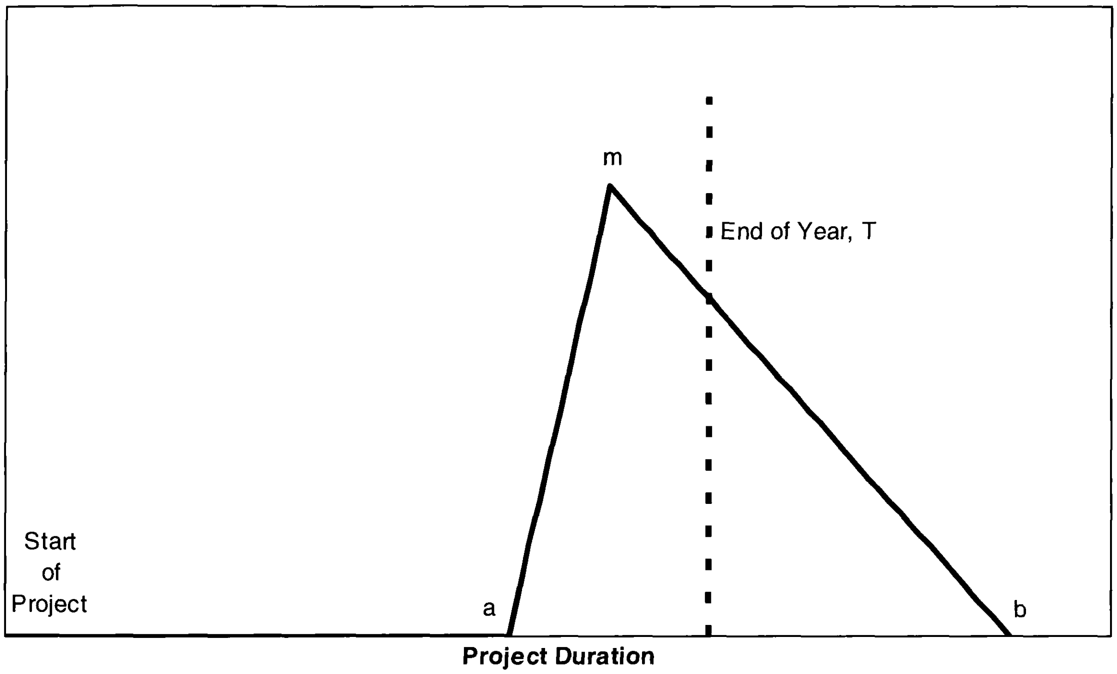

Figure 2 shows a triangular probability distribution for the duration of the project using "a" to indicate the shortest possible duration a project could be implemented in, "m" is the most likely duration (the mode of the distribution), and "b" is the longest possible duration. "T" is used to annotate the end of the year and the left-most edge of the diagram is the start of the project.

For each individual project selected for implementation, we need to find the expected value and variance of the carryover in order to add those quantities and find the expected value and variance of the aggregate carryover. With those quantities in hand, the model has enough information to constrain project selection so that predictions of carryover fall within the decision maker's tolerance.

In cases where the end of the fiscal year will occur prior to the earliest possible completion date of the project ($T<a$), the project will definitely cause carryover. The expected value of the carryover is equal to the cost per week of the project's implementation (the expected cost divided by the expected duration) times the expected number of weeks of implementation to occur during the next fiscal year (the duration minus the time until the end of the year) given that any of the duration will occur in the next fiscal year. This is shown mathematically in (6).

$$E(Carryover) = \frac{E(C)}{E(D)}\left[E(D \mid D > T) - T\right] \tag{6}$$

$E(C)$ is the expected total cost of the project

$E(D)$ is the expected duration of the project, $E(D) = \frac{a + m + b}{3}$

$E(D \mid D > T)$ is the duration given that the duration exceeds the end of the year

Similarly, the variance of the carryover is shown in (7).

$$Var(Carryover) = \frac{E(C)}{E(D)}\left[E\left(D^2 \mid D > T\right) - T\right] - E^2(Carryover) \tag{7}$$

Below, we calculated the expected carryover and the variance of carryover for four possible cases: Case 1: T<a; Case 2: a<T<m; Case 3: m<T<b; and Case 4: T>b.

Case1: T<a

When the earliest possible completion date of the project falls after the end of the fiscal year (T<a), the probability of the duration exceeding the time until the end of the year is 100%. In that case, $E(D \mid D > T) = E(D)$. So equation (6) for the expected carryover can be simplified as shown:

$$E(Carryover)_{T<a} = \frac{E(C)}{E(D)}[E(D) - T] \tag{8}$$

The variance of the carryover is calculated by multiplying the ratio of the expected cost to the expected duration by the general formula for variance of a triangular distribution, fitting the individual project. Variance in this case is:

$$Var(Carryover)_{T<a} = \left[\frac{E(C)}{E(D)}\right]^2 \left(\frac{a^2 + m^2 + b^2 - ab - am - bm}{18}\right) \tag{9}$$

Case 2: a<T<m

Finding the expected value of the carryover and its variance is more involved when the end of the fiscal year falls between the earliest possible and latest possible project finish dates (a<T<b). The general form of the equation for the expected value of the carryover still holds, but since the duration may or may not exceed the time until the end of the year, the specifics of the equation are much more involved. The general form is the same as shown in (6). To find the expected carryover given the conditional probability that the duration will exceed the time remaining in the fiscal year, the following substitution is made to develop:

$$E(Carryover) = \frac{E(C)}{E(D)}\left[\int_T^{\infty} \frac{x f_D(x)}{P(D>T)}dx - T\right] \tag{10}$$

Where $f_D(x)$ is the probability density function for a triangular distribution and $P(D>T)$ is the probability that the duration will exceed the time remaining in the fiscal year.

Similarly, the general equation for the variance of the project's carryover is shown below in (11):

$$Var(Carryover) = \left[\frac{E(C)}{E(D)}\right]^2 \int_T^\infty \frac{x^2 f_D(x)}{P(D > T)} - E^2(Carryover) \tag{11}$$

The general form for the expected carryover can be further expanded as shown in (12) by substituting the equations for the probability density function and the probability that the duration will exceed the time remaining in the fiscal year:

$$E(Carryover)_{a \le T \le m} = \frac{E(C)}{E(D)}\left[\int_T^m \frac{\frac{2x(x-a)}{(b-a)(m-a)}}{1-\frac{(T-a)^2}{(b-a)(m-a)}}dx + \int_m^b \frac{\frac{2x(b-x)}{(b-a)(b-m)}}{1-\frac{(T-a)^2}{(b-a)(m-a)}}dx - T\right] \tag{12}$$

Simplifying (12) down to its algebraic equivalent generates:

$$E(Carryover)_{a \le T \le m} = \frac{\left(\frac{E(C)}{E(D)}\right)\left[\frac{2\left(\frac{m^3}{3}-\frac{am^2}{2}-\frac{T^3}{3}+\frac{aT^2}{2}\right)}{(b-a)(m-a)} + \frac{2\left(\frac{b^3}{2}-\frac{b^3}{3}-\frac{bm^2}{2}+\frac{m^3}{3}\right)}{(b-a)(b-m)} - T\right]}{1-\frac{(T-a)^2}{(b-a)(m-a)}} \tag{13}$$

Variance is found through a similar sequence of events beginning with the general form of (11). Then, substituting the probability density function and the probability that the duration exceeds the time remaining in the fiscal year, (11) expands to:

$$Var(Carryover) = \left[\frac{E(C)}{E(D)}\right]^2 \left[\int_a^m \frac{\frac{2x^2(x-a)}{(b-a)(m-a)}}{1-\frac{(T-a)^2}{(b-a)(m-a)}}\,dx + \int_m^b \frac{\frac{2x^2(b-x)}{(b-a)(b-m)}}{1-\frac{(T-a)^2}{(b-a)(m-a)}}\,dx\right] - E^2(Carryover) \tag{14}$$

In turn, (14) simplifies to equation:

$$Var(Carryover)_{a\le T\le m} = \frac{2\left[\frac{E(C)}{E(D)}\right]^2 \left[\frac{\frac{m^4}{4}-\frac{am^3}{3}-\frac{T^4}{4}+\frac{aT^3}{3}}{(b-a)(m-a)} + \frac{\frac{b^4}{3}-\frac{b^4}{4}-\frac{bm^3}{3}+\frac{m^4}{4}}{(b-a)(b-m)}\right]}{1-\frac{(T-a)^2}{(b-a)(m-a)}} - E^2(Carryover) \tag{15}$$

Case 3: m<T<b

In order to find the expected value of the carryover when the end of the fiscal year falls between the most likely finish date and the latest possible finish date $(m < T \leq b)$, the general form of the expected carryover equation (8) is used again.

The probability density function $f_D(x)$ is simpler this time, since only one side of the triangular distribution is involved. Substituting in both the probability density function and the probability that the duration exceeds the time remaining in the fiscal year, the expected value of the carryover in this case is shown in (16).

$$E(Carryover) = \frac{E(C)}{E(D)}\left[\int_T^{\infty}\frac{\dfrac{2x(x-a)}{(b-a)(b-m)}}{1-\dfrac{(b-T)^2}{(b-a)(b-m)}}dx - T\right] \tag{16}$$

Working through calculus, (16) simplifies to:

$$E(Carryover)_{m<T\leq b} = \frac{E(C)}{E(D)}\left[\left(\frac{2\left(\dfrac{b^3}{3}-\dfrac{ab^2}{2}-\dfrac{T^3}{3}+\dfrac{aT^2}{2}\right)}{(b-a)(b-m)\left(1-\dfrac{(b-T)^2}{(b-a)(b-m)}\right)}\right)-T\right] \tag{17}$$

Still dealing with the situation where the end of the year falls between the most likely finish date and the latest possible finish date, the derivation for the variance of the carryover is begun with the general form of (11). Substituting in the probability density function and the probability the duration will exceed the time remaining in the fiscal year, the variance of the carryover is shown:

$$\begin{array}{l} Var(Carryover)_{m<T\leq b} = \left[\frac{E(C)}{E(D)}\right]^2 \int_T^b \frac{\frac{2x^2(x-a)}{(b-a)(b-m)}}{1-\frac{(b-T)^2}{(b-a)(b-m)}} dx - E^2(Carryover) \\ Var(Carryover) \end{array} \qquad (18)$$

Integrating and simplifying, (19) develops from equation (18):

$$Var(Carryover)_{m<T\leq b} = \left[\frac{E(C)}{E(D)}\right]^2 \frac{2\left(\frac{b^4}{4}-\frac{ab^3}{3}-\frac{T^4}{4}+\frac{aT^3}{3}\right)}{(b-a)(b-m)\left(1-\frac{(b-T)^2}{(b-a)(b-m)}\right)} - E^2(Carryover) \qquad (19)$$

Case 4: T>b

Finally, on projects where the latest possible project completion date occurs prior to the end of the fiscal year $(b < T)$, we begin again with the general equation for expected carryover from (6).

The conditional expected duration given that the duration exceeds the time remaining in the fiscal year, $E(D|D > T)$, is ZERO in this case because there is no probability of the project's duration extending past the end of the fiscal year.

Given this logic, the expected carryover is formally stated: $E(Carryover)_{b<T} = 0$.

The general form of the variance of the carryover in this situation again begins with (11). Using similar logic to that used for expected carryover for this situation, the probability of the duration lasting past the end of the fiscal year is equal to zero. Since the duration cannot extend past the end of the fiscal year, the equation above for the variance of the carryover is undefined. But as a practical matter, the variance is assumed to be zero since the probability of any carryover is also zero: $Var(Carryover)_{b<T} = 0$

The expected values and variances of carryover are fully defined for all possible relationships between each project's duration distribution and the proximity of the end of the fiscal year. These quantities, when calculated for each project selected into the portfolio for implementation, can be used to define the chance-constraint on the aggregate level of carryover for the portfolio through application of the central limit theorem.

The chance constraint employed to ensure a high probability of remaining within the unplanned carryover tolerance is stated generally as (20) (Gurgur and Luxhoj (2003)):

$$P\left(\sum_{i=1}^{L} X_i CO_i \leq T_{CO}\right) \geq \alpha_{CO},\ X \in \{0,1\} \tag{20}$$

where,

L: total length of the list of projects available for implementation

X_i: binary decision variable for project inclusion into the portfolio

CO_i: unplanned carryover associated with project i

T_{CO}: dollar value of the unplanned carryover that could be tolerated

α_{CO}: probability the overrun will be less than the tolerance T_{CO}

The deterministic equivalent of the above general statement of the chance constraint is necessary for implementation in the spreadsheet and is formulated as (21) (Gurgur and Luxhoj (2003)):

$$\sum_{i=1}^{L} X_i E[CO_i] + \Phi^{-1}(\alpha_{CO})\sqrt{Var\left(\sum_{i=1}^{L} X_i CO_i\right)} \leq T_{CO} \tag{21}$$

The amount of unplanned carryover caused by all the active projects is referred to as aggregate unplanned carryover. Aggregate unplanned carryover is constrained using the same method as the budget overrun constraint. The decision maker dictates a level of allowable unplanned carryover and the probability that the chosen portfolio of projects would carry over less than that amount. The probability of carrying over less than the allowable amount was found by adding the mean unplanned carryover amounts of the selected projects to the inverse of the standard normal deviate corresponding to the specified probability times the square root of the sum of the selected project unplanned carryover variances as in (21) (Gurgur and Luxhoj (2003)).

In practice, the director specified that he wanted a portfolio that kept a ninety-five percent probability of carrying over less than five hundred thousand dollars.

Integration of both the unplanned carryover and budget overrun constraints into the model is shown mathematically in the Appendix section titled "Summary of Mathematical Model."

3.4 Mandates and Exclusions

Realistic considerations necessitate an override capability in the model. Some of the projects on the list absolutely must be implemented, whether they produce a high utility or not—either because they were started in previous fiscal years and had to be finished, or because company executives have dictated they must be implemented.

A "Mandate" column is included so projects could be forced into the selected portfolio. The Mandate column allows the user to enter a "1" in the same row as the project that must be implemented. A constraint was added to the model so that mandated projects are necessarily selected into the portfolio.

It became clear very early in the population of the model with real data that some of the projects on the list would be impossible to implement during the next fiscal year. Some individual projects were actually phases of a larger project. The first phase of the larger project should be considered for the next fiscal year, but more than that phase could not be implemented during a year. Subsequent phases needed to be disallowed.

Other projects needed to be disallowed when the department knew they were too resource constrained to implement a large group of similar projects in the same fiscal year. So in that case, some subset of those similar projects had to be disallowed so the model could not select more projects than could be implemented. Further projects were excluded when the decision makers realized that strategic business initiatives underway across the site would render the proposed project irrelevant in soon after implementation.

An "Exclude" column is included so projects like these cannot be selected into the portfolio even if they possess high utility values. The user can enter a "0" in the same row as projects they needed to keep out of the portfolio and another constraint is included so that the model will not select the excluded projects.

The ability to mandate or exclude a certain project into or out of the portfolio is implemented by adding the following binary constraints: $M_i \leq X_i \leq E_i$, $i = 1, \ldots, L$.

where,

X_i: binary decision variable for project inclusion into the portfolio

$$M_i = \begin{bmatrix} \text{1 if project i is to be mandated} \\ \text{0 otherwise} \end{bmatrix}$$

$$E_i = \begin{bmatrix} \text{1 if project i is to be excluded} \\ \text{0 otherwise} \end{bmatrix}$$

CHAPTER 4

APPLICATION

By the time the model was constructed and verified, the deadline for submitting a capital plan of recommended projects had passed. The department had submitted its capital plan based primarily on expert opinion and budget constraint. In terms of the ultimate effectiveness of the model, this chain of events would prove invaluable in demonstrating how the selected portfolio would affect total spending and unplanned carryover.

The department's experts had selected a portfolio consisting of twenty five projects. Some time after that portfolio was submitted, the model was set to work to see what results it would produce. It recommended a portfolio of seventy nine projects. A comparison of the two portfolios yielded interesting insight.

The seventy nine projects the model recommended included seventeen of the projects the experts selected. Four of the projects they had in common were mandated in the model. The twenty five projects the experts selected were generally more expensive and of longer duration than those recommended by the model. Both methods of portfolio selection conformed to the constraint of a ninety-five percent probability there would be no overrun. The model-recommended portfolio conformed to the carryover constraint, while the expert-selected portfolio did not.

Figure 3 shows the portfolio selected by the department and entered into the model, with projects selected in order of descending priority, i.e. the first projects selected into the portfolio are those with the highest utility-to-cost ratios. The horizontal line is the spend level allowed with a ninety-five percent probability. It is easy to see how careful the department is to choose a portfolio that will not cause current-year budget overruns since the predicted spend level line approaches, but does not cross the tolerance of a $20 million budget.

Figure 4 shows the same portfolio as in Figure 3 as it relates to the unplanned carryover constraint. The figure predicts a violation of the unplanned carryover constraint when the eighteenth project is selected into the portfolio. The constraint in the model was set to limit the selection of projects such that the decision makers could be ninety-five percent sure they would experience less than $500k of unplanned carryover. We can see from the figure that as the experts chose their entire list of twenty five projects, they increased the unplanned carryover level substantially.

The fact that significant levels of unplanned carryover are associated with the expert-chosen portfolio was not surprising to the department's primary decision makers. These capital allocation decisions have been made for many years based on budgetary information alone. The department has a history of mitigating unplanned carryover at the end of the year as it becomes clear that some projects were unlikely to complete in time. Our model showed that some of the projects mandated into the portfolio had very long expected durations with associated high probabilities of unplanned carryover – indicating that much of the unplanned carryover was in fact designed in from the start. These long-duration projects would make ideal candidates for splitting into multi-year projects before mandating them into the portfolio.

The project managers have to apply a great deal of pressure to themselves, their project teams, and their subcontractors while they scramble to limit unplanned carryover at the end of the year. It is hoped that implementation and effective use of this model will reduce the stress on the department once better project plans are selected at the start of the year so that less pressure has to be applied at the end of the year.

Another interesting comparison can be drawn between the utility scores of the portfolio mandated by the experts and those of the portfolio recommended by the model. Since the experts' portfolio violates the carryover constraint, prior to the comparison, we forced the mandated portfolio to comply with the constraints by removing projects with low utility-to-cost ratios from the bottom of the mandate list until the unplanned carryover constraint was met.

The sums of the individual attribute scores and the total utility scores for each portfolio are shown in Table 8. Our model has improved the department's performance in every attribute (except for the *Business* attribute, since all potential projects in 2006 had a zero score in that attribute, i.e. there were no high value projects that supported the winning of contracts the company classified as “must win”.)

Figure 3: Predicted Cumulative Spend (Expert Selection)

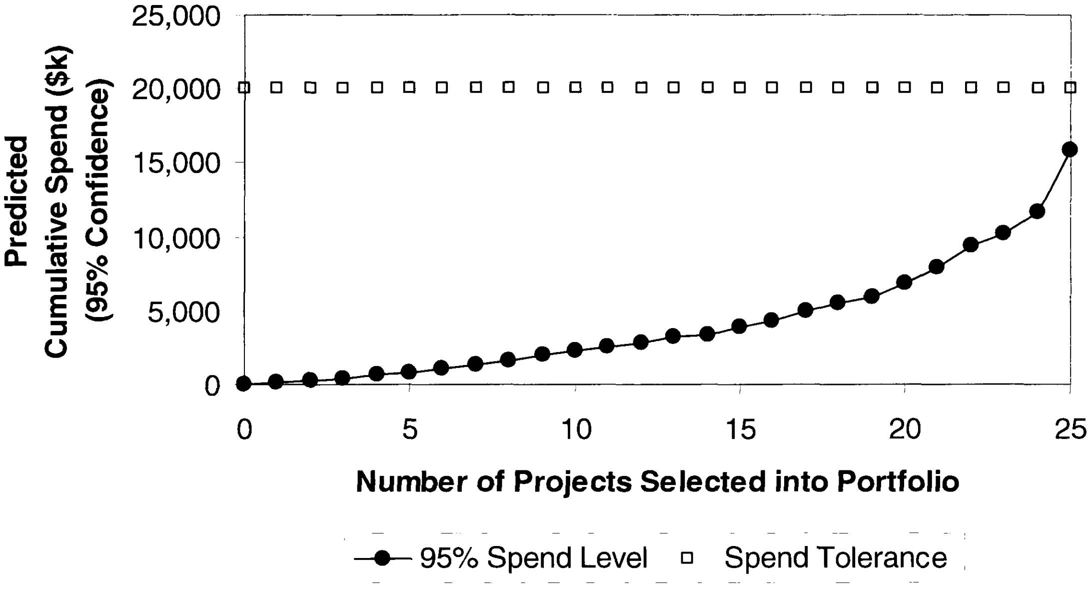

Figure 4: Predicted Carryover (Expert Selection)

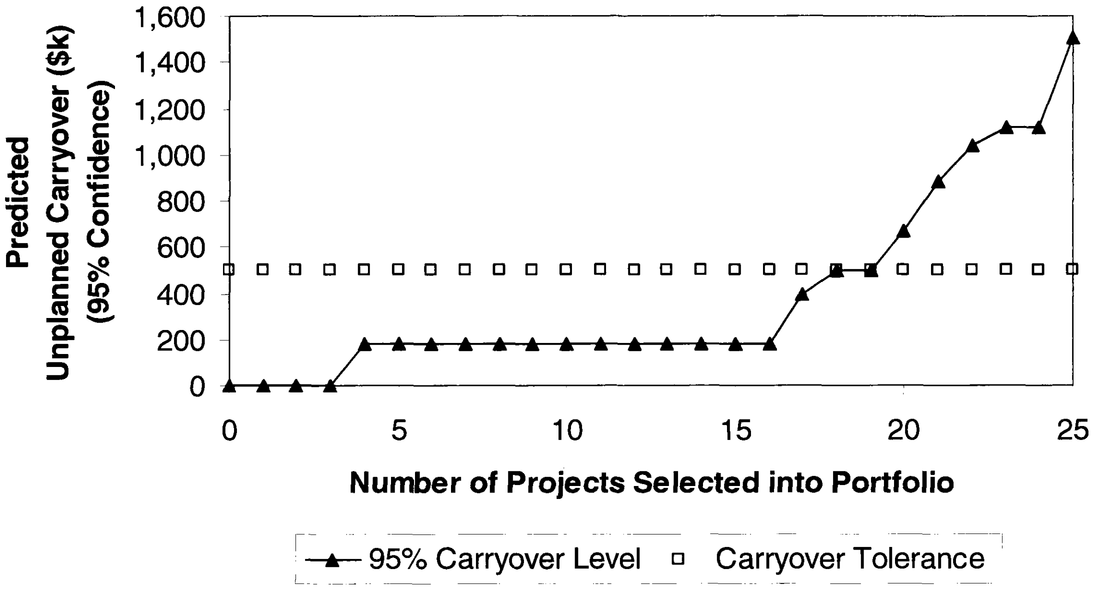

Table 8: Portfolio Utility Comparison

Optimized Portfolio Score	Mandated Portfolio Score	Attribute
2.485	0.909	Regulatory
0.409	0.255	Modernization
6.082	2.045	Risk
12.145	2.855	Infrastructure
0.000	0.000	Business
21.121	6.064	TOTAL

CHAPTER 5

CONCLUSION

The mere existence of the model has garnered credibility for the department and reinforced its reputation for rigorous capital management practices. These benefits from the model, coupled with the solid project management practices already in place, have translated into increased funding for the department for the 2007 fiscal year.

In practice, the 2006 fiscal year closed with substantial budget overrun and unplanned carryover. At least two projects planned for 2007 will be postponed for later years as a result. This model did not exist at the time the 2006 portfolio was selected, but the fact that the 2007 portfolio is significantly biased toward unplanned carryover may imply that the unplanned carryover from 2006 was also unintentionally designed in from the portfolio's inception.

The plan for the immediate future is to provide the decision makers a simplified version of the model's capabilities. A spreadsheet-based Monte Carlo simulation will be employed to generate probability distributions for budget overrun and unplanned carryover for the 2007 fiscal year based on projects they have chosen without the aid of the model. No initial attempt will be made to recommend projects—only to predict the financial results of the projects the decision makers choose themselves. It is hoped that as the decision makers become more comfortable with this interim descriptive model, they will become more receptive to the prescriptive model outlined in this thesis. The intervening period will allow further refinement of the attributes and project valuation strategy. It is hoped that the decision makers' increasing receptiveness to analytical modeling and the model's improved valuation strategy will converge to a truly effective implementation of the model in the near future.

Ongoing work on this thesis will center on developing a Visual Basic®-based tool as a front end to the model presented here. The control and ease of use provided in this framework should move the model toward wider acceptance and ease of use.

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APPENDIX

A.1. Summary of the Mathematical Model

The objective function is:

$$\max_{X_1,\ldots,X_L} \sum_{i=1}^{L} X_i U_i$$

Subject to the constraints:

$$\sum_{i=1}^{L} X_i E[C_i] + \Phi^{-1}(\alpha_B)\sqrt{Var\left(\sum_{i=1}^{L} X_i C_i\right)} \leq B + T_B,$$

$$\sum_{i=1}^{L} X_i E[CO_i] + \Phi^{-1}(\alpha_{CO})\sqrt{Var\left(\sum_{i=1}^{L} X_i CO_i\right)} \leq T_{CO},$$

$$M_i \leq X_i \leq E_i \ \forall i,$$

$$X_i \in \{0,1\} \ \forall i$$

where,

L: total length of the list of projects available for implementation

X_i: binary decision variable for project inclusion into the portfolio

U_i: each project's individual project utility, where Project Utility $= \sum_{i=1}^{6} r_i w_i$ and

r_i: project's score relative to attribute i

w: weight of attribute i

C_i: total capital expenditure for project i during the year

B: is the capital budget

T_B: dollar value of the overrun that could be tolerated

α_B: probability the budget overrun will be less than the tolerance T_B

CO_i: unplanned carryover for project i

α_{CO}: probability the aggregate carryover will be less than the tolerance T_{CO}

$$M_i = \begin{cases} 1 \text{ if project i is to be mandated} \\ 0 \text{ otherwise} \end{cases}$$

$$E_i = \begin{cases} 1 \text{ if project i is to be excluded} \\ 0 \text{ otherwise} \end{cases}$$

A.2. Implementation in Microsoft ® Excel

We used Microsoft Excel for both developing our model and presenting the results to the director of the department, as well as to the engineers, architect, strategic planners, interior designers, project managers, managers, and supervisors who historically had decided which projects would be implemented with the next year's capital were assembled. One clear advantage of using spreadsheet software was its transparency, where the users had a clear understanding of how the model works and how the model parameters can be easily updated upon request.

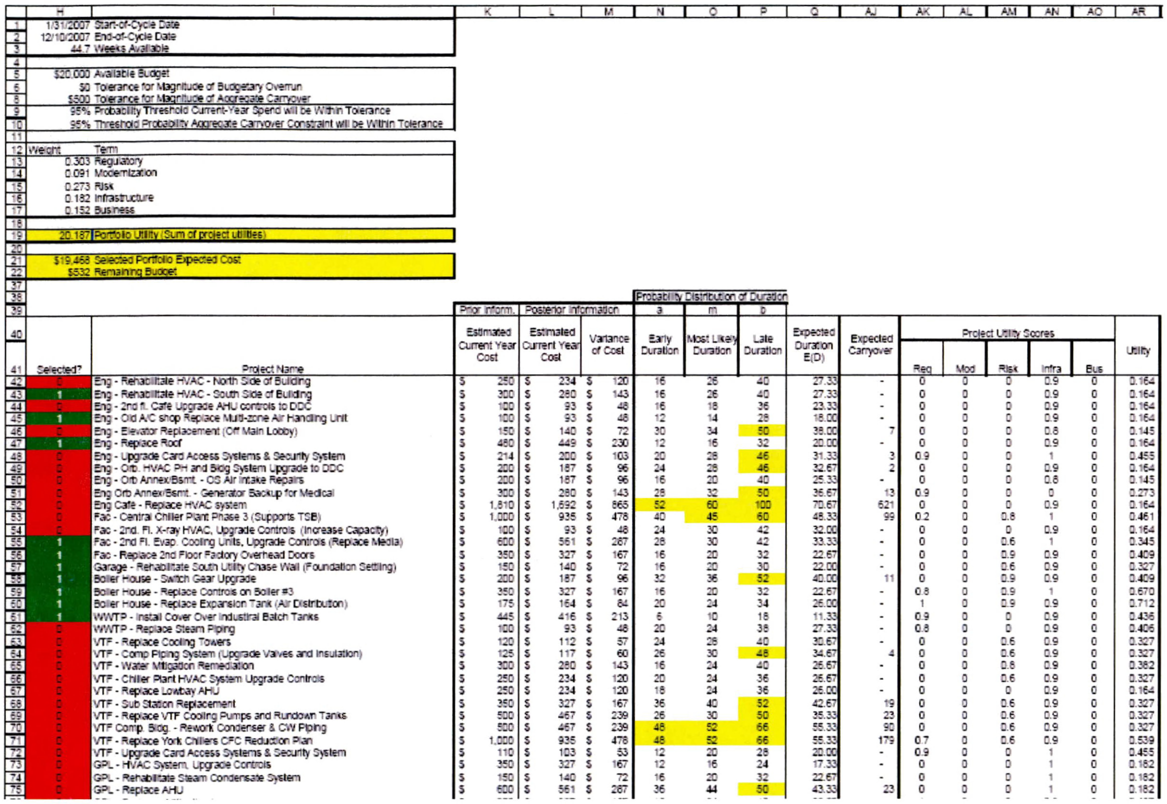
Another operational advantage of using Microsoft Excel to implement the model is its inherent portability. The department's list of potential projects was stored in Excel well before model development, so importing the list of projects with their associated expected costs was fairly easy. But the real benefit came when each project had to be classified as "construction", "installation", or "purchase" and the triangular distributions for project durations needed to be specified. The model's Excel file was copied and sent to the decision makers with a written explanation for what data was needed and how it was to be specified. The decision makers considered the needed data independently then supplied the data collaboratively while viewing a projected image of the spreadsheet in a conference room.

Building the model in spreadsheet format allowed the decision makers to interact with the model on their own instead of being limited strictly to supplying information to the modeler. Since they could view the underlying calculations within the spreadsheet while considering the data required of them, they could become as comfortable as they chose to with the model's basic operations. Exposing the inner workings of the model like this went a long way to removing skepticism about the model's objectivity and level of sophistication.

The list containing all potential capital projects the group knew of consisted of 212 projects. Those projects caused there to be the same number of binary decision variables handled by Solver. There are a total of 2 constraints: the budget overrun constraint and the aggregate carryover constraint. There are 424 bounds satisfied by Solver: two for each project—one for the possibility to mandate and the other for the possibility to exclude. The set cell to maximize is the cumulative utility of the projects selected into the portfolio.

The standard evolutionary solver algorithm from Frontline Systems Excel Solver Premium was used to solve for the optimal, or near optimal, portfolio subject to the nonlinear chance constraints.

Figure 5: Microsoft® Excel Main Model Screen



	H	I
1	1/31/2007	Start-of-Cycle Date
2	12/10/2007	End-of-Cycle Date
3	44.7	Weeks Available
4		
5	$20,000	Available Budget
6	$0	Tolerance for Magnitude of Budgetary Overrun
8	$500	Tolerance for Magnitude of Aggregate Carryover
9	95%	Probability Threshold Current-Year Spend will be Within Tolerance
10	95%	Threshold Probability Aggregate Carryover Constraint will be Within Tolerance
11		
12	Weight	Term
13	0.303	Regulatory
14	0.091	Modernization
15	0.273	Risk
16	0.182	Infrastructure
17	0.152	Business
18		
19	20.187	Portfolio Utility (Sum of project utilities)
20		
21	$19,468	Selected Portfolio Expected Cost
22	$532	Remaining Budget

	H	I	K	L	M	N	O	P	Q	AJ	AK	AL	AM	AN	AO	AR
37																
38						Probability Distribution of Duration										
39			Prior Inform.	Posterior Information		a	m	b								
40			Estimated Current Year Cost	Estimated Current Year Cost	Variance of Cost	Early Duration	Most Likely Duration	Late Duration	Expected Duration E(D)	Expected Carryover	Project Utility Scores					Utility
41	Selected?	Project Name									Req	Mod	Risk	Infra	Bus	
42	0	Eng - Rehabilitate HVAC - North Side of Building	$ 250	$ 234	$ 120	16	26	40	27.33	-	0	0	0	0.9	0	0.164
43	1	Eng - Rehabilitate HVAC - South Side of Building	$ 300	$ 280	$ 143	16	26	40	27.33	-	0	0	0	0.9	0	0.164
44	0	Eng - 2nd fl. Café Upgrade AHU controls to DDC	$ 100	$ 93	$ 48	16	18	36	23.33	-	0	0	0	0.9	0	0.164
45	1	Eng - Old A/C shop Replace Multi-zone Air Handling Unit	$ 100	$ 93	$ 48	12	14	28	18.00	-	0	0	0	0.9	0	0.164
46	0	Eng - Elevator Replacement (Off Main Lobby)	$ 150	$ 140	$ 72	30	34	50	38.00	7	0	0	0	0.8	0	0.145
47	1	Eng - Replace Roof	$ 480	$ 449	$ 230	12	16	32	20.00	-	0	0	0	0.9	0	0.164
48	0	Eng - Upgrade Card Access Systems & Security System	$ 214	$ 200	$ 103	20	28	46	31.33	3	0.9	0	0	1	0	0.455
49	0	Eng - Orb. HVAC PH and Bldg System Upgrade to DDC	$ 200	$ 187	$ 96	24	28	46	32.67	2	0	0	0	0.9	0	0.164
50	0	Eng - Orb Annex/Bsmt. - OS Air Intake Repairs	$ 200	$ 187	$ 96	16	20	40	25.33	-	0	0	0	0.8	0	0.145
51	0	Eng Orb Annex/Bsmt. - Generator Backup for Medical	$ 300	$ 280	$ 143	28	32	50	36.67	13	0.9	0	0	0	0	0.273
52	0	Eng Café - Replace HVAC system	$ 1,810	$ 1,692	$ 865	52	60	100	70.67	621	0	0	0	0.9	0	0.164
53	0	Fac - Central Chiller Plant Phase 3 (Supports TSB)	$ 1,000	$ 935	$ 478	40	45	60	48.33	99	0.2	0	0.8	1	0	0.461
54	0	Fac - 2nd. Fl. X-ray HVAC, Upgrade Controls (Increase Capacity)	$ 100	$ 93	$ 48	24	30	42	32.00	-	0	0	0	0.9	0	0.164
55	1	Fac - 2nd Fl. Evap. Cooling Units, Upgrade Controls (Replace Media)	$ 600	$ 561	$ 287	28	30	42	33.33	-	0	0	0.6	1	0	0.345
56	1	Fac - Replace 2nd Floor Factory Overhead Doors	$ 350	$ 327	$ 167	16	20	32	22.67	-	0	0	0.9	0.9	0	0.409
57	1	Garage - Rehabilitate South Utility Chase Wall (Foundation Settling)	$ 150	$ 140	$ 72	16	20	30	22.00	-	0	0	0.6	0.9	0	0.327
58	1	Boiler House - Switch Gear Upgrade	$ 200	$ 187	$ 96	32	36	52	40.00	11	0	0	0.9	0.9	0	0.409
59	1	Boiler House - Replace Controls on Boiler #3	$ 350	$ 327	$ 167	16	20	32	22.67	-	0.8	0	0.9	1	0	0.670
60	1	Boiler House - Replace Expansion Tank (Air Distribution)	$ 175	$ 164	$ 84	20	24	34	26.00	-	1	0	0.9	0.9	0	0.712
61	1	WWTP - Install Cover Over Industrial Batch Tanks	$ 445	$ 416	$ 213	6	10	18	11.33	-	0.9	0	0	0.9	0	0.436
62	0	WWTP - Replace Steam Piping	$ 100	$ 93	$ 48	20	24	38	27.33	-	0.8	0	0	0.9	0	0.406
63	0	VTF - Replace Cooling Towers	$ 120	$ 112	$ 57	24	28	40	30.67	-	0	0	0.6	0.9	0	0.327
64	0	VTF - Comp Piping System (Upgrade Valves and Insulation)	$ 125	$ 117	$ 60	26	30	48	34.67	4	0	0	0.6	0.9	0	0.327
65	0	VTF - Water Mitigation Remediation	$ 300	$ 280	$ 143	16	24	40	26.67	-	0	0	0.8	0.9	0	0.382
66	0	VTF - Chiller Plant HVAC System Upgrade Controls	$ 250	$ 234	$ 120	20	24	36	26.67	-	0	0	0.6	0.9	0	0.327
67	0	VTF - Replace Lowbay AHU	$ 250	$ 234	$ 120	18	24	36	26.00	-	0	0	0	0.9	0	0.164
68	0	VTF - Sub Station Replacement	$ 350	$ 327	$ 167	36	40	52	42.67	19	0	0	0.6	0.9	0	0.327
69	0	VTF - Replace VTF Cooling Pumps and Rundown Tanks	$ 500	$ 467	$ 239	26	30	50	35.33	23	0	0	0.6	0.9	0	0.327
70	0	VTF Comp. Bldg. - Rework Condenser & CW Piping	$ 500	$ 467	$ 239	48	52	66	55.33	90	0	0	0.6	0.9	0	0.327
71	0	VTF - Replace York Chillers CFC Reduction Plan	$ 1,000	$ 935	$ 478	48	52	66	55.33	179	0.7	0	0.6	0.9	0	0.539
72	0	VTF - Upgrade Card Access Systems & Security System	$ 110	$ 103	$ 53	12	20	28	20.00	-	0.9	0	0	1	0	0.455
73	0	GPL - HVAC System, Upgrade Controls	$ 350	$ 327	$ 167	12	16	24	17.33	-	0	0	0	1	0	0.182
74	0	GPL - Rehabilitate Steam Condensate System	$ 150	$ 140	$ 72	16	20	32	22.67	-	0	0	0	1	0	0.182
75	0	GPL - Replace AHU	$ 600	$ 561	$ 287	36	44	50	43.33	23	0	0	0	1	0	0.182

A.3. FO&S Director Appraisal of Model Contribution

Dennis Garegnani, Director of Facility Operations & Services for Lockheed Martin in Denver, Colorado, 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 will undoubtedly benefit 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 cannot help but bolster the effectiveness of the department and build 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 was 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.”

“Organization of past financial performance data to predict and control future financial performance has long been needed. The analysis used to support this model will prove invaluable in the future.”

“Having the model at our disposal has already added another level of credibility to the department among its peers. I look forward to applying the model again in the immediate future to recommend projects to start and finish before the end of the current year. 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 Mr. Morley has developed has been a huge success and directly effects our productivity and ability to deliver positive results. It has already been recognized as a best practice.”