

# Technology Portfolio Management: Optimizing Interdependent Projects Over Multiple Time Periods

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**Abstract**—In order to maintain competitiveness, companies need to continually invest in technology projects. However, resource limitations require an organization to strategically allocate resources to a subset of possible projects. A variety of tools and methods can be used to select the optimal set of technology projects. However, these methods are only applicable when projects are independent and are evaluated in a common funding cycle. When projects are interdependent, the complexity of optimizing even a moderate number of projects over a small number of objectives and constraints can become overwhelming. This paper presents a model developed for the Boeing Company, Seattle, WA, to optimize a portfolio of product development improvement projects. Using a dependency matrix, which quantifies the interdependencies between projects, a nonlinear, integer program model was developed to optimize project selection. The model also balances risk, overall objectives, and the cost and benefit of the entire portfolio. Once the optimum strategy is identified, the model enables the team to quickly quantify and evaluate small changes to the portfolio.

**Index Terms**—Portfolio management, product development.

## NOMENCLATURE

$C_{it}$	Cost allocated to project $i$ in year $t$ .
$D_i$	Net effect of project $i$ for a given portfolio.
$d_{ij}$	Level of dependence of project $i$ on project $j$ .
$M_i$	Minimum benefit level for project $i$ .
$N_{im}$	Strategic objectives matrix. Binary matrix where value = 1 if project $i$ supports objective $m$ .
$n_p$	Number of projects.
$n_i$	Total number of years for ACPS.
$P_i$	Probability of success for project $i$ .
$R_{it}$	Return for project $i$ in year $t$ .
$W_{ij}$	Normalized dependency.
$X_i$	Binary value indicating funding of project $i$ .
$X_{it}$	Starting year for project $i$ . $X_{it} = 1$ when project begins and $\sum X_{it} = 1$ .

## I. INTRODUCTION

*“We precisely put the smart bomb through the wrong window.” General Rod Kadish USAF*

Manuscript received September 23, 1999; revised January 15, 2001. Review of this manuscript was arranged by Dept. Editor R. Balachandra.

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Publisher Item Identifier S 0018-9391(01)10260-6.

General Kadish’s quote illustrates the importance of technology portfolio management. An enterprise may have the best technology, but if it does not apply it in the proper way, at the proper time, and in support of the overall objectives of the company, it may have minimum impact. The concept of building business portfolios emerged in the late 1950s and evolved through the 1970s to become an established planning tool [10]. Early applications of portfolio management balanced resource allocation between business units. In the 1980s and 1990s, companies extended the use of portfolio management into new product selection and R&D resource allocation. Though the tools and uses have changed over time, the basic need remains the same—companies must allocate a limited set of resources to projects in a way that balances risk, reward, and alignment with corporate strategy.

There is a wide range of technology portfolio management tools with varying metrics and selection methods. The metrics used to select projects range from quantitative (e.g., return on investment) to qualitative (e.g., alignment with company strategy) measures [4]. Different portfolio management tools have been developed to maximize different metrics. Mathematical and scoring models are used where quantitative metrics are available. Graphics and charting are used to evaluate qualitative metrics. Using a mixture of qualitative and quantitative tools makes it difficult to define an optimum technology portfolio and can lead to information overload [2]. Consequently, technology portfolio managers often select their portfolio using a mixture of professional judgment or a scoring/weighting method.

### A. Existing Portfolio Management Tools

Portfolio management must satisfy the following three goals [3]:

- 1) maximize the value of the portfolio;
- 2) provide balance;
- 3) support the strategy of the enterprise.

The weighting of each factor is organization-dependent. Organizations must balance risk versus reward goals, market versus product line goals, and near term versus long term goals. A variety of tools have been proposed [8]. Cooper *et al.* break technology portfolio tools into three categories [5]:

- 1) mathematical programming;
- 2) classical;
- 3) mapping.

**Mathematical Programming:** The earliest portfolio management techniques optimized a portfolio’s commercial value within its resource constraints using a mathematical model [1], [6], [9]. These models were supported by the management

science community, though they often lacked credibility in practice. Early modeling techniques focused on maximizing value, but paid little attention to balance or aligning the portfolio with a company's strategy. Second, the models relied on financial projections of each project's commercial value. Relying principally on a single criterion that had a high degree of uncertainty reduced its credibility [4]. However, in recent years, mathematical programming and project selection models have become more practical and realistic [5].

*Classical Portfolio Tools:* Classical portfolio tools include scoring and sorting models and checklists. These methods maximize the value of the portfolio through either financial or non-financial measures. For example, English China Clay International uses a method called Expected Commercial Value to maximize the commercial worth of the portfolio [4]. This method evaluates the expected financial cost and benefit of a project using a probability decision tree to account for the uncertainty about a project's technical and commercial potential success. This method and other financially based models are often criticized for over reliance on financial data and an inability to optimize the mix of projects.

The U.S. Corporate Research and Technology unit of Hoechst-A.G., a large chemical company, [5], uses a nonfinancial scoring model. Projects are rated based on a set of criteria in five categories:

- 1) probability of technical success;
- 2) probability of commercial success;
- 3) reward;
- 4) business strategy fit;
- 5) strategic leverage.

The scores for each category are summarized into a single rating—the Program Attractiveness Score. While this method can balance multiple metrics, it is time consuming to execute and, because the criteria are qualitatively assessed, it can falsely measure the relative attractiveness of projects.

The checklist, a variation on the scoring model, uses multiple criteria in multiple categories, however, instead of assigning a score, the criteria is answered with a yes/no based on a minimum acceptance criteria [5]. A single “no” answer kills the project. Using this tool, poor projects can be weeded out quickly. However, checklists do not rank projects within a portfolio and are not able to evaluate the balance within a portfolio.

*Mapping Portfolio Tools:* Mapping portfolio tools use graphical and charting techniques to visualize a portfolios balance. Typically, two-axis diagrams are used to display the trade-off between two criteria: e.g., risk versus reward, probability of success versus value, or ease of implementation versus attractiveness. For example, 3M uses a bubble diagram and ellipses to plot probability of success against net present value (NPV) [5]. Mapping tools can incorporate multiple portfolio criteria into a single diagram, but are not capable of prioritizing projects.

Groenveld [7] describes a mapping tool that relates research technologies to the potential products and to final markets. Using a precedence network approach, the method maps the interdependencies between projects and their potential economic benefit. The product-technology roadmaps are graphed against

a horizontal time scale. This method displays the links between projects and the strategy of the company; but it does not address the balance of the portfolio or maximize its financial return.

### B. Portfolio Management at Boeing

In 1996, Airbus Industries, the European airplane consortium, announced that they were going to develop a “super-jumbo,” the A3XX [11]. The plane would be larger than the 747, fly farther, and have a lower per-passenger operating cost. With this new plane, Airbus expected to take away the lucrative top end of the market currently dominated by Boeing and the 747 [12]. To secure their leadership, Boeing immediately began working on an upgraded version of the 747. Boeing's strategy was to position the new 747 between the existing 747 and the proposed A3XX. This plane would steal away enough market share from Airbus so that the remaining A3XX sales would not justify Airbus's development cost [13]. It was believed that the 747 upgrade could be accomplished for less money and in less time than Airbus would require designing a completely new aircraft. The initial 747-X concept was a stretched version of the existing airframe with new avionics. As the program developed and customers for the aircraft were identified, the statement of work expanded to include numerous improvements including a new wing design.

To obtain final approval, the 747-X program leaders assembled the financial data for the presentation to the president of Boeing Commercial Airplanes. At this point, they realized that the net present value of the airplane's sales revenue would never offset the cost and time required for the 747-X's development. The ramifications were staggering. Boeing could no longer afford to develop and to introduce large new airplanes. The President canceled the 747-X development program and chartered a new team. The charter statement was to “initiate an intensive ‘program’ type effort to find a different way to approach new airplane development and production to be able to eventually build a new airplane”<sup>1</sup> in half the time and at half the cost. The new team came to be known as the Airplane Creation Process Strategy Team (ACPS).

A core team of process experts from across the company was assembled. The team was directed to focus on nonrecurring processes and development costs for a new airplane from firm engineering configuration to delivery to the first customer. A sub-team began by collecting time and costs data on recent new airplane programs to baseline Boeing's current product development costs and flow-times. The costs were categorized by functional group (engineering, tooling, QA, etc.) and by production assembly (e.g., outboard spar assemblies). Costs were further divided into labor and nonlabor categories. In addition, product development times were collected and related to the timing of the financial expenses in each category. The result was a financial model that linked program cost with program flow-time. The model was consistent and accurate when validated against other program plans and historical data. In addition, seven broad product development objectives were identified. For example, one objective was to establish a common platform design center for all of Boeing Commercial Airplanes<sup>2</sup>.

<sup>1</sup>Quoted from Boeing internal documents.

<sup>2</sup>The other six objectives are not give for proprietary reasons.

To manage the ACPS program, a gate review process and portfolio management process was developed. The tools employed were typical of the portfolio tools described in the literature section. The content of the portfolio differed from the typical R&D focused application—the ACPS had to optimize a portfolio of projects to improve the product development process. Optimizing product development improvement portfolios is more complex than optimizing R&D portfolios. Product development improvements projects are interdependent (the success of project A depended on the success of projects B, C, and D). In addition, funding for the project could be initiated in one of many funding cycles.

Initially, ACPS employed a combination of classical and mapping tools to manage their portfolio. However, these tools were difficult and time consuming to apply. The complexity introduced by the project interdependency required a new integrated decision support tool to assist in the portfolio balancing process.

### C. Paper Objective

This paper presents a method to quantify the interdependencies of technology projects and a nonlinear, integer optimization model integrated with ACPS' existing portfolio tools. The model selects if, and when, to start funding a project over a four-year period. The effectiveness of a project is influenced by whether or not the projects it depends upon are also funded in the same period. The optimization model identifies the funding strategy that maximizes the potential return, subject to budgetary and portfolio balance constraints. Once the optimum strategy is found, the model can be used evaluate, in real-time, the impact of minor changes to the portfolio. At any point, the portfolio's balance and performance can be displayed in graphic formats that are similar to Boeing's existing portfolio management tools.

## II. ACPS PORTFOLIO MANAGEMENT PROCESS

Once the ACPS team and management methods were determined, teams within and outside the ACPS group began to develop proposals to improve the airplane creation process. The implementation of ACPS was expected to occur over a number of stages. The early stages of ACPS were roughly coordinated with the fiscal budgeting cycle.

To assist in the ACPS project, a cross-functional portfolio management board (PMB) was set up. The PMB was given the responsibility of managing the ACPS development funnel (Fig. 1). Their responsibility is to define, on a yearly basis, a portfolio that balances near- and long-term benefits, cost, risk, and strategic objectives. For each cycle, the PMB selects the project portfolio and holds four gate reviews for each project. At each review, the PMB decides if a project goes ahead as planned, is modified, is combined with another project, or is killed.

The PMB received about 80 project proposals for the first gate review of Stage A. The proposals were submitted in a common format called a situation-target-proposal (STP). The STPs described the current process (situation), the near-term and vision for the process (target), and how to change or replace the aircraft development process (proposal). In addition, supporting

### ACPS STP Development Funnel - Stage A

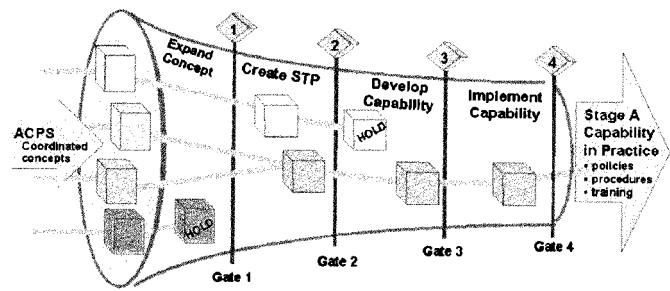


Fig. 1. ACPS stage gate selection funnel.

data including financial costs and benefits was also included in the STP. From the eighty proposals the PMB selected a balanced portfolio using a variety of tools including a financial analysis, risk analysis, and strategy analysis.

### A. Financial Summary

STPs had to include a standard business case analysis based on the baseline financial model (described in the introduction). Each STP identified how much cost and flow-time could be removed from the baseline program if the project succeeded. The output was a business case summary containing yearly implementation costs, projected program savings (assuming a new aircraft in two years), and net present value (Fig. 2).

### B. Probability of Success

Each STP's probability of success had to account for both the technical feasibility and the chances of successful implementation. The PMB used General Electric's Quality  $\times$  Acceptance = Effectiveness measure. Quality was measured by the project's feasibility and its potential to correct the target problem. Acceptance was measured by probability of a proposal being fully implemented given Boeing's culture. Both were measured on a qualitative scale of one to ten. For example, an STP with a quality value of eight and an acceptance value of five results in an overall probability of success of 40%.

The PMB used the probability of success in three ways. First, the value was used as a gate review criteria. Second, the PMB used the measure to communicate to the submitting team whether a weakness was technically or culturally based. Finally, the probability of success was multiplied by the STP's projected revenue to calculate the expected return.

### C. Project Interdependence

During Stage A, the PMB understood that many of the projects were interdependent, especially those supporting a common ACPS strategic objective. To account for the interdependencies, the PMB created a wall-sized dependency network for all Stage A STPs. Unfortunately, the network was so complicated that they had difficulty interpreting the data. Furthermore, they did not have a way to quantitatively incorporate the interactions into the portfolio selection process. Consequently, they accounted for the dependency using the qualitative assessments of the portfolio board members.

## Sample STP Business Case Analysis Summary

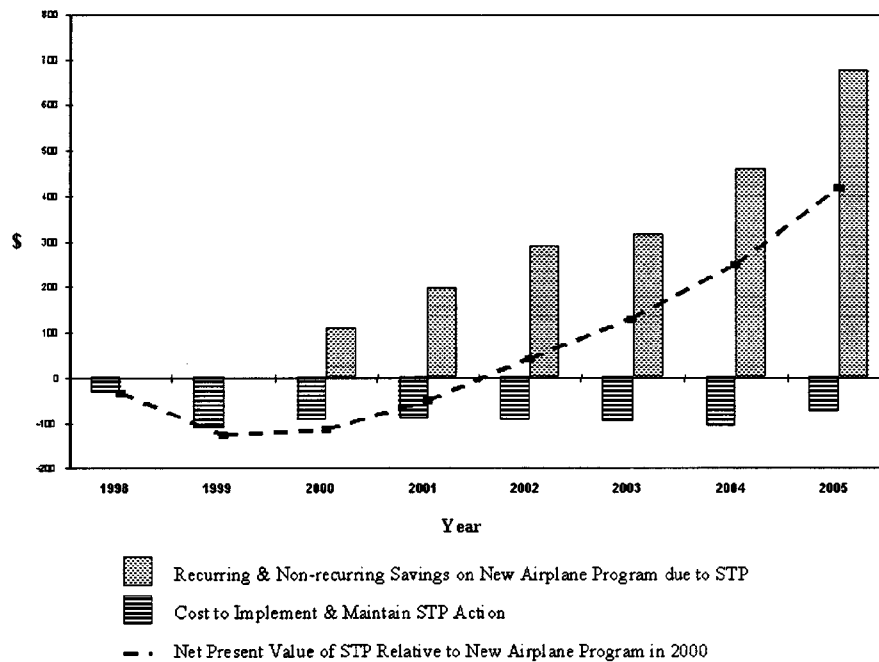


Fig. 2. Sample STP financial summary.

### D. Capability and Process Change

To balance risk versus reward, the PMB mapped the magnitude of the change (risk) against the resulting capability enabled by the process (reward). The magnitude of change and capability were ranked between “None” to “New Core Process/Capability” (Fig. 3). Projects in the lower left corner were entitled “Planning STPs” because they were low risk and generally provided infrastructure for later stages of implementation. The next zone, titled “Incremental STPs,” contained near term payoff projects with medium risk. These STPs typically modified an existing process. The final region, “Platform STPs,” were higher risk projects which developed new processes and capabilities. Each of the three zones was assigned a unique color to add visual clarity. The status of the projects was encoded using shape and color. Red circles identified projects that were either on hold or about to be canceled. Blue squares represented project proposals that were being revised or combined with other STPs. The black squares identified the STPs that were given the go ahead at the last gate review.

### E. Strategic Objectives

Finally, the portfolio had to be balanced across the seven strategic objectives. The PMB aligned each project with the objective it most strongly supported. Then, they ranked the projects within each objective (Fig. 4). The colors from the three zones of the Capability and Process Change Matrix were carried forward with each STP to provide a visual indication of risk.

### F. Portfolio Selection

Given Stage A’s implementation budget, only about 30 projects could be funded. The final portfolio was generated by the board members who qualitatively selected the projects to balance the three portfolio metrics. This required detailed discussions of the merits of each project and how the project related to the overall portfolio balance. The result was a painstaking and time-consuming process. The PMB created four balanced portfolios based on different scenarios of the Capability and Process Change Matrix. The outcome was a ranked list of projects. After the cutoff was made, the financial model was used to estimate the financial return of the whole portfolio, taking into account the probability of success of each project’s pay back. The model estimated the portfolio’s cost and flow-time savings based on the baseline business case.

The Stage A portfolio balancing process was considered a mixed success. The process successfully synthesized a large amount of data from the STPs using a limited number of portfolio management tools. However, the effort required by the PMB was unacceptably high. Consequently, when updated financial information became available in the latter part of Stage A, the portfolio was not rebalanced using the original process. Instead, they chose to make minor adjustments to the original portfolio and re-estimate its cost and potential return. The two drawbacks of the PMB’s portfolio balancing method were its inability to quantify project interdependencies and to account for the risk-reward trade-off at the individual project level.

An updated portfolio selection process was needed. Stage B would bring even greater complexity because latter gate reviews of Stage A would overlap with the early gate reviews of Stage

<sup>3</sup>The Capability and Process Change Matrix was adapted from [15]

### ACPS Capability / Process Matrix with Gate 2 STPs

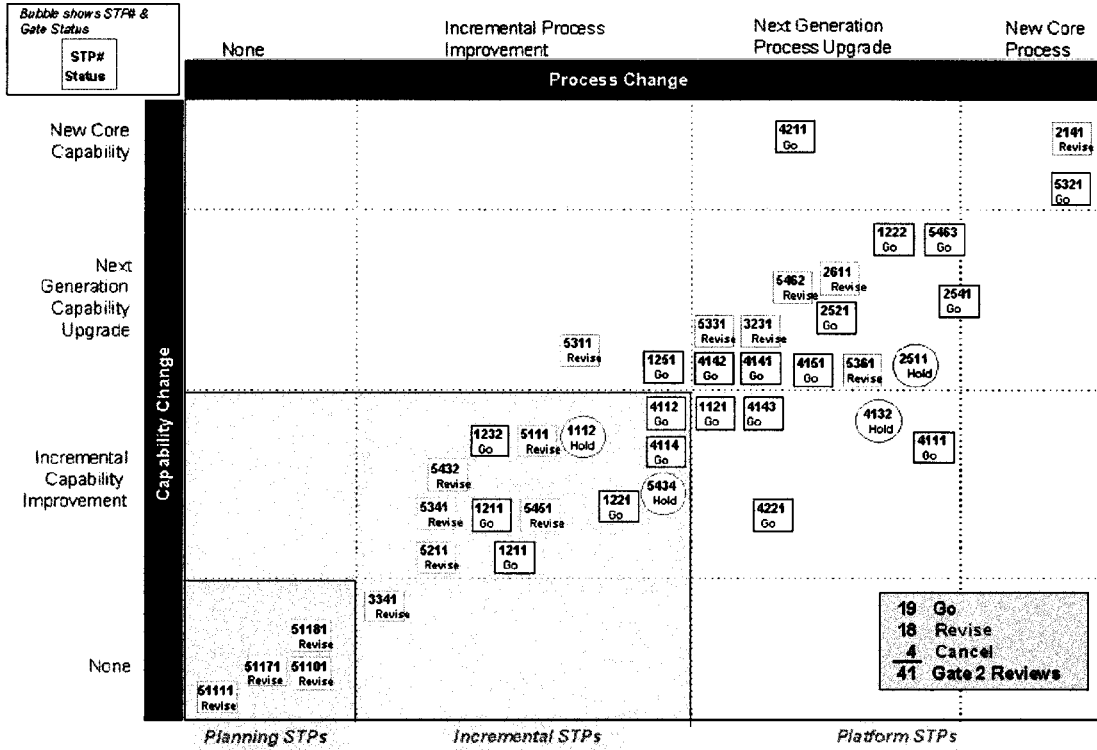


Fig. 3. Sample capability and process change matrix <sup>3</sup>.

### Sample Strategic Objectives Ranking

Objective 1		Objective 2		Objective 3		Objective 4		Objective 5		Objective 6		Objective 7	
STP Number	STP Name	STP Number	STP Name	STP Number	STP Name	STP Number	STP Name	STP Number	STP Name	STP Number	STP Name	STP Number	STP Name
5451		2521	xxxx	711		1252		3341		5451	xxxx	3231	xxxx
5463	xxxx	4142	xxxx	51171	xxxx	1121	xxxx	3351	xxxx	5211	xxxx	2611	xxxx
4141		2511		51101	xxxx	1111	xxxx	3411	xxxx	5452		2541	xxxx
2141	xxxx	2451		5111		1112		2413	xxxx	5453		4131	xxxx
5472	xxxx	4211	xxxx	5321	xxxx	4133	xxxx	3421	xxxx	1211	xxxx	5311	xxxx
5471	xxxx			51111	xxxx	4114		3431	xxxx	1251	xxxx	2411	xxxx
51181	xxxx			5341		1222	xxxx	3441	xxxx	5434		5251	
3131	xxxx			5351	xxxx	4151	xxxx	3451	xxxx	5431	xxxx	5241	xxxx
2431	xxxx			5331	xxxx	1221				4143			
4221	xxxx			5351	xxxx	1331	xxxx			4121			
5462	xxxx									4112	xxxx		
										4111	xxxx		
			Planning STP										
			Incremental STP										
			Platform STP										
			Canceled STP										

Note: Project names have been removed from the chart due to the proprietary nature of the data.

Fig. 4. Sample balance of the strategic objectives.

B. The PMB did not have a means to balance the ACPS program level portfolio when STP interdependency crossed stages. The team was faced with a more complex problem requiring more work.

### III. OPTIMIZING INTERDEPENDENT PROJECTS OVER MULTIPLE TIME PERIODS

To address this problem, a quantitative method was developed that streamlined the selection process. This research culminated in two new portfolio tools. First, the *Dependency Matrix* was developed to document and to quantify the interdependencies between project proposals. The matrix is a scaleable and flexible method and enables a portfolio to be evaluated for a single period or across multiple periods.

The second tool is a spreadsheet-based *Optimization Model* that integrates the Portfolio Management Board's existing tools into a nonlinear, integer program. The model incorporates data from the Dependency Matrix and the estimated financial performance to directly calculate the total performance of any portfolio. The optimization model then maximizes the estimated financial return of the portfolio subject to portfolio balance and budget constraints. Once the optimum strategy is found, the model can be used to rapidly explore the impact of changes to the portfolio strategies. At any point, the portfolio and its performance are displayed in graphic formats similar to those in Stage A.

#### A. Dependency Matrix

The Dependency Matrix is a square matrix of size  $n_p$ , the number of projects. Each project represents one column and one row ordered identically, similar to a Design Structure Matrix [14]. Each element in the matrix,  $d_{ij}$  varies from zero to one. The value of  $d_{ij}$  represents the level of dependency that project  $i(1, 2, \dots, n_p)$  has on project  $j(1, 2, \dots, n_p)$ . A value of zero implies that the project  $i$  is entirely independent of project  $j$  for its financial success. A value of one implies that project  $i$  is entirely dependent on project  $j$  for its financial success. A  $d_{ij}$  value of one also indicates that the PMB should consider combining the two projects at the next gate review. It is not the case that  $d_{ij}$  must equal  $d_{ji}$ . Where  $i$  equals  $j$ , the  $d_{ij}$  elements are zero. The Dependency Matrix is generated jointly by the PMB and the project proposers. The values of the Dependency Matrix elements do not have to be precise, but the criteria for establishing the values must be consistently applied.

After the matrix is generated, it is necessary to calculate what percentage of a project's revenue is attributable to itself and how much is attributable to its interdependencies. To do this, a new input variable is introduced called the Minimum Benefit Level ( $M_i$ ).  $M_i$  is the percent of revenue expected if project  $i$  was funded without funding the projects it depends on. For example, if  $M_i$  were 0.85, STP  $i$  was the only project funded, and the maximum expected revenue from project  $i$  was 10 K, we would expect a benefit of 8.5 K from the portfolio.

The remaining benefit of project  $i(1 - M_i)$  is allocated to its dependant projects. The distribution is based on their relative dependency values,  $d_{ij}$ . The value of  $W_{ij}$  is the percentage dependency of project  $i$  on project  $j$ .

$$W_{ij} = (1 - M_i) \left( \frac{d_{ij}}{\sum_{\alpha=1}^{n_p} d_{i\alpha}} \right) \quad (1)$$

To evaluate the net return for a given portfolio at a given time, it is necessary to model which projects are currently funded.

The binary array  $X_j$  identifies which projects are funded at a given time. The net effect of the dependency,  $D_i$ , (i.e., what percentage of the revenues is due to the dependant projects) is the sum of the weighted dependencies,  $W_{ij}$ , for all funded projects.

$$D_i = \sum_{j=1}^{n_p} X_j W_{ij} \quad (2)$$

The following example illustrates the process. Project 1 is dependent on two other projects, 2 and 3, both with dependency values ( $d_{ij}$ ) of 0.2. Project  $i$ 's minimum benefit level ( $M_i$ ) is estimated at 0.8. The business case analysis projected revenue for project 1 at \$100 000. If project 1 is funded, but 2 and 3 are not, then the expected revenue from project 1 is \$80 000. The remaining 20% ( $1 - M_i$ ) of the potential benefit of project 1 is distributed between 2 and 3 based on the relative weight of their dependency values ( $d_{ij}$ ); in this case 0.10 or \$10 000 each. Thus, if project 1 and 2 are funded, the expected revenue from project  $i$  would be \$90 000.

As the portfolio management process adds, cancels, and/or combines projects, the Dependency Matrix can be easily updated. If a new project is developed, it is added to the Dependency Matrix as a new column and row. The new elements of  $d_{ij}$  are added and new values of  $W_{ij}$  are automatically calculated.

#### B. Optimization Model

The Optimization Model is an Excel-based nonlinear integer program. The goal is to maximize a portfolio's net present value subject to budgetary and portfolio balance constraints. The model utilizes the Dependency Matrix to estimate each project's revenue based on the entire portfolio. Once the optimal solution is found, the performance of the portfolio is displayed in the graphs and charts similar to those used by the PMB for Stage A. The solution provided by the model is then used as a starting point to explore and evaluate alternative portfolio mixes. Changing the content and timing of the portfolio mix in the spreadsheet immediately updates the performance metrics and graphics.

1) *Input Data:* In addition to the dependency matrix, several additional variables need to be modeled. The data required for the model is available as part of the STP gate review business case.

**Timing:** The years,  $t$ , are enumerated from year 0 to year  $n_t$ . The year in which a project starts to receive funding is modeled by the matrix  $X_{it}$  where  $X_{ik} = 1$  when project  $i$  is slated to start in year  $t = k$ . The project can only be started once and is subject to the constraint:

$$\sum_{t=0}^{n_t} X_{it} \leq 1 \quad (3)$$

**Portfolio Cost:** The financial model in the STP includes a total yearly cost, which includes capital expenditures, cost of implementation and sustaining costs. It is assumed that cost is independent of the year in which a project is launched (i.e., it does not become more expensive or less expensive to start projects). The project costs for the entire portfolio are captured in a matrix  $C_{it}$  where each element represents the incremental

cost of project  $i$  in calendar year  $t$ . This matrix is based on the STP's predicted costs and the matrix  $X_{it}$ . Once a project is started, it is assumed that funding continues for all years.

**Portfolio Revenue:** The STP financial model also includes a projected revenue for each project by year; however, the revenue generated by a project is dependent both the year the project is started and the year the airplane program is initiated (i.e., when the project is applied to an airplane program). Generally, ACPS projects require one or two years of implementation before they are able to achieve their full revenue potential on an airplane development program. The value in each element of the revenue matrix  $R_{it}$  represents the total projected savings from project  $i$  in calendar year  $t$  if the new airplane program was launched in calendar year  $l$ .

**Probability of Success:** The PMB rated each project,  $i$ , on its probability of success,  $P_i$ , on a scale of zero to one.

**Strategic Objective:** The PMB aligned each project with a single strategic objective (Fig. 4). The mapping of strategic objectives to projects is captured in the matrix  $N_{im}$  whose variables are a binary and where  $i$  is the project and  $m$  is the objective. In the model, a project can only support one strategic objective, although in reality it might support several objectives.

**Risk/reward:** As a relative measure of risk in the portfolio, the PMB rated each project on its impact on the capabilities and the processes of the company (Fig. 3). The measures of capability and process change for each project are not assigned variables here because they are not a constraint or decision variable in the model. They are included solely to provide the graphical output for the PMB's metric of risk.

2) *Intermediate Calculations:* Next, the net effect of project  $i$  in calendar year  $t$ ,  $D_{it}$ , is calculated from the normalized dependency matrix,  $W_{ij}$ . To do this, we need an intermediate binary variable ( $Y_{it}$ ) to indicate if project  $i$  is funded in year  $t$ . As stated earlier, once a project is started, it remains funded.

$$Y_{it} = \sum_{\beta=1}^t X_{i\beta} \quad (4)$$

and

$$D_{it} = \sum_{j=1}^{n_p} W_{ij} Y_{jt} \quad (5)$$

3) *Constraints:* Three constraints are imposed on the model:

- 1) budget;
- 2) quantity of projects in the portfolio;
- 3) quantity of projects supporting each strategic objective.

The budget,  $B_i$ , represents the maximum amount of money available to spend on the portfolio of projects  $i$  for each calendar year  $t$ . The cost in any given year cannot exceed the budget available.

$$\sum_{i=1}^{n_p} C_{it} Y_{it} - B_t \leq 0 \quad (6)$$

The second constraint is the maximum number of projects,  $Q$ , in a given year. This constraint provides flexibility to use the

model as a tool to evaluate alternate portfolios. Using the model to evaluate the portfolio options is discussed below.

$$\sum_{i=1}^{n_p} Y_{it} - Q \leq 0 \quad (7)$$

The last constraint sets the number of projects that must support each of the strategic objectives ( $M_m$ ) of the program. The PMB decides which objectives to emphasize with the portfolio by identifying a minimum quantity of projects to support each objective.

$$\sum_{i=1}^{n_p} N_{im} Y_{it} - M_m \geq 0 \quad (8)$$

4) *Model Objective Function:* The model selects the projects to start funding in each calendar year to maximize the net present value of the entire portfolio subject to the budget, project quantity, and strategic alignment constraints. The revenue contributed by each project is influenced by its probability of success  $P_i$  and the effects of the Dependency Matrix  $M_i$  and  $D_{ik}$ . In the equation below, the net present value discount factor for each calendar year  $t$  is represented by  $F_t$ .

$$\sum_{t=0}^{n_t} \sum_{i=1}^{n_p} Y_{it} R_{it} F_t P_i (M_i + D_{it}) - \sum_{t=0}^{n_t} \sum_{i=1}^{n_p} Y_{it} C_{it} F_t \quad (9)$$

*Model Output:* The standard PMB portfolio metrics are displayed graphically. Changing the content and timing of the portfolio mix ( $X_{ik}$ ) in the spreadsheet immediately updates the performance metrics and the graphs. The Capability and Process Change Balance (Fig. 5) counts the number of funded projects in each category of process and capability change and portrays them as a percent of the whole. This chart is a modified version of the original Capability and Process Change Matrix (Fig. 3) and provides the PMB with the relative balance of risk and reward in the portfolio.

The second graph displays the number of project associated with each strategic objective (Fig. 6). This graph is a summary of the PMB's Strategic Objective chart (Fig. 4).

The financial summary (Fig. 7) portrays the cost, benefit, and net present value of the funded projects over four calendar years of the model. The revenue shown is the sum of the product of each project's revenue ( $R_{it}$ ), probability of success ( $P_i$ ), and its Dependency Matrix effect ( $M_i + D_{it}$ ). The NPV uses the sum of the costs beginning from year one, but only the revenue in the year of interest (e.g., NPV in 2000 considers cost from '98, '99, and '00, but benefit in '00 only). The ACPS data is constructed to allocate the benefit one year after the start of a new airplane development program. As stated earlier, the value in each element of the revenue matrix  $R_{it}$  represents the total projected savings from project  $i$  in calendar year  $t$  if the new airplane program was launched in calendar year  $l$ .

#### C. Application of Dependency Matrix and Optimization Methods

The Optimization Model was developed in Microsoft Excel and used Frontline Systems' Premium Solver Plus to solve the

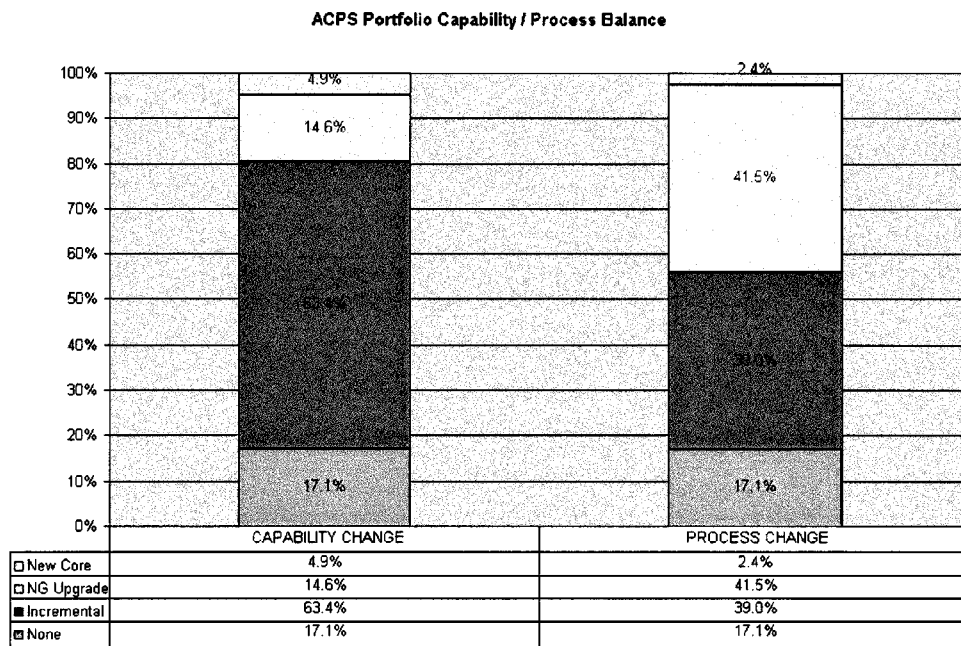


Fig. 5. The capability and process change balance.

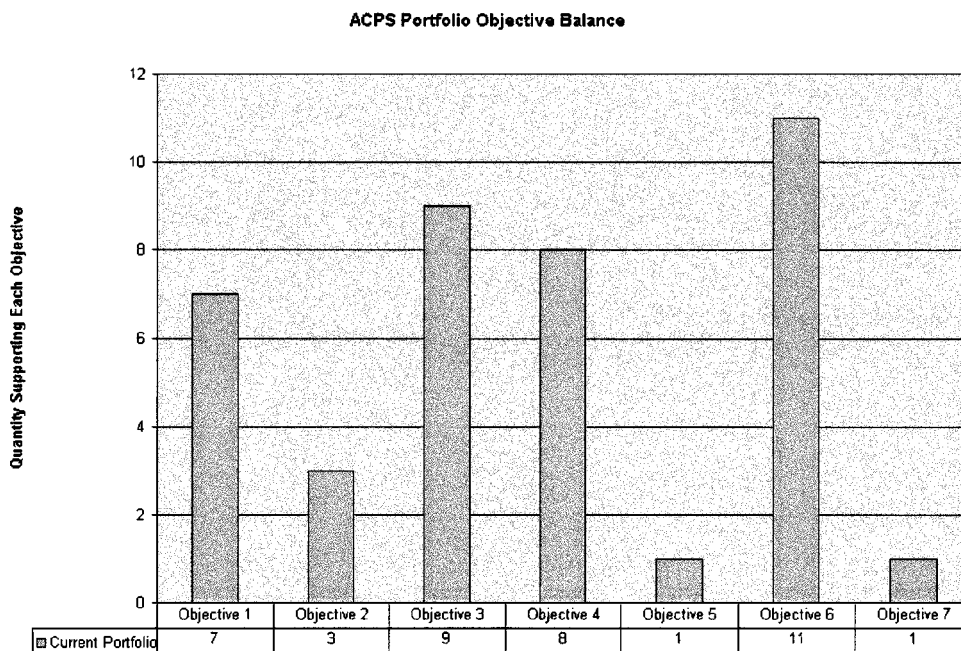


Fig. 6. Balance of support for seven objectives.

nonlinear, integer optimization program. The Dependency Matrix and the Optimization Model were developed just after the Stage A gate decisions were finalized and before data was available for the Stage B proposals. Consequently, the model was tested and validated using Stage A data.

The solver was not able to solve to optimality the problem with the integer restriction. However, when the integer constraint on the decision variable was revised to  $0 \leq X_{it} \leq 1$ , the model quickly converged to a solution. Typically, only one or two out of the 60 projects were assigned fractional values. These fractional values were always biased heavily toward a single solution (e.g., 0.7 or more assigned to a single year  $t$ ). This became

the optimal solution for comparison with binary-constrained solutions and the solution generated earlier in Stage A by the PMB.

The output of the Optimization Model was validated against the ACPS financial model by comparing several identical portfolios with each tool. Next, the optimal solution for Stage A was compared with the original portfolio selected PMB. There were three important findings. First, the total revenue of the two portfolios was very similar, however the cost of the optimized portfolio was roughly 15% lower. This generated a higher net present value for the optimized portfolio. Second, the number of projects ( $Q$ ) in the two portfolios was very close. Third, approximately 40% of the projects were common to both portfolios.

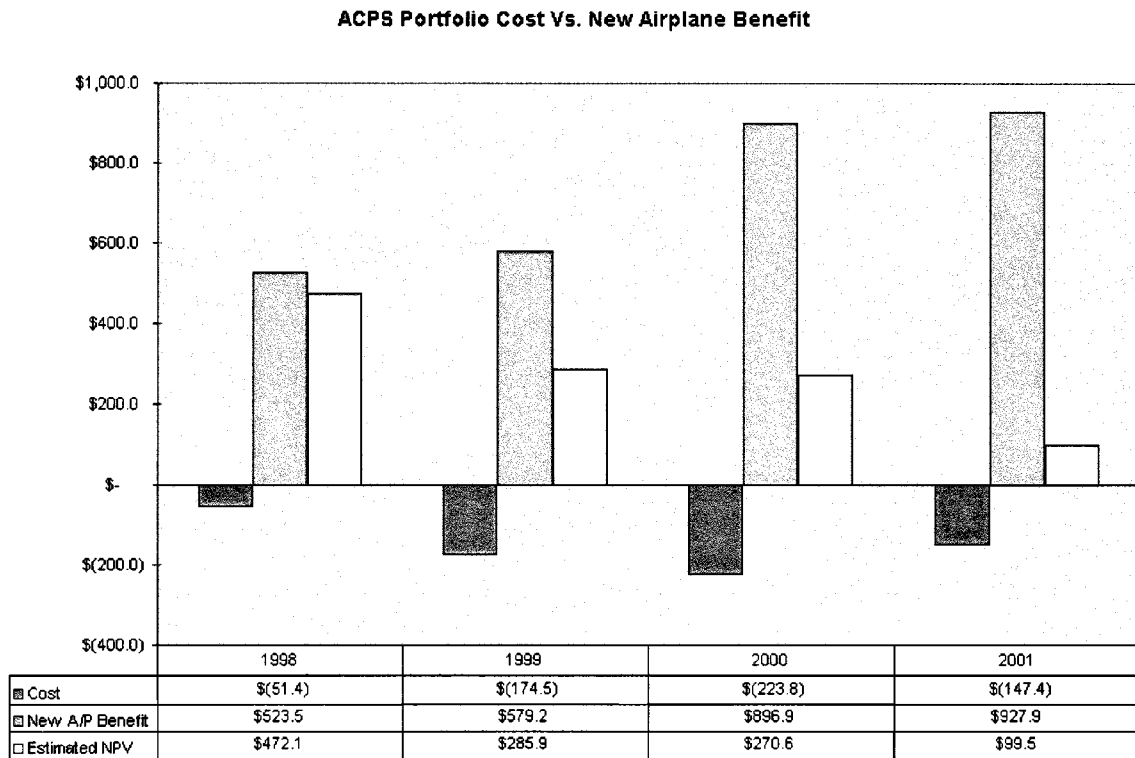


Fig. 7. Sample summary financial performance of the portfolio.

The NPV-based objective function seemed to weigh costs more heavily than in the PMB's original process. To test if this were true, the objective function was altered to maximize total revenue instead of NPV and the model was resolved. Surprisingly, when revenue was maximized, the commonality of the projects in the two portfolios diverged even farther, but the optimal solution resulted in slightly higher total revenue. After some examination of the data, it became apparent that many of the projects had projected revenues of the same magnitude. Thus, there were numerous potential solutions to achieve nearly identical total portfolio revenues.

Decoupling the Dependency Matrix from the rest of the model creates a linear version that provides a means to examine the effects of project dependency. In the case of Stage A data, less than 5% of the elements ( $d_{ij}$ ) in the Dependency Matrix were populated with values greater than zero. The mean value of the elements was roughly 0.3. The Dependency Matrix, therefore, had a weaker effect on the Stage A solutions than anticipated. The most noticeable effect of the Dependency Matrix was that it formed groups of interdependent projects. These project groups tended to stay together either in or out of the portfolio, especially when many optimization constraints were binding.

#### IV. CONCLUSION

This work proposes a quantitative method that enables a team to evaluate and optimize a technology portfolio where the projects are highly coupled and are initiated in different funding cycles. The Dependency Matrix is a simple tool to document and quantify the interdependencies between projects.

The format of the matrix provides flexibility to add, remove or combine projects with little effort. The Optimization Model utilizes existing data, incorporates the aggregate effect of the Dependency Matrix, and integrates the existing portfolio management tools used in the ongoing ACPS program. Using the optimal funding strategy as a starting point, the model's spreadsheet format provides flexibility to evaluate performance of alternative solutions. To simplify interpretation, the performance of the portfolio is summarized using graphical formats similar to the PMB's existing portfolio management tools.

The mathematical nature of the model requires the input data to be numerically quantifiable. Many optimization models have been criticized in the past because they rely too heavily on financial data that is either not available or not very accurate [2]. In the ACPS program, the financial predictions were developed using a detailed, validated, rigorous, and standardized method. Consequently, the results were credible to the team.

The generation of the Dependency Matrix is another potential weak point of the analysis. The values of the minimum benefit level and the matrix do not have to be precise, but their relative ranges do have to be consistently applied. It is pointless for PMB members to argue over whether a particular element should be 0.98 or 0.95. However, it does matter that they agree on the general magnitude and that the values within the matrix are judged on the same relative scale.

The model has many benefits that outweigh these concerns. First, the model's spreadsheet architecture made it simple to quickly answer a variety of questions: "If we could fund one more project this year, which one best supports the existing portfolio?" or "If we had  $X$  more dollars to spend this year, how much would it increase the NPV of the portfolio?" Second,

the model minimized the time required to re-evaluate the entire portfolio when project metrics were updated. For instance, new financial projections became available just prior to a scheduled stage gate review. With the Optimization Model, all of the new data could be imported into the model and the entire portfolio could be re-evaluated instantaneously. Third, the model allows the PMB to focus on balancing the portfolio without losing alignment with the overall objectives of the company. Finally, the Dependency Matrix itself provided an unanticipated, but very powerful benefit. The matrix format facilitated the discussion of how the various projects related to one another and documented the results. The PMB members were able to quickly uncover and discuss their different perceptions of the interdependencies of the projects.

When the PMB was shown the tool, they immediately realized its benefits. One board member commented, "The two scenarios you just solved for in five minutes took six of us eight hours to do on a Saturday." The model was perceived as a faster method of comparing alternate portfolios, not as a financial estimator for the program.

Dr. W. E. Deming summarized it best when he said, "All models are wrong. Some models are useful." The Dependency Matrix and the Optimization Model are not a magic bullet to solve the portfolio management process. They provide additional tools to support the complex decision process to satisfy all three goals of portfolio management: maximize the value of the portfolio, provide balance, and support the strategy of the enterprise. They effectively provide a means to optimize and balance interdependent projects over multiple periods in a technology portfolio.

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