PROJECT PORTFOLIO SELECTION:

A DECISION SUPPORT APPROACH

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Abstract

Selecting projects to develop from the many that are usually possible, or "*project portfolio selection*" is a crucial decision in many organizations. Many different methods for portfolio selection have been suggested in the literature but no integrated framework has been developed for carrying it out. In this thesis, we suggest a framework that builds on the strengths of existing methods. The proposed framework separates the project portfolio analysis and selection process into distinct stages and allows users to choose the techniques they find the most suitable for each stage.

Since finding the optimal solution is the most sophisticated part of the proposed framework, we developed a zero-one linear integer-programming model for this stage that overcomes the shortcomings of existing models and advances previous work in this area. The model we developed considers multiple, conflicting goals, including qualitative objectives, and selects and schedules the optimal set of projects. The solution maximizes benefits according to pre-specified priorities without violating any constraints such as resource limitations, project interdependencies, and portfolio balancing.

We implemented the proposed framework in the form of a decision support system (DSS) to facilitate and encourage decision maker involvement throughout the process. For this purpose we developed PASS (Project Analysis and Selection System). PASS is a user-friendly DSS that suits the knowledge level of potential users and allows interaction with the system as well as intervention to make adjustments to the solution it provides. We tested the usefulness, perceived usefulness and perceived ease of use of PASS in a lab setting and gained significant results in support of the developed hypotheses. We also presented our approach to two high-tech firms who wanted to investigate the feasibility of PASS for project portfolio selection, and received very promising feedback from these companies.

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Table of Contents

Chapter 1

Introduction

A *project* can be defined as "a complex effort, made up of interrelated tasks, performed by various organizations, with a well-defined objective, schedule, and budget." (Archibald, 1992). A *project portfolio* is a group of projects that are carried out under the sponsorship and/or management of a particular organization. These projects must compete for scarce resources (such as people, finances, and time) available from the sponsor. That is because there are usually not enough resources to carry out every proposed project which meets the organization's minimum requirements on certain criteria such as potential profitability. *Project portfolio selection* is the periodic activity involved in selecting a portfolio, from available project proposals and projects currently underway, that meets the organization's stated objectives in a desirable manner without exceeding available resources or violating other constraints.

Project portfolio selection is a crucial decision in many organizations, where serious efforts are made to estimate, evaluate, and choose optimal sets of projects (Dos Santos, 1989). Cooper et al. (1997b) describe eight key reasons for the vital importance of portfolio management. In spite of its importance, portfolio management is relatively new to most businesses, with half of all businesses reporting their portfolio management approaches in place for two years or less. Top performers have had their method in place longer (Cooper et al., 1997b).

Some of the issues that have to be addressed in the process of project portfolio selection are the organization's objectives and priorities, financial benefits, intangible benefits, availability of resources, and risk level of the project portfolio (Schniederjans and Santhanam, 1993). Difficulties associated with project portfolio selection result from several factors, as explained below.

1. There are multiple and often-conflicting objectives (or criteria) associated with the selection of projects to include in a project portfolio. Even when all objectives have been identified, one still has the problem associated with determining the tradeoffs among the various criteria. For example, are economic objectives more important than political objectives, and if so, how much more important?
2. Some of the objectives are qualitative, as opposed to quantitative, in nature. For example, enhancing the image of the organization or promoting national pride through performing ambitious projects are qualitative objectives. Integrating qualitative and quantitative objectives for such projects is difficult.
3. There is a large amount of uncertainty associated with the scoring of individual projects on a specific criterion. For example, the net present value (NPV) of a new product that is under development can be highly uncertain. Moreover, there are certain risks, such as technical and market risk, that should be addressed during project portfolio selection.
4. Some projects may be highly interdependent in nature. For example, an Executive Information System (EIS) may require the completion of one or more precursor projects, such as upgrades or installation of certain transaction processing

applications (TPS), each of which could have benefits in its own right. Mutually exclusive projects (a set of projects among which only one can be selected), is another example of project interdependence that should be addressed.

5. In addition to the difficulties associated with portfolio objectives, due to resource limitations there are usually constraints such as finance, work force, and machine time, to be considered in the decision making process. As some researchers have noted, a major reason why some projects are selected but not completed is that resource limitations are not always formally included in the project portfolio selection process. Therefore, in cases where resource limitations are at fault for a failed project, a selection model that incorporates resource limitations may aid the decision maker in avoiding such mistakes (Schniederjans and Santhanam, 1993). Project portfolio selection becomes more difficult when resource availability and consumption are not uniform over time.
6. The selected portfolio may need to be balanced in terms of factors, such as risk and time to completion, that are of importance to decision makers. For example, although high-risk projects in many cases have greater expected benefits, one should be careful about putting too many resources into high-risk projects.
7. The number of feasible portfolios is often enormous. For example, if there were twenty candidate projects for a time frame of five periods, the number of combinations (project portfolios) that could be considered is 2^{100}, assuming a go/no go decision for each project in each period.

There are more than one hundred divergent techniques that can be used to estimate, evaluate, and choose project portfolios (Cooper, 1993; Dos Santos, 1989). Many of these techniques are not widely used because they address only some of the above issues, they are too complex and require too much input data, they may just be too difficult to understand and use, or they may not be used in the form of an organized process (Cooper 1993).

Traditional optimization techniques such as linear programming models are the most fundamental quantitative tool for project portfolio selection (Jackson, 1983) that address most of the above-mentioned issues. However, these techniques have largely failed to gain user acceptance (Mathieu and Gibson, 1993). Few modeling approaches, from the variety of modeling approaches that have been developed, are being utilized as aids to decision making in this area (Liberatore and Titus, 1983). According to Hess (1993) "management science has failed altogether to implement project selection models, we have proposed more and more sophistication with less and less practical impact" (Hall and Nauda, 1990). One of the major reasons for the failure of traditional optimization techniques is that they prescribe solutions to project portfolio selection problems without allowing for the judgment, experience and insight of the decision maker (Mathieu and Gibson, 1993).

Among the published methodologies, there has also been little progress towards achieving an integrated framework that simultaneously considers all the different criteria in determining the most suitable project portfolio. This is partly because of the complexities involved in project portfolio selection, as explained before.

In an attempt to overcome these difficulties, we have developed an integrated framework for project portfolio selection, which takes advantage of the best characteristics of some of the existing methods. The proposed framework combines methods which have a good theoretical base with other methods that may not be strong theoretically, but which are commonly used because of their desirable decision support characteristics. The framework includes a staged approach, where the most relevant and appropriate methods can be selected by the organization and used at each stage in order to build a portfolio with which decision makers can be confident.

In order to increase the likelihood of user acceptability of the developed framework, we followed the lead of Bard et al. (1988), and Liberatore and Titus (1983) and took a decision support approach for implementing the proposed framework. This approach is consistent with the recent shift of researcher interest from solving well-structured problems under often unrealistic assumptions, to developing decision support systems that support decision makers in capturing and making explicit their own actual preferences, interacting with them in several steps of decision making (Dyer et al., 1992).

In the following, first we will review the existing literature. Some of the most popular models used for project evaluation and portfolio selection that are relevant to this work are discussed briefly and the advantages, disadvantages, and limitations of each method are described. Then an integrated framework is proposed which integrates the best aspects of these methods in a manner that allows a choice of techniques. After that we briefly introduce decision support systems (DSS). In order to demonstrate the potential of such an approach, we describe a prototype interface, called PASS, we developed for use in the "portfolio selection" and "portfolio adjustment" stages of the process. Following that, we describe the hypotheses that we developed to test PASS usefulness, perceived usefulness and perceived ease of use. Then we describe the experiment designed to test the prototype and results of a lab experiment that was conducted to test the hypotheses. After that we explain the feedback that we received from industry about our approach to project portfolio selection and finally, we outline some of the additional work needed to address some related and unsolved issues in project portfolio selection.

Chapter 2

Literature Review

2.1 Introduction

While there are many possible methodologies that can be used in selecting a portfolio, there is no consensus on which are the most effective. As a consequence, each organization tends to choose, for the project class(es) being considered, the methodologies that suit its culture and that allow it to consider the project attributes it believes are the most important. There have been many published articles and books on the subject of project evaluation and selection, discussing well over one hundred different techniques (Cooper, 1993). Certain taxonomies of these techniques have appeared in the literature (Hall and Nauda, 1990; Martino, 1995), but for the purpose of our discussion we can classify project evaluation and selection techniques into three categories: strategic techniques, benefit measurement techniques, and portfolio selection techniques.

Techniques used in the first category can assist in the determination of a strategic focus and overall budget allocation for the portfolio, while those in the second category can be used to evaluate a project independently of other projects. The third category deals with the selection of portfolios based on candidate project parameters, including their interactions with other projects through resource constraints or other interdependencies.

In the following, we will discuss these three categories and introduce some of the most commonly used methods in each category. Since, in this research, it is assumed that strategic direction and focus of organization is already determined, we will only introduce some of the techniques in the first category to give a general idea of strategic techniques. For the other two categories, however, we will first introduce the methods used in each category and then discuss the advantages and disadvantages of each method.

2.2 Strategic Techniques

The strategic implications of portfolio selection are complex and varied (Hax and Majluf, 1984; Hax and Majluf, 1996; Cooper, Edgett, and Kleinschmit, 1997c), and involve considerations of factors both external and internal to the firm, including the marketplace and the company's strengths and weaknesses. These considerations can be used to build a broad perspective of strategic direction and focus, and specific initiatives for competitive advantage. This strategy can be used to develop a focused objective for a project portfolio and the level of resources needed for its support. Strategic approaches that have been discussed in the literature include:

2.2.1 Cognitive Mapping

Cognitive mapping or policy capturing examines global decisions to determine the components (actual decision processes) that went into them (Schwartz and Vertinsky, 1977; Martino, 1995). Their intent is to calibrate the decision process so that future decisions can be consistent within the context of previous decisions.

2.2.2 Cluster Analysis

This technique helps in selecting projects that support the strategic positioning of the firm by finding clusters of similar projects (Mathieu and Gibson, 1993).

2.2.3 Project Portfolio Matrices

This method has been used to evaluate the strategic positioning of the firm, where various criteria for a firm's position are shown on one or more displays on two descriptive dimensions (Hax and Majluf, 1996). These displays can be used by decision makers to evaluate their current position and where they would like the firm to be in the future. Similar approaches are used by the Boston Consulting Group (Hax and Majluf, 1996) and Arthur D. Little Inc. (Roussel et al., 1991) for portfolio development and planning purposes. Cooper, Edgett, and Kleinschmit (1997c) describe a few portfolio matrices that are being used in project portfolio selection for new products.

2.2.4 Project Mapping

Wheelwright and Clark (1992) discuss a project mapping approach, which develops a strategic direction for the firm. The strategic direction of the firm must be determined before individual projects can be considered for a project portfolio, and many firms do extensive preparation and planning of corporate strategy before considering individual projects (Cooper, Edgett, and Kleinschmit, 1997a).

2.3 Project Evaluation Techniques

The benefit derived through project evaluation methods is measured in terms of each project's individual contribution to one or more organizational objectives (for example, net present value). This category includes the methods described below.

2.3.1 Economic Return

This includes Net Present Value (NPV), Internal Rate of Return (IRR), Return on Original Investment (ROI), Return on Average Investment (RAI), PayBack Period (PBP), and Expected Value (EV) (Martino, 1995; Remer et al., 1993). The latter allows a consideration of risk at various project stages, usually based on either IRR or NPV. These techniques include time dependency consideration of investment and income flows. A 1991 industry survey of the use of the above techniques indicated a movement towards the use of NPV, a moderate reduction in use of IRR, and a significant reduction in the use of PBP when compared to a 1978 survey (Remer et al., 1993). Due to the widespread use of NPV although this method has certain shortcomings, some approaches such as "options thinking" have been suggested in the literature to overcome these shortcomings (Faulkner, 1996).

2.3.2 Benefit/Cost Techniques

These techniques involve the calculation of a ratio of benefits to costs, where inputs may be derived from present value calculations of both benefits and costs, to transform them to the same time basis (Canada and White, 1980).

The advantages of both economic return and benefit/cost techniques are: 1) comparisons are easy to understand, and 2) the best projects are clearly identified by calculated measures

The disadvantages are: 1) it is difficult to include non-tangible benefits, and 2) detailed data are needed for estimated cash flows, etc.

2.3.3 Risk Analysis Techniques

Risk is a combination of the probability of an event (usually an undesirable occurrence) and the consequences associated with that event. Every project has some risk associated with not meeting the objectives specified for the project. This is an important characteristic to consider when considering the inclusion of a project in a portfolio since, for example, including too many high-risk projects may jeopardize the future of the organization. Information used in estimating risk can be derived from expert opinion or from previous experience with similar projects. Models used in analyzing risk include decision theory and Bayesian statistical theory (Canada and White, 1980; Hess, 1993; Martino 1995; Riggs et al., 1994) and decision theory combined with influence diagram approaches (Krumm and Rolle, 1992; Rzasa, et al. 1990).

Advantages: 1) more than one stage in a project can be considered and 2) the expected value of outcomes at each stage can be determined.

Disadvantages: 1) these approaches require estimates of the probabilities of possible outcomes, which are usually difficult to determine, and 2) the Bayesian approach is not universally regarded by mathematicians as valid.

2.3.4 Market Research

Market research approaches can be used to collect data for forecasting the demand for new products or services, based on concepts or prototypes presented to potential customers, to gauge the potential market. Techniques used include consumer panels, focus groups, perceptual maps, and preference mapping, among many others (Wind et al., 1981).

Advantages: 1) market is the driving force for any new product or service. Resources should not be wasted on developing products or services with little or no demand, 2) projections of market demand and pricing are essential to the determination of resources that can be devoted to development projects.

Disadvantages: 1) market research does not consider other factors such as development, production, and distribution costs and timing, 2) these techniques are useful only for market-driven products and services and cannot be used for internally consumed products and services, such as information systems, and 3) unless the product or service being considered is similar to one already in the market, the uncertainty in the forecasted customer acceptance rate will be high.

2.4 Portfolio Selection Techniques

Portfolio selection involves the simultaneous comparison of a number of projects on particular dimensions, in order to arrive at a desirability ranking of the projects. The most highly ranked projects under the evaluation criteria are then selected for the portfolio, subject to resource availability. Classes of available portfolio selection techniques include:

2.4.1 Ad Hoc Approaches

Ad hoc approaches include methods such as:

Profiles (Martino, 1995), is a crude form of scoring model, where limits are set for the various attribute levels of a project, and any projects which fail to meet these limits are eliminated. Study of the human-computer interface aspects of such approaches has shown (Todd and Benbasat 1993) that users prefer these minimum effort approaches, whether or not they give an optimal solution.

Advantages: 1) it is very efficient, and 2) it judges all the projects on the same basis, given the values of particular attributes.

Disadvantages: 1) it is very arbitrary, and requires specific limits to be set on various criteria. These may be difficult to determine, and 2) projects that are marginally below the cut-off points will be eliminated even though they may be better overall than other projects which survive the cut off.

Interactive selection (Hall and Nauda, 1990) involves an interactive and iterative process between project champions and responsible decision maker(s) until a choice of the best projects is made.

Advantages: 1) project managers have an incentive to make their projects look more attractive to the decision maker (this may be a disadvantage too), 2) it helps managers to become very familiar with all aspects of the project, and 3) the projects are more likely to fit the strategic objectives of the decision maker(s).

Disadvantages: 1) this may make all the projects look more alike than they really are.

2.4.2 Comparative Approaches

Comparative approaches include Q-Sort (Souder, 1984), pair-wise comparison (Martino, 1995), the Analytic Hierarchy Procedure (AHP) (Saaty et al., 1980), dollar metric, standard gamble, and successive comparison (Churchman and Ackoff, 1954; Pessemier and Baker, 1971). Q-Sort is the most adaptable of these in achieving group consensus. In these methods, first the weights of different objectives are determined, then alternatives are compared on the basis of their contributions to these objectives, and finally a set of project benefit measures is computed. Once the projects have been arranged on a comparative scale, the decision maker(s) can proceed from the top of the list, selecting projects until available resources are exhausted. With these techniques, both quantitative and qualitative and/or judgement criteria can be considered.

Advantages: 1) most of these techniques are relatively easy to understand and use, 2) pair-wise comparison help to better focus on the issue, and to understand and discuss it, and 3) they allow the integration of quantitative and qualitative attributes.

Disadvantages: 1) the large number of pair-wise comparisons involved in these techniques makes them difficult to use when there are a large number of projects to compare, 2) any time a project is added or deleted from the list, the entire process must be repeated, and 3) they do not answer the question "are any of these projects really good?"

2.4.3 Scoring Models

Scoring models (Martino, 1995) use a relatively small number of decision criteria, such as cost, work force availability, and probability of technical success, to specify project desirability. The merit of each project is determined with respect to each criterion. Scores are then combined (when different weights are used for each criterion, the technique is called "Weighted Factor Scoring") to yield an overall benefit measure for each project.

Advantages: 1) although the benefit measures are relative, projects can be added or deleted without affecting the benefit scores of other alternatives, 2) they allow the integration of quantitative and qualitative attributes, and 3) these techniques are relatively easy to understand and use.

Disadvantages: 1) weights are required, which are cumbersome and difficult to evaluate, 2) these techniques are not well suited for situations where selection of one project influences the desirability of another, and 3) they do not answer the question "are any of these projects really good?"

2.4.4 Portfolio Matrices

Portfolio matrices can be used as strategic decision making tools. They can also be used to prioritise and allocate resources among competing projects (Morison and Wensley, 1991). This technique relies on graphical representations of the projects under consideration, on two dimensions such as the likelihood of success and expected economic value. This allows a representative mix of projects based on the dimensions represented.

Advantages: 1) portfolio matrices are well organized, disciplined methodologies that facilitate the selection of a project portfolio, 2) otherwise, managers may neglect using a rational economic approach. Portfolio matrices lead managers to make decisions that are more rational than if they used unaided judgement, 3) portfolio matrix methods are judged to be successful for strategic planning by those who use them. A survey of Fortune 1000 companies showed that almost all respondents believed their use of portfolio planning methods had a positive impact (Hespelagh, 1982), 4) portfolio matrices present information to decision makers in a user-friendly manner. They can also be used by groups of managers in decision-making meetings, 5) portfolio matrices give an overall perspective of all projects underway, on a single map, 6) they help to reach a better-balanced portfolio in terms or risk and other dimensions of interest, and 7) portfolio matrices tend to enforce a strategic discipline in decision making and to provide a commonly understood vocabulary to facilitate idea exchange among decision makers.

Disadvantages: 1) the scope of portfolio matrices ignores other relevant strategic issues, 2) portfolio matrices have little theoretical or empirical support (Armstrong and Brodie, 1994), 3) use of project labels (such as, "pear" and "oyster") that are common in this approach, are appealing and easy to use, but they may lead decision makers to overlook profit maximization (Armstrong and Brodie, 1994), 4) no single empirical study has demonstrated that portfolio matrices are valuable as decision aids (Armstrong and

Brodie, 1994), 5) research has shown that the BCG matrix approach interferes with profit maximizing, as may other matrix methods (Hax and Majluf, 1983). Some researchers have advised against using matrix methods under all circumstances, until evidence is produced that they give superior results (Armstrong and Brodie, 1994), 6) thus far, portfolio matrix techniques have seen limited success (Cooper, 1993), 7) excessive rigidity, which is inherent in these methods, could lead to a mechanistic type of thinking which would stifle rather than enhance creativity. When used by uninitiated decision makers, portfolio matrices could hinder a truly creative way of thinking (Hax and Majluf, 1984), and 8) portfolio matrices are sensitive to the operational definition of the dimensions, cut-off points, weighting scheme, and the specific model used. For example, using different portfolio models in strategic planning could classify the same project as a "dog", "star", "cash cow", or "problem child" (Wind et al., 1983).

2.4.5 Optimization Models

Optimization models select from the list of candidate projects a set that provides maximum benefit (e.g. maximum net present value). Optimization models are generally based on some form of mathematical programming, which supports the optimization process and also includes project interactions such as resource dependencies and constraints, technical and market interactions, or program considerations (Martino, 1995; Santhanam et al., 1989). Some of these models also support sensitivity analysis (Canada and White, 1980), but most do not seem to be used extensively in practice (Souder, 1973; Hall and Nauda, 1990; Mathieu and Gibson, 1993; Hess, 1993). Probable reasons for disuse include the need to collect large amounts of input data, the inability of most such models to include risk considerations, and model complexity. Optimization models may also be used with other approaches, which calculate project benefit values. For example, 0-1 integer linear programming can be used in conjunction with the Analytical Hierarchy Process (AHP) to handle qualitative measures and multiple objectives, while applying resource utilization, project interaction, and other constraints (Ghasemzadeh et al., 1996).

Advantages: 1) mathematical programming approaches maximize overall portfolio objectives, 2) they address multiple resource limitation issues, 3) they allow for interdependencies among projects, 4) they handle balancing issues, and 5) they are based on sound theories.

Disadvantages: 1) they may require data that are not available, 2) there is danger that the results may give a false sense of accuracy, even if the input data are highly uncertain, 3) with the exception of goal programming they don't explicitly handle multiple criteria, and 4) top managers usually do not understand them and so usually they are not employed for strategic decisions.

2.5 Summary

Our literature review indicated the major categories of methods that can be used for project evaluation and portfolio selection and the advantages and disadvantages of some of these methods. Although some of the benefit measurement techniques such as scoring and economic return are widely used for project selection because of their simplicity, they do not offer the comprehensiveness that is necessary to make appropriate choices and to achieve the required balance in complex portfolio situations. However, these techniques are very useful for evaluating different attributes (such as NPV, and ROR) of individual projects, and provide valuable input for project portfolio selection techniques.

Project portfolio selection techniques, on the other hand, address issues that should be considered in portfolio selection decisions. Each technique considers certain issues that might not be addressed by other techniques. For example, project interdependence and mutually exclusive projects are handled only by optimization techniques, and only portfolio matrix and optimization techniques explicitly consider overall project risk for portfolio selection.

AHP is popular among decision makers because of its ability to consider a broader range of issues (such as multiple objectives and qualitative criteria) and also because of the structure that it gives to the problem, which helps decision makers to focus on smaller sets of decisions (Harker, 1989). However, it does not allow the consideration of multiple resource constraints and project interdependencies. Portfolio matrices are also commonly used for portfolio selection partly because of their ease of use, in spite of the fact that they lack a solid theoretical ground and that no empirical study has demonstrated their value as a decision aid.

Among all of the techniques that are available, optimization techniques are the most fundamental quantitative tool for project portfolio selection (Jackson, 1983) that address most of the important portfolio selection issues. However, they have largely failed to gain user acceptance (Mathieu and Gibson, 1993), and few modeling approaches, from a variety of optimization approaches that have been developed, are being utilized as aids to decision making in this area (Liberatore and Titus, 1983; Coopers, 1993).

The literature review clearly shows that although there are many different methods for project evaluation and portfolio selection that have their own advantages, no single technique addresses all of the issues that should be considered in project portfolio selection. Among published methodologies for project portfolio selection, there has been little progress towards achieving an integrated framework that a) takes advantage of the best characteristics of existing methods by decomposing the process into a flexible and logical series of activities and applying the most appropriate technique(s) at each stage and b) involves full participation by decision makers. A few attempts to build integrated support for portfolio selection have been reported (Hall and Nauda, 1990; De Maio et al, 1994; Kira et al., 1990) in the literature. However, these have been limited and specific to the methods used, rather than providing flexible choices of techniques and interactive system support for users.

Chapter 3

A Framework For Project Portfolio Selection

3.1 Introduction

The existence of a sound theoretical basis for portfolio selection greatly increases the likelihood that its application will produce a result which can be trusted by decision makers. However, even if the method is theoretically strong, decision makers will be unlikely to consider using it unless they can understand and work with it. For example, optimization techniques are well grounded in theory, and may take into account more portfolio selection factors than other methods that are commonly used, but they are not widely used, mainly because they are usually hard for decision makers to understand. On the other hand, methods such as portfolio matrices that do not have a strong theoretical basis, but instead are very user-friendly, are commonly used for portfolio selection.

In an effort to take advantage of the best characteristics of existing methods, in this chapter we will propose an integrated framework for project portfolio selection. The proposed framework combines the methods that are well grounded in theory and those that are easy to understand, and applies them in a logical order. The object is to help decision makers to find an optimal portfolio based on both quantitative and qualitative objectives, subject to resource limitations and project interdependencies. The selected portfolio can be displayed by a decision support system which allows for interaction between the decision maker and the system. Adjustments can then be made, in order to find a solution that is acceptable. In the following, we will discuss the major issues that should be considered for developing a framework for portfolio selection, and then we will describe the proposed framework in detail.

3.2 Major Issues In Developing The Framework

There are several issues that should be considered, in developing a framework for project portfolio selection. In the following, we will discuss these issues.

3.2.1 Developing Strategies in Advance

The strategic direction of the firm and the objective for the project portfolio must be determined before individual projects can be considered for selection. Many firms do extensive preparation and planning of strategy before considering individual projects (Cooper, et al., 1997a). This helps to align the project portfolio objectives with the strategic direction of the organization.

3.2.2 Flexibility

While there are many possible methodologies that can be used in selecting a portfolio, there is no consensus on which is the most effective and suitable. As a consequence, each organization tends to choose, for the project class(es) being considered, the methodologies that suit its culture and that allow it to consider the project attributes it believes are the most important (Cooper, 1993; Hall and Nauda, 1990; Krumm and Rolle, 1992; Mukherjee, 1994). Also, the methodologies most useful in developing a portfolio for one class of projects may not be the best for another. For example, good estimates of quantitative values such as costs and time may be readily available for certain construction projects, but qualitative judgement is more likely to be used in the development of advanced new products. A project selection framework should be flexible enough so that stakeholders can choose in advance the particular techniques or methodologies with which they are more comfortable, in analyzing relevant data and making choices among the type of projects at hand.

3.2.3 Staged Approach

A major concern with most of the models for choosing project portfolios is that they are complex and difficult to use (Cooper, 1993; Cooper et al., 1997a). Another problem is the variety of techniques that can be used for project evaluation and portfolio selection. To alleviate these problems, the portfolio selection process should be simplified by breaking it down into a number of stages, allowing decision makers to move logically towards an integrated consideration of projects most likely to be selected. Each step should have a sound theoretical basis in modeling, and should generate suitable data to feed the following step.

3.2.4 User-Friendliness

The proposed framework should accommodate the use of user-friendly computer interfaces through which users can use and interact with the more sophisticated computer models without requiring them to understand in detail or even to see these models. Besides, users should have access to the data underlying the models, with "drill-down" capability, to develop confidence in the data being used and the decisions being made. At the same time, they should not be overloaded with unneeded data; it should be available only when needed and requested. Users also need training in the use of techniques that specify project parameters to be used in making decisions (Kao and Archer, 1997). An overall balance must be achieved between the need to simplify and the need to generate well-founded and logical solutions.

3.2.5 Common Measures

The use of specific project evaluation techniques is situation dependent. For example, a product development organization may use market research or economic return to determine project characteristics. A government agency, on the other hand, may use cost benefit measures. Measures used may be qualitative or quantitative, but regardless of which techniques are used to derive them, a set of common measures should be used so projects can be compared equitably during portfolio selection. This will allow a fair comparison of projects during the portfolio selection process.

3.2.6 Re-Evaluation of Current Projects

Selection of, or adjustments to, a project portfolio is a process which recurs. Existing projects require resources from the available pool, and therefore their schedules and resource requirements interact with potential new projects. It is common practice to re-evaluate projects at major "milestones" (Meredith and Mantel, 1995) or "gates" (Cooper, 1993) to determine whether they merit continuing development. Current projects should be re-evaluated at the same time as new projects being considered for selection. This allows a combined portfolio to be generated within available resource constraints at regular intervals due to a) project completion or abandonment, b) new project proposals, c) changes in strategic focus, d) revisions to available resources, and e) changes in the environment.

3.2.7 Screening

The number of projects which may be proposed for the portfolio may be quite large (Cooper et al, 1997a), and the complexity of the decision process and the amount of time required to choose the portfolio increases geometrically with the number of projects to be considered. In addition, the likelihood of making sound business choices may be compromised if large numbers of projects must be considered unnecessarily. For this reason, screening processes should be used to eliminate projects in advance that are clearly deficient, before the portfolio selection stage of the process begins. For example, screening may be used to eliminate projects which do not match the strategic focus of the firm, do not yet have sufficient information upon which to base a logical decision, or do not meet a marginal requirement such as minimum internal rate of return. In the proposed framework screening should be applied, based on carefully specified criteria, to remove undesirable projects from further consideration before the portfolio selection process is undertaken.

3.2.8 Project Interactions

Multiple and often conflicting objectives (or criteria) may be associated with portfolio selection, and projects may be highly interdependent. This could be due to value contribution, resource utilization, or mutual exclusion. For example, before project C can be undertaken, projects A and B must be completed, since their outputs feed project C. In addition, resource constraints such as available capital and technical workforce over the planning horizon should be considered, including resource time dependencies. The proposed framework should include techniques that consider project interactions such as direct dependencies or resource competition.

3.2.9 Time-Dependent Resource Limitations

Many portfolio selection techniques do not consider the time-dependent resource requirements of projects (Martino, 1995), and most implicitly assume that all projects selected will start immediately. This does not fit the reality of project management, where projects compete for limited resources, should be scheduled to use resources as smoothly as possible in time, and should be completed within some planned interval. The proposed framework should include techniques that take into account the time-dependent nature of project resource consumption.

3.2.10 Providing User Interaction

One of the drawbacks of computer model-based optimal portfolio selection methods (Martino, 1995; Santhanam et al., 1989) is that they may proceed to portfolio selection without intervention by decision maker(s) who may wish to make desired adjustments to the selected portfolio (Morison and Wensley, 1991). If the emphasis is to support users rather than make decisions for them, decision makers must be able to make adjustments at their convenience. However, they should receive feedback on the resulting consequences, in terms of optimality changes and effects on resources. The proposed framework should provide decision makers with interactive mechanisms for controlling and overriding portfolio selections generated by any algorithms or models, and they should also receive feedback on the consequences of such changes.

3.2.11 Group Support

Portfolio selection is usually a committee process, where objective criteria such as predicted rate of return and expected project cost are mingled with subjective criteria relating to the needs of the different organizations represented on the project selection committee. All committee members should have access to information with which project inter-comparisons are made, as well as information on the project portfolio as a whole. Decision making environments for group decision support are available, which allow interactions among decision makers as well as between decision makers and the support system (Turban, 1998). This allows portfolio selection decisions to be made that more closely meet the overall objectives of the organization. As a result, the proposed framework must be adaptable to group decision support environments.

3.3 Stages Of The Proposed Framework

Project portfolio selection should be considered as a continuous process that includes several steps, rather than just evaluating and scoring projects or solving an optimization problem. The framework we have developed consists of discrete stages, which progress from initial broad strategy considerations towards the final solution. This is depicted in Figure 3.1. The ovals in the diagram represent pre-process activities, which we will also discuss. Post-process stages (that follow the portfolio adjustment stage) are also shown for completeness, since these may result in data generation and project evaluation during development, that may also affect portfolio selection at some future time. We now consider the sequential activities that go into developing the portfolio. Since we know the desired end result, which is an optimal or near-optimal portfolio that satisfies the constraints placed on it by the selection committee, it is best to analyze the process from end to beginning, to show how information needed for models/techniques used at each stage is made available from previous stages. The portfolio selection process is completed when the portfolio adjustment stage ends.

3.3.1 Portfolio Adjustment

The end result is to be a portfolio which meets the objectives of the organization optimally or near-optimally, but with provisions for final judgmental adjustments, which are difficult to anticipate and include in a model. Selecting a project portfolio is a strategic decision, and the relevant information must be presented so it allows decision makers to evaluate the portfolio without being overloaded with unnecessary information.

The final stage in the framework is the portfolio adjustment stage where an overall view of the portfolio is required. Here, the characteristics of projects of critical importance in an optimized portfolio (for example risk, net present value, and time-to-complete) can be represented, using matrix-type displays, along with the impact of any

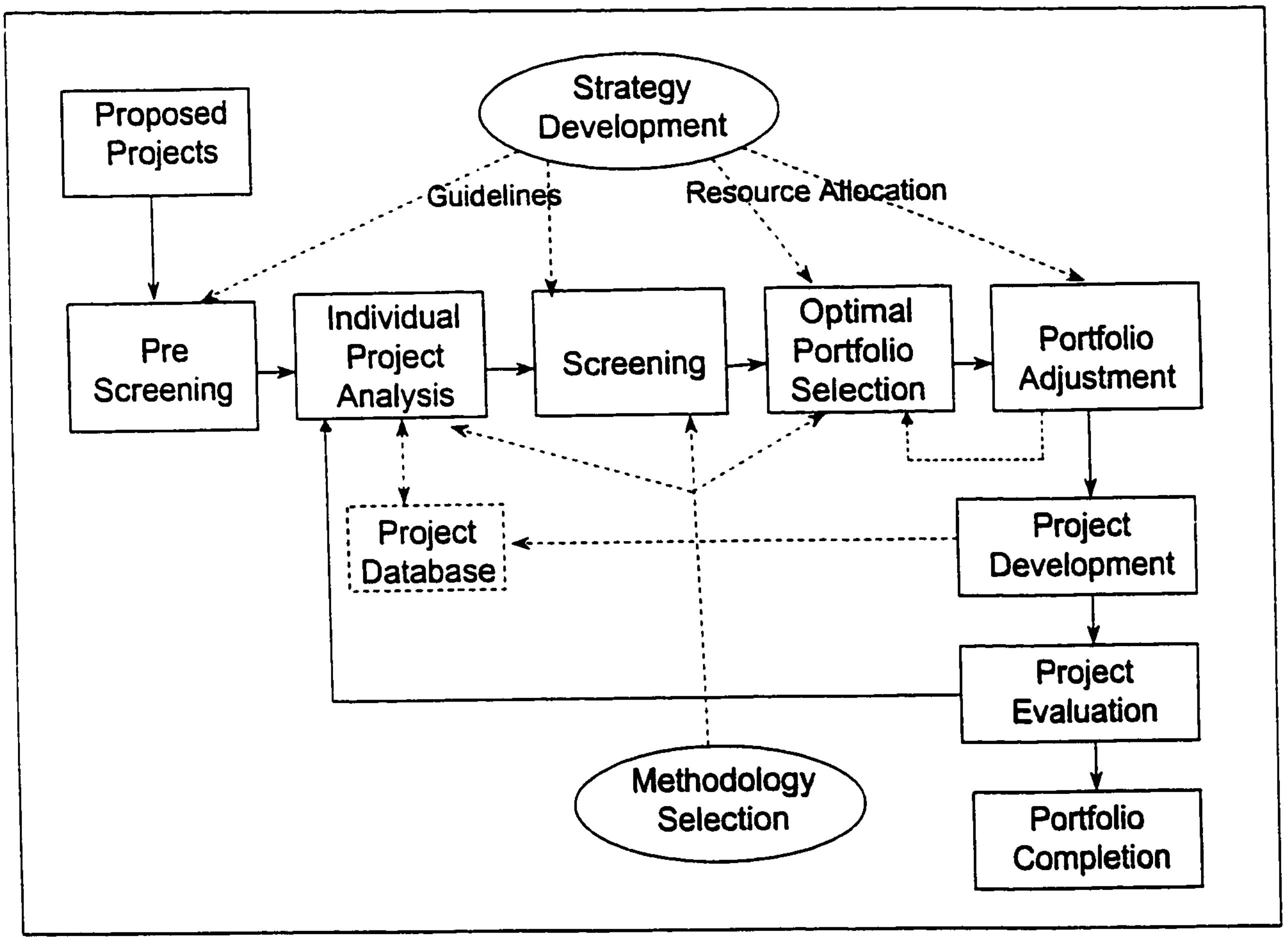

Figure 3.1 Project portfolio selection process

suggested changes on resources or selected projects. A list of dimensions that can be considered in portfolio matrix displays is presented in Cooper et al. (1997c). It is important to use only a limited number of such displays, to avoid confusion (cognitive overload) while the final decisions are being made.

Users should be able to make changes, by adding or deleting projects, at this stage and observe the impact of the change on the optimality of the solution and also on availability of resources. Once the user makes such changes to the portfolio to make it more acceptable, it is necessary to re-cycle back to re-calculate portfolio parameters such as project schedules and time-dependent resource requirements. In addition, sensitivity analysis should be available to predict and display the impact of change in certain parameters (such as resource availability and minimum attractive rate of return) on the selected portfolio.

An important aspect of portfolio adjustment is achieving some form of balance among the projects selected, again through user interaction. Cooper et al. (1997c) explain some of the methods and diagrams companies use to deal with balance and discuss the problems with the quest for balance. Portfolio balancing may require interactive displays on certain portfolio dimensions, such as risk, size of project, and short term vs. long term projects, on which adjustments can be made to achieve the desired balance. For example, the proportion of high-risk projects should not be too high due to the fact that failures of several of these projects could be dangerous to the future of the company. On the other hand, low risk projects may not carry the high return that is sometimes typical of risky projects, so the expected return from the portfolio may be too low if project selection is too conservative on the risk dimension.

Balance on project size is also important, because the commitment of a high proportion of resources to a few large projects can be catastrophic if more than one fails. And too many long-term projects, no matter how promising they are, may cause financing or cash flow problems. Those projects not chosen for the final portfolio are of course still available for consideration in a future portfolio selection process.

3.3.2 Optimal Portfolio Selection

Optimal portfolio selection is performed in the second last stage. Here, interactions among the various projects are considered, including interdependencies, competition for resources, and timing, with the value of each project determined from a common set of parameters that were estimated for each project in the previous stage. AHP, scoring models, and portfolio matrices are popular among decision makers for portfolio selection, because they allow users to consider a broad range of quantitative and qualitative characteristics as well as multiple objectives. However, none of these techniques consider multiple resource constraints and project interdependence. AHP, pair-wise comparison, and Q-Sort also become cumbersome and unwieldy for larger numbers of projects. A serious drawback of portfolio matrices is that they do not appear to meet stated objectives such as profit maximization (Armstrong and Brodie, 1994), so this approach should not be considered for the portfolio selection stage.

We suggest a two-step process for the portfolio selection stage. In the first step, the relative total benefit is determined for each project. A comparative approach such as Q-Sort, pair-wise comparison, or AHP, may be used in this step for smaller sets of projects, allowing qualitative as well as quantitative measures to be considered. This may involve extensive work by committee members in comparing potential project pairs. For large sets of projects, scoring models are more suitable as these do not involve comparison of large numbers of project pairs. The result of either of these approaches would be to establish the relative worth of the projects.

In the second step of this stage, all project interactions, resource limitations, and other constraints should be included in an optimization of the overall portfolio, based on the relative worth of each proposed project. If there is only one criterion of interest that should be optimized and that criterion can be expressed quantitatively (for example, net present value), the foregoing step could be omitted since optimization could be performed directly in the second step. In the unusual case where interdependence and timing constraints were not important, and there is only one resource that is binding, it might be tempting in the second step to simply select the highest valued projects until available resources were used up. However, this does not necessarily select an optimal portfolio (combinations of certain projects may produce a higher total benefit than individual projects with higher individual benefits). The relative worth of each project should therefore be input to a computerized process, which can be a 0-1 integer linear programming model that applies resource, timing, interdependence, and other constraints to maximize total benefit (Ghasemzadeh et al., 1996). Goal programming (Santhanam et al., 1989) may be used for multiple objectives in this step, if more than one objective is explicitly identified and a clear priority exists among these goals. More detailed discussion about a suitable optimization model that we have developed for this purpose is presented in chapter 4.

It should be noted that traditional optimization techniques such as linear programming models are the most fundamental quantitative tools for project portfolio selection, they address most of the important issues that should be considered, but they have largely failed to gain user acceptance. One of the major reasons for the failure of optimization techniques is that algorithms prescribe solution without allowing for the judgment, experience and insight of the decision maker (Mathieu and Gibson, 1993). This is the major reason for the addition of the portfolio adjustment stage which follows the optimization stage, and is the final stage in the process as we discussed before.

3.3.3 Screening

Screening is shown in Figure 3.1 following the individual project analysis stage. Screening may use such techniques as profiles. Here, project attributes from the previous stage are examined in advance of the regular selection process, to eliminate any projects or inter-related families of projects, which do not meet certain pre-set criteria. These criteria could include, for example, estimated rate of return, except for those projects which are mandatory or required to support other projects still being considered. The intent is to eliminate any non-starters and reduce the number of projects to be considered simultaneously in the portfolio selection stage. Care should be taken to avoid setting thresholds which are too arbitrary, to prevent the elimination of projects which may otherwise be very promising.

3.3.4 Individual Project Analysis

Individual project analysis is the fourth from last stage, where a common set of parameters required for the next stage is calculated separately for each project, based on estimates available from feasibility studies and/or from a database of previously completed projects. Such techniques were discussed before; for example, project risk, net present worth, and return on investment can be calculated at this point, including estimated uncertainty in each of the parameter estimates. Scoring, benefit contribution, risk analysis, market research, or checklists may also be used. Note that current projects which have reached certain milestones may also be re-evaluated at this time, but estimates related to such projects will tend to have less uncertainty than those projects which are proposed but not yet underway. The output from this stage is a common set of parameter estimates for each project. For example, if the method to be used were a combination of net present value combined with risk analysis, data required would include estimates of costs and returns at each development stage of a product or service, including the risks. Uncertainty could be in the form of likely ranges for the uncertain parameters. Other data needed could include qualitative variables such as policy or political measures. Quantitative output could be each project's expected net value, risk, and resource requirements over the project's time frame, including calculated uncertainties in these parameters.

3.3.5 Pre-Screening

Pre-screening precedes individual project analysis. This uses manually applied guidelines developed in the strategy development stage, and ensures that any project being considered for the portfolio fits the strategic focus of the portfolio. Essential requirements before the project passes this stage should also include a feasibility analysis and estimates of parameters needed to evaluate each project, as well as a project champion who will be a source of further information. Mandatory projects are also identified at this point, since they will be included automatically in the remainder of the portfolio selection process. Mandatory projects are projects agreed upon for inclusion, including improvements to existing products no longer competitive, projects without which the organization could not function adequately, etc.

A pre-process stage provides high level guidance to the portfolio selection process. Activities in this stage appear in the ovals in Figure 3.1. These include Strategy Development (determination of strategic focus and setting resource constraints), and Methodology Selection (choosing the techniques the organization wishes to use for portfolio selection). Determination of strategic focus may be carried out at higher managerial levels than the portfolio selection committee, because it very much involves the firm's strategic direction. Strategy development is an unstructured process, which can consume a great deal of managerial time (Cooper et al., 1997a), but is crucial if the portfolio selected is to promote the business objectives of the firm. Only occasional adjustments will be needed for strategic guidelines developed at this point in the process, although the portfolio selection process itself recurs at regular planning intervals.

Resource allocation to different project categories also involves high level decisions, which must be made before the portfolio selection process. Choosing and implementing techniques that suit the project class at hand, the organization's culture, problem-solving style, and project environment may also depend upon previous experience. Methodology selection should be based on committee understanding of, and experience with, the candidate methodologies, or their willingness to learn new approaches. The methodology selection stage would not normally be repeated, unless the committee found other methodologies at some future time which were better matches to their preferences.

Stages in the project portfolio selection framework (Figure 3.1) are organized logically, in a manner, which allows decision makers to work through the portfolio selection process logically. Each stage involves methodology choices, which are at the discretion of users, in order to gain maximum acceptance and co-operation of decision makers with the portfolio selection process. A post-process stage follows the portfolio selection process. In this stage projects are developed and evaluated regularly until they are completed. The post-process stage also provides information for the project database and the individual project analysis stage of the framework. Table 3.1 summarizes the stages in the framework, the associated activities, and some of the potential methodologies previously mentioned, for each stage.

Process Stage	Selection Stage	Activity	Potential Methodologies
Pre-Process	Strategy Dev't, Methodology Selection	Development of strategic focus, resource constraints, choice of model techniques	Strategic mapping, portfolio matrices, cluster analysis, etc.
Portfolio Selection Process	Pre-Screening	Rejection of projects which do not meet portfolio criteria	Manually applied criteria; strategic focus, champion, feasibility study avail.
	Individual Project Analysis	Calculation of common parameters for each project	Decision trees, NPV, uncertainty est., ROI, resource req'ts est., etc.
	Screening	Rejecting non-viable projects	Ad hoc techniques (e.g. profiles)
	Portfolio Selection	Integrated consideration of project attributes, resource constraints, interactions	AHP, constrained opt'n, scoring models, sensitivity analysis
	Portfolio Adjustment	User-directed adjustments	Matrix displays Sensitivity analysis
Post-Process	Final Portfolio	Project development	Project management techniques, data collection

Table 3.1 Activities and methodologies in the portfolio selection framework

3.4 Summary

In this chapter, first we introduced the major issues that should be considered in project portfolio selection process and then proposed a framework that simplifies this process by dividing the work into distinct stages. Each stage in the framework accomplishes a particular objective and creates inputs to the next stage. At the same time, users are free to choose the techniques they find the most suitable for each stage, or in some cases to omit or modify a stage if this will simplify and expedite the process.

Chapter 4

Optimal Portfolio Selection

4.1 Introduction

Optimal portfolio selection is a major stage in the framework, which applies the most sophisticated models in the process. An optimization model uses the data that has been produced in the previous stages in order to find the optimal solution. The model addresses most of the important issues that should be considered in project portfolio selection.

As project portfolio selection is usually a multi-objective problem involving optimization of benefits in several categories under certain constraints, one approach to solving this problem is using zero-one multiple criteria decision making (0-1 MCDM) techniques. For example, goal programming can be used when more than one objective is explicitly identified and a clear priority exists among these goals. In goal programming, multidimensional goals are met in a sequential manner, where the goal with highest priority is first achieved, followed by the second highest priority and so on (Santhanam et al, 1989). For a comprehensive review of 0-1 MCDM techniques see Rasmussen (1986).

Since the multiple objectives in project portfolio selection problems are usually conflicting in nature, we employed a "value function approach" to the problem of maximization of benefits in different categories, this allows integrating multiple objectives and reducing them to one objective that will be maximized by the model. It obviates the problems associated with pure multiple-objective optimization, such as difficulty in choosing appropriate functions to represent the objectives and also algorithmic and computational difficulties in solving such problems. See Rasmussen (1986) and Evans (1984) for detailed discussion on difficulties with pure multiple objective problems and Evans and Fairbairn (1989) for discussion on value function approach. This approach allowed the adoption of zero-one integer programming model for formulating and solving the problem. A zero-one model was selected since projects are either selected or not selected.

In the next section we will describe a zero-one integer linear programming (0-1 ILP) model that considers the entire feasible solution space and finds a portfolio that maximizes the overall objectives of the organization, while satisfying constraints such as resource limitations and interdependencies among projects. In our model, we suggest that, when there is more than one objective involved in decision making, the multiple objectives be first integrated by means of a weighted value function, and reduced to one objective that will be maximized by the model. Also, in order to avoid the difficulties associated with non-linear problems, we have assumed the use of a linear additive value function (Evans and Fairbairn, 1989). This permits the use of a 0-1 ILP model.

The model we developed: a) considers multiple, conflicting goals, b) considers qualitative objectives, c) explicitly considers constraints such as resource limitations, project interdependencies, and portfolio balancing, and d) selects and schedules the optimal set of projects that will maximize benefits according to the pre-specified priorities without violating any of the constraints.

Few 0-1 ILP models have been suggested in the literature for project portfolio selection. The models proposed by Evans and Fairbairn (1989) and Kira et al. (1990) address many real issues; more so than other models in the project portfolio selection literature. However, in spite of their advantages, these models have some shortcomings in that they either do not take project starting point into consideration (Evans and Fairbairn, 1989) and implicitly assume that all of the projects start in the first period of the planning horizon, or assume that the amount of resource that is consumed in each period is fixed over time (Kira et al.1990).

If projects are assumed to start in the first period of the planning horizon, incorrect estimates are made of the total amount of resource to be used in each period. This can cause the unnecessary elimination of some projects from the portfolio because of perceived shortages of resources in specific periods, whereas this shortage would not happen in reality when some projects could start in later periods.

The assumption of a fixed rate for resource consumption during the execution period is not a valid assumption either. For example, in some real world cases, such as construction projects, the rate of resource consumption is low in the earlier periods and increases as time passes, finally reaching a peak and declining to zero at the end of the project (for more details see Nicholas, 1990).

The proposed model overcomes the above mentioned shortcomings. It not only suggests a set of projects that should be incorporated in the optimized portfolio, but also determines the period in which each of the selected projects should start. The model also handles the situations in which the amount of consumed resources varies in different periods. The other advantage of the proposed model is that it is not limited to certain pre-defined scheduling or resource consumption alternatives (as is the case with previously mentioned models), and searches the entire solution area in order to find the global optimal solution. In the next section we will discuss the proposed model.

4.2 A 0-1 ILP Model For Project Portfolio Selection & Scheduling

Many integer programming problems can be developed in several ways; formulating a "good" model is of crucial importance to solving the model efficiently. Nemhauser et al. (1989) propose a number of methods to formulate a "good" model. For example, although it is instinctive to believe that computation time increases and computational feasibility decreases as the number of constraints increases, systematic addition of constraints (known as cutting planes) is one of the main algorithmic approaches to improving models (Nemhauser et al., 1989). Also appropriate choice of variables might have major impact on the solution time especially in 0-1 models where addition of only one variable doubles the solution space.

The initial 0-1 ILP model that we developed for project portfolio selection (that was a project portfolio selection problem for ten projects to be selected and scheduled in five periods) had very high run times (more than two hours on a Pentium® 166 MHz with 32 MB of RAM) for solving some instances of the model. Since this run time was much higher than the acceptable run time for our DSS (that was a few minutes) we decided to restructure the model and managed to bring the number of variables down from 120 in the initial version of the model to 60. This structural change of the model had major impact on run times and, along with the other actions that we took, helped us to bring the run time down to our acceptable limit (see Appendix 4 for details). The older version of the model is presented in Ghasemzadeh et al. (1996) and the final version of it is described in the next section. The decision variables, objective function, and constraints of the proposed 0-1 ILP optimization model are as follows:

4.2.1 Decision Variables

The decision variables are defined by:

$$X_{ij} = \begin{cases} 1 & \text{if project i is included in the portfolio and starts in period j} \\ 0 & \text{otherwise} \end{cases}$$

for i = 1,..., N, where N is the total number of projects being considered, and j = 1,..., T, when the planning horizon is divided into T periods.

4.2.2 Objective Function

Project portfolio selection is usually a multi-objective problem in which objectives in several categories should be maximized or minimized. There are two major problems associated with multi-objective problems, which make them difficult to solve. The first is that some of the objectives are qualitative in nature, such as political or environmental objectives, and the second problem is that objectives often conflict with each other. Different techniques are available to help quantify qualitative objectives and to integrate different objectives within one framework. By using these techniques, an overall score can be assigned to each project that reflects its relative contribution. From the many different methods that can be applied to score individual projects, the Analytic Hierarchy Process (AHP) has received wide application in a variety of areas (Golden et al., 1989) and has a voluminous body of literature (Zahedi, 1986). In this method, first qualitative and quantitative criteria for selecting projects are identified and integrated into a hierarchical structure; then pair-wise comparisons among projects are used to weight the criteria. Finally, based on the amount of benefit contribution of each project to each criteria, the AHP score of individual projects is determined. A higher AHP score reflects a higher project utility. Decision makers may also use other techniques, such as weighted factor scoring (Martino, 1995) that seem more objective or more appealing.

Several techniques have been suggested for solving multi-objective zero-one models (Rasmussen, 1986; Evans, 1984). In this research, however, in order to obviate some of the difficulties and problems associated with pure multiple objective optimization, such as goal programming, we apply a "value function approach" to the problem of maximization of objectives in the various categories. We will also assume the use of a linear additive value function in the model. For a detailed discussion of the value function approach see Evans and Fairbairn (1989).

As a result of the above assumptions, the objective function is given by

$$\text{Maximize } Z = \sum_{i=1}^{N}\sum_{j=1}^{T} a_i X_{ij} \qquad (1)$$

where Z is the value function to be maximized, and a_i is the score of project i (for example, the AHP score) calculated in the previous step. If the organization wants to maximize only a single quantitative objective, such as net present value (NPV), there is no need to score the projects. In this case, a_i would be the amount of that criteria say NPV, that is earned by project "i" if it is incorporated in the portfolio.

4.2.3 Constraints

The following set of constraints will guarantee that each project, if selected, will not start twice during the planning horizon.

$$\sum_{j=1}^{T} X_{ij} \leq 1 \qquad \text{for i = 1,...,N} \qquad (2)$$

Appropriate sets of constraints can be established for each limited resource such as finance, work force and machine time. The amount of resource available to carry out a set of projects may vary over time. For example, if the planning horizon is divided into T planning periods, and the maximum allowed cost for all projects during period k should not exceed a certain amount (AF_k), then the set of constraints would be

$$\sum_{i=1}^{N} \sum_{j=1}^{k} C_{i,k+1-j} X_{ij} \leq AF_k \qquad \text{for k = 1,...,T} \qquad (3)$$

where AF_k is the total financing available in period k and $C_{i,k+1-j}$ is the financing required by project i in period k. Note that if project i starts in period j, it is in its $(k-j+1)_{th}$ period in period k, and so will need $C_{i,k+1-j}$ units of financing. This constraint also guarantees that each project, if started, should continue to completion within the planning horizon.

All of the selected projects should finish within the planning horizon. The following set of constraints address this issue.

$$\sum_{j=1}^{T} jX_{ij} + D_i \leq T+1 \qquad \text{for } i=1,\ldots,N \qquad (4)$$

where D_i is the duration of project i (the number of periods it takes to complete project i). Increased or reduced levels of resources may result in a faster or slower rate of project completion. The same project supported at different levels of funding can be represented as a separate project in the objective function and resource constraints (Bell et al., 1967). The coefficient for this separate project will not be the same in the resource constraints, reflecting the change in the level of funding as well as any difference in the efficiency with which the resource is utilized at the new funding level (Jackson, 1983). In such cases, the following constraint must be added to ensure that only one version of the project will be selected

$$\sum_{i \in S_v} \sum_{j=1}^{T} X_{ij} \leq 1 \qquad (5)$$

where S_v is the set that contains different versions of an individual project.

Mandatory projects may exist in the selected portfolio. These are the projects that, based on certain considerations, are to be definitely included in the portfolio. Moreover, at periodic revisions of the portfolio, it is normal for many or all of the ongoing projects to be continued, and therefore must be included in the portfolio. It is important to address the issues of mandatory and ongoing projects in the model because such projects compete with the others for scarce resources and we may want to perform sensitivity analyzes that determine the opportunity cost of including them. The following set of constraints guarantees the inclusion of these types of projects in the selected portfolio.

$$\sum_{j=1}^{T} X_{ij} = 1 \qquad \text{for} \quad i \in S_m \tag{6}$$

where S_m is the set of mandatory projects, and

$$X_{i1} = 1 \qquad \text{for} \quad i \in S_0 \tag{7}$$

where S_o is the set of ongoing projects that should be continued. Constraint 7 guarantees that ongoing projects will not be interrupted.

The following set of constraints could be used to determine the impact of exclusion of certain ongoing projects from the portfolio. This would be useful for sensitivity analysis purposes.

$$\sum_{j=1}^{T} X_{ij} = 0 \qquad \text{for} \quad i \in S_d \tag{8}$$

where S_d is the set of ongoing projects that should be excluded from the portfolio.

Interdependence among projects is another important issue that must be considered. For example, if project B is dependent on project A, then project A must be selected if project B is included in the portfolio. However, project A could be included in the portfolio even if project B is excluded. As an example in the case of information systems projects, the development of an executive support system application (ESS) might be dependent on the development or expansion of certain transaction processing applications (TPS), or implementing a certain data warehousing project. These types of interdependencies among projects can be considered in the model by the following sets of constraints

$$\sum_{j=1}^{T} X_{ij} \geq \sum_{j=1}^{T} X_{lj} \qquad (9)$$

$$\sum_{j=1}^{T} jX_{lj} + (T+1) * (1 - \sum_{j=1}^{T} X_{lj}) - \sum_{j=1}^{T} jX_{ij} \geq D_i \sum_{j=1}^{T} X_{ij} \qquad (10)$$

for $i \in P_l$, where P_l is the set of precursor projects for a particular project l, l = 1,..., L.

Constraint 9 guarantees the selection of its precursor projects, once a project is selected, and constraint 10 guarantees that all of the precursor projects will be finished before the successor project starts.

Mutual exclusiveness is another important type of interdependence that should be addressed. A set of projects is considered to be mutually exclusive if we can only include one of its projects in the portfolio. For example, in the case of development projects for joining two different cities, two mutually exclusive projects could be the construction of a highway or a railroad. Once one of these projects is selected the others should be excluded from the portfolio. If there are P sets of mutually exclusive projects, and S_p is the pth set of such projects, then the set of constraints is given by

$$\sum_{i \in S_p} \sum_{j=1}^{T} X_{ij} \leq 1 \qquad \text{for } p = 1, \dots, P \tag{11}$$

Many other types of constraints can be added to this model, depending on the situation at hand. For example, one could specify required relationships for different types of projects (e.g., the percent of resources that will be used for each category of projects should not exceed a certain amount, or the number of projects in a certain category must be at least twice the number of projects in another category). As another example, management may prefer a portfolio of projects that balances the overall development risk. In many cases, high-risk projects have greater expected benefits if implemented successfully. For instance, a balanced portfolio might include a small investment in high-risk, high benefit (potential) projects as well as more investment in low-risk projects with more modest expected benefits. A mixture of projects with different risks will allow an organization to achieve acceptable results while taking on some risk in large, unstructured, or relatively high technology projects (Davis and Olson, 1985). Simply adding the required set of constraints to the model can do this.

Solving the model we have developed will provide a portfolio of projects that maximizes the total benefit of the portfolio and satisfies all the constraints. Moreover, the model determines the period in which each of the selected projects should begin to satisfy limitations on available resources in each period. Once the model is solved and a certain solution is obtained, we can examine the robustness of the solution to changes in different variables and parameters of the model by performing sensitivity analysis. For example, we can change the predicted resource consumption, the amount of available resources, or perform other adjustments and observe their impacts on the solution. It should be noted that sensitivity analysis is critical for integer linear problems because a very small change in one of the coefficients can cause a relatively large change in the solution. Shadow prices are not applicable in 0-1 ILP models. As an alternative, because of the extreme sensitivity of the optimal solution to the constraint coefficients in integer programming models, the model should be re-solved several times with slight variations in the coefficients each time before attempting to choose an optimal solution for implementation (Anderson et al., 1994).

4.3 Summary

Since optimization is a critical stage in the framework, in this chapter we proposed a 0-1 integer linear programming model that selects an optimal project portfolio, based on the organization's objectives and constraints such as resource limitations and interdependence among projects. The proposed model not only suggests projects that should be incorporated in the optimal portfolio, but it also determines the starting point for each project. Scheduling considerations can have a major impact on the combination of projects that can be incorporated in the portfolio, and may allow the addition of certain projects to the portfolio that might not have been selected otherwise.

Chapter 5

Project Portfolio Selection Through DSS Support

5.1 Introduction

As we can see from the foregoing chapters, in all stages of the portfolio selection process, decision makers and analysts should be able to interact with the system, which provides models and data to support the decision process. Provision for continuous interaction between system and decision makers is important because: a) it is extremely difficult to formulate explicitly in advance all of the preferences of decision makers, b) involvement of decision makers in the solution process indirectly motivates successful implementation of the selected projects, and c) interactive decision making has been accepted as the most appropriate way to obtain the correct preferences of decision makers (Mukherjee, 1994). If this interaction is to be supported by a computer-based system, then there is a need for a sub-system to manage the related techniques/models, another sub-system to support the data needs of the process, and finally a sub-system that acts as an interface between the decision maker and the system. This is illustrated in Figure 5.1, and is a system which is equivalent conceptually to a DSS, or Decision Support System (Turban 1998).

In the following, first we briefly review decision support systems in general. The types of support that a DSS can provide at each stage of the proposed framework will be discussed, followed by a description of the components of a project portfolio selection DSS. In the next chapter, we will discuss a user-friendly prototype DSS that supports portfolio selection and adjustment stages of the proposed framework.

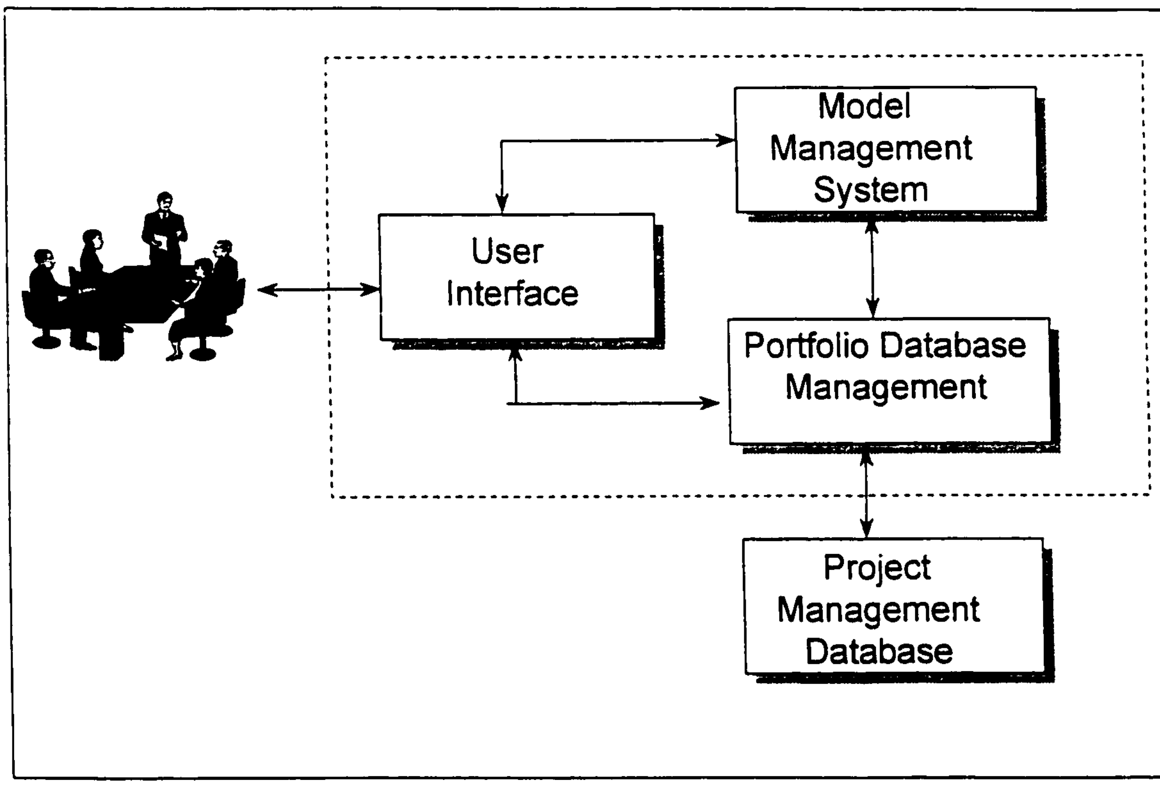

Figure 5.1 Project Portfolio selection DSS

5.2 Decision Support Systems (DSS)

The concepts involved in DSS were first articulated in the early 1970s by Scott-Morton under the term *management decision systems* (Turban, 1998). He defined such a system as "interactive computer-based system, which help decision makers utilize data and models to solve unstructured problems" (Scott-Morton, 1971, Gorry and Scott-Morton, 1971). A refinement of Gorry and Scott-Morton's definition was provided by Little (1970), who defines a DSS as a "model-based set of procedures for processing data and judgement to assist a manager in his decision making". He argues that in order to be successful, such a system must be 1) simple, 2) robust, 3) easy to control, 4) adaptive, 5) complete on important issues, and 6) easy to communicate with (Turban, 1998). Since then many researchers (Moore and Chang, 1980; Bonczek et al., 1980; Keen, 1980; Alter, 1980; Turban, 1988) have presented different definitions of DSS.

The definitions of DSS do not provide a consistent focus and they ignore the central issue in DSS; that is, to support and improve decision making. Turban (1998) provides a more comprehensive definition that basically covers a range from a basic to an ideal DSS. According to Turban "A Decision Support System (DSS) is an interactive, flexible, and adaptable computer-based information system, specially developed for supporting the solution of a non-structured management problem for improved decision making. It utilizes data, it provides an easy-to-use interface, and it allows for the decision maker's own insights. A DSS also utilizes models, is built through an interactive process (frequently by end-users), and supports all the phases of decision making. It may also include a knowledge base".

Clearly then, a DSS must have the capability to manage models, data, and dialog. It may also have an intelligent component to assist decision makers in making decisions in a particular problem situation, or to assist in decisions about which models to use in solving certain problems.

5.2.1 DSS Components

A DSS, as presented in Figure 5.2, is composed of the following subsystems:

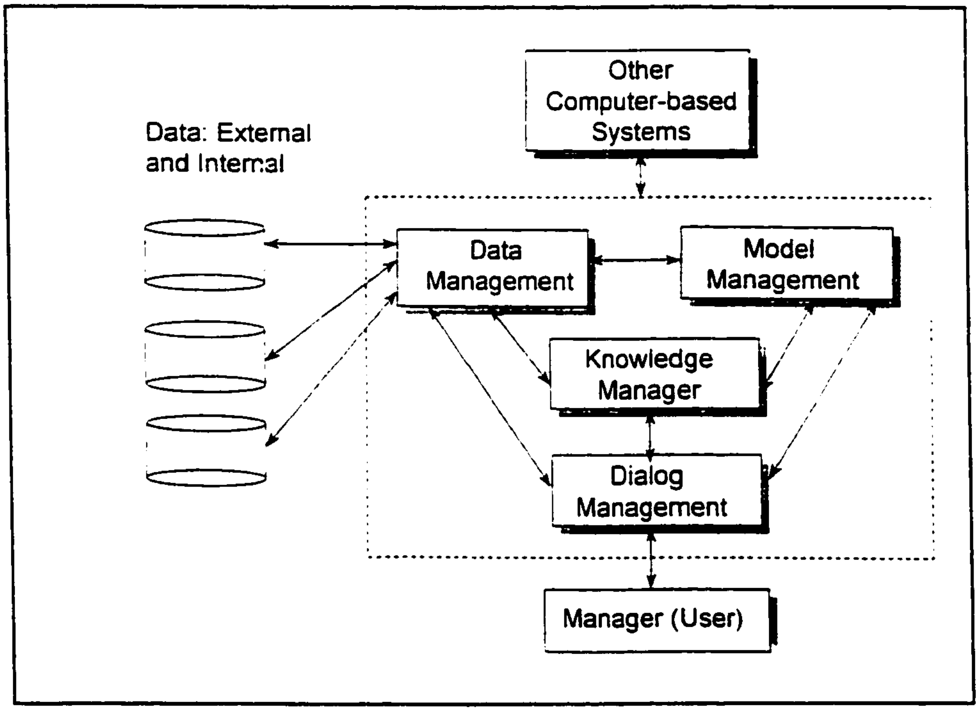

Figure 5.2 Conceptual model of DSS (Adopted from Turban, 1998)

5.2.1.1 Data Management

Data management includes the database(s), which contain relevant data for the situation and is managed by software called a database management system (DBMS).

5.2.1.2 Model Management

A software package that includes financial, statistical, management science or other quantitative models that provides the system's analytical capabilities, and appropriate software management.

5.2.1.3 Communication (Dialog Subsystem)

The user can communicate with and command the DSS through this subsystem. It provides the user interface.

5.2.1.4 Knowledge Management

This optional subsystem can support any of the other subsystems or act as an independent component.

5.2.2 Individual versus Group DSS

Many decision support systems are used to support an individual decision maker, but most major decisions are made collectively. Group Decision Support Systems (GDSS) expand the definition of DSS in that they are DSS, which facilitate the solution of unstructured problems by groups of decision makers. This is accomplished by providing support for the exchange of ideas, opinions, and preferences within groups (Finholt and Sproull 1990), and is clearly a requirement of a portfolio selection DSS. A GDSS may be implemented at one location where it provides computer support for a group of decision makers, or it may involve simultaneous communication among decision makers at different sites.

5.2.3 Institutional versus Ad Hoc DSS

Donovan and Madnick (1977) classify decision support systems as institutional and ad hoc DSS. Ad hoc DSS deal with specific problems that are usually neither anticipated nor recurring. Institutional DSS, on the other hand, deal with decisions of a recurring nature. A Project portfolio selection DSS is a typical example of an institutional decision support system. An institutional DSS may be developed and refined as it evolves over a number of years because the DSS will be used repeatedly to solve identical or similar problems (Turban, 1998).

5.2.4 DSS Usability

A DSS, once built, will not be accepted until it is shown to perform satisfactorily in real application environments. Adelman (1991) discusses several techniques which can be used for validating DSS designs (factorial experiments, case studies, and quasi-experimental designs). Even if a DSS is validated and really can improve the decisions, decision makers are unlikely to use it unless they perceive it as a useful and easy to use tool. Davis (1989) defines *perceived usefulness* as "the degree to which a person believes that using a particular system would enhance his or her performance" and *perceived ease of use* as "the degree to which a person believes that using a particular system would be free of effort". Although certainly not the only variables of interest in explaining user behavior (for other variables, see Cheney, et al., 1986; Davis, et al., 1989; Swanson, 1988) these two variables appear likely to play a central role (Davis, 1989).

5.3 DSS For Project Portfolio Selection

The framework we outlined in the previous chapter can be used for project portfolio selection in an environment which is only partially supported by computerized modeling and databases, since users are given the flexibility of choosing their own techniques or models at each stage. However, the proposed framework can be integrated into a decision support system (DSS) that supports the main stages (shadow outlined boxes of Figure 3.1) in the framework. The types of support that such a DSS can provide at each stage of the process is described in the following.

5.3.1 Types Of Support At Each Stage

5.3.1.1 Methodology Selection

At this pre-process stage, a decision support system can help users to select an appropriate optimization model (such as a 0-1 integer linear programming or goal programming model) that fits their situation. It can also help to formulate the objective function and constraints of the model and to support the input of required parameters and variables.

5.3.1.2 Pre-Screening

At this stage, a decision support system could be used to input the guidelines that have been developed in the strategy development stage, and also to enter the characteristics of the candidate projects. The DSS then can help decision makers to compare the characteristics of candidate projects with the predefined guideline and eliminate projects that do not fit with the organization's strategy.

5.3.1.3 Individual Project Analysis

At this step, a DSS can help the decision maker in selecting and/or developing suitable techniques for measuring the benefits and scoring the projects; it should also provide assistance for inputting of data that is required for evaluating projects. When the models are selected and/or developed and the required data are entered into the system, the DSS would help calculate benefit contributions of each project. If there is more than one benefit involved in decision making, the DSS can be used to calculate a score (such as the AHP score) for each individual project that integrates its quantitative and qualitative benefits. Moreover, the decision support system allows the decision maker to perform sensitivity analysis at this stage. For example, the users can modify the economic characteristics (cost and revenues) of projects, minimum attractive rate of return (MARR), or change their judgments in pair-wise comparisons (when comparative approaches are used) and observe the impact on the results. Recognizing the inherent difficulty of quantifying subjective judgments, this interactive approach could help decision makers in making better estimates.

5.3.1.4 Screening

A DSS can be used to screen out the projects that do not fall into certain thresholds. For example, projects with rate of return below 10% or payback period above ten years could be eliminated. The important advantage of using a DSS for this stage is its sensitivity analysis capability. Since the cut-off points are arbitrary, performing sensitivity analysis at this stage could reduce the chance of eliminating projects that are marginally near the thresholds. DSS can also help to avoid eliminating projects that are near cut-off points themselves but which are predecessors of other projects with high benefits.

5.3.1.5 Optimal Portfolio Selection

At this stage, a DSS can provide decision makers with an optimal solution. It could also allow them to perform sensitivity analysis; for example, they can change certain parameters and see the impact of the changes on the optimality of the solution. Since shadow prices are not applicable in zero-one problems, this feature is very important for project portfolio selection.

5.3.1.6 Portfolio Adjustment

At this stage, a DSS can be applied to display optimal project portfolio on a portfolio matrix, as a pictorial presentation of all of the projects on two dimensions selected by the users. The optimal solution which has been produced by the optimization model, can serve as a starting point for decision makers. The DSS would allow decision makers to apply their judgment to create a balance between the selected projects in terms of the dimensions that are of importance to them, such as risk and time to complete; this can be done by including or excluding certain projects in the portfolio. The DSS also allows the users to observe the impact of any imposed changes on the optimality of the solution. This process of intuitive improvement can continue until the portfolio is perceived as satisfactory by decision makers.

5.3.2 Major Components

The project portfolio selection DSS requires a carefully designed model management module to handle models of the many different types which may be chosen. The DSS also requires a database in which data can be stored and through which data can be interchanged among models and also between users and models. It must also have a user-friendly interface, which hides the complexities of the system and its models from decision makers. On the other hand, analysts wishing to develop or modify models must have easy access to these models. The user interface allows decision makers to interact easily with the system in order to develop appropriate project portfolios. The major components of a decision support system for project portfolio selection were shown in Figure 5.1 and are described in the following.

5.3.2.1 Model Management

A portfolio selection DSS should contain a model management module that handles models of many different types. This module helps decision makers to select or develop the appropriate models that they want to be applied in the project evaluation and portfolio selection stages of the framework. It also allows for integration of models that would be applied in the portfolio selection process.

In the approach that we propose, several types of models would be applied in different stages. Financial models (such as NPV, IRR, and PBP), and scoring models (such as AHP or Q-Sort) would be applied in the project evaluation stage. Optimization models (such as 0-1 ILP or goal programming) would be used in the portfolio selection stage, and finally conceptual models (such as project portfolio matrices) could be used in the portfolio adjustment stage.

The output of the financial models (benefit measures) serves as input to the scoring models. The output of the scoring model (overall score of each project) would be in turn used in the optimization model (if only one benefit is being considered, the output of the financial model. for example NPV, may be fed directly into the optimization model). And finally, the portfolio matrix model can use the output of the optimization model (the optimized portfolio) to present the results graphically to decision makers. Changes may be made by decision maker during the adjustment stage by including or excluding certain projects from the portfolio. Once the changes have been made, feedback could be sent to the optimization model, which re-calculates a new optimized portfolio based on the imposed changes, and the new results can be sent back to the portfolio matrix model again. This iteration continues until the decision maker comes up with satisfactory balanced portfolio.

As we can see, a large number of interactions exist among the models. Since these models are usually supported in separate software modules, the integration of these models can be an extremely difficult task during the development of the appropriate DSS. DSS design should therefore involve considerations of model representation and integration (Dolk and Kottemann, 1993; Geoffrion, 1987; Kottemann and Dolk, 1992; Muhanna and Pick, 1994). Model integration can be viewed from two different aspects: *schema integration*, and *solver integration* (Dolk, 1993; Dolk and Kottemann, 1993).

Schema integration, which is supported by *structured modeling*, *logic modeling*, and *graph grammars*, is useful only when homogenous models from the same paradigm, are to be integrated. In this case the same solver can be applied to the entire integrated model. Integration of local transportation models into a national transportation model is a good example of schema integration. Since the models in our integrated model are not homogenous, schema integration cannot be applied in this case.

Process integration, on the other hand, is useful when heterogeneous models from different paradigms, are to be integrated. Since heterogeneous models (financial, optimization, conceptual and so on) are to be used in the proposed framework, process integration applies in our approach, where inputs and outputs relating to specific models are exchanged through a common database.

The major issues that arise during process integration are *synchronization* and *variable correspondence*. Synchronization deals with the order in which models must be executed, and timing of dynamic interactions among the models. Variable correspondence deals with input/output relationships among the component variables in the various models, and assuring dimensional consistency among these variables.

In the proposed framework, models are not executed in parallel. They typically terminate after transferring their outputs for use by subsequent models, so synchronization in this case is not a critical issue. To handle variable correspondence, a central database can be used, which acts as an intermediary between the models and can make the necessary conversions of the input/output variables to ensure that the integrated model is dimensionally consistent. For example, if financial resources are described in terms of "dollars" in the optimization model and "thousands of dollars" in the portfolio matrix model, the database module could carry out the necessary conversion.

5.3.2.2 Portfolio Database

The project portfolio database is a repository for relevant data collected from other sources for use in the portfolio selection process. Data can either be keyed in directly, generated by models as they are used, or extracted from existing project management databases containing information useful to the analysis of the candidate projects. The project portfolio database contains relevant information about all of the projects being considered. For example, certain data from the organization's project management database(s) would be essential to making decisions about ongoing projects and for estimating parameters (and their uncertainties) and risks to be associated with new projects.

Suggested information includes, for each project, a description and objectives, precursor and follow-up projects, mutually exclusive projects, the time, cost and other critical resources that are necessary to accomplish the project, project parameters such as risk, and so on. The portfolio database can be updated during the portfolio selection process through direct user input, interactions with associated project databases, and from the outputs of models and their components. Portfolio database updates also include relevant data extracted from other databases that relate to ongoing management of existing projects.

In the portfolio database, individual candidate projects can be categorized according to a hierarchy which is organized according to the needs of the organization. For example, in a product development organization, projects could be classified according to whether they involved basic science investigations, engineering research, market need investigations, or modifications to existing products. The reason for this suggested classification is that different research and development teams would likely be involved in these classifications. This classification would allow clustering of projects according to the sub-organization involved, where the data needs would also be similar within each sub-organization.

The portfolio database also serves as an interface between the other components of the integrated portfolio selection system. Each model that is used receives its input from this database and stores its output in it. This allows communication of variable values among different models. Data for information displays are also stored in and retrieved from the database. For this reason, great care must be taken in choosing the type of database used so that information can be transferred to and from it easily. This is enhanced if the database package conforms to the ODBC (Open Database Connectivity) standard, that can provide the necessary support for the variety of modules which may be used with the system. The ODBC standard originated at Microsoft® to provide standardized software drivers in application packages and programming languages that require access to databases. Hundreds of applications and languages currently support the ODBC standard (Sarna & Febish 1995). More details on ODBC are given in Appendix 2.

5.3.2.3 User Interface

As shown in Figure 5.1, the user interface provides a bridge between users and the components of the decision support system (model management system, portfolio database, and processing subsystems). It is used by decision makers to input data and decisions, to retrieve data from related project management databases, and to provide direction and control of the system. It also presents the results of computations to users through a user-friendly interface and allows them to interact with the system to arrive at satisfactory solutions.

5.4 Summary

In this chapter, we introduced decision support systems, their components, and the factors that affect the adoption and use of DSS. We also explained the type of support that a DSS can provide at each stage of the project portfolio selection process. Finally we described the major components of a DSS for project portfolio selection: model management, portfolio database, and user interface, and the major issues related to each component. In the following, we will describe the design and implementation of a prototype DSS that we have developed for project portfolio selection.

Chapter 6

Design And Implementation Of PASS

6.1 Introduction

In this chapter, we will describe a prototype DSS called PASS (Project Analysis and Selection System) that we have developed to support decision makers in the optimal portfolio selection and portfolio adjustment stages of our proposed framework. DSS support of project portfolio selection can be divided into off-line and on-line sessions. Decision analysts are the major players in the off-line sessions. Tasks such as data entry, pre-screening, individual project evaluation and scoring, screening, and optimization model definition can be performed in off-line sessions with or without the direct involvement of decision makers. Decision analysts can use commercially available software for these purposes. For example, an Excel® spreadsheet can be used for individual project evaluation and Expert Choice® for calculating the AHP score of projects. As a future extension of PASS we will include support of the off-line sessions. In the on-line sessions, the most important stages of the framework are performed directly by decision makers. The current version of PASS supports decision makers in on-line sessions.

One of the most important and sophisticated features of any DSS that is intended to support project portfolio selection is to provide a beginning optimal portfolio. Decision makers must then be allowed to make adjustments, based on their experience and intuition, to the solution in order to reach a satisfactory portfolio. Decision makers must also be able to add other previously unselected projects, and drop any of the selected projects. For this adjustment process, the DSS must provide decision makers with data that indicates how sensitive the optimal solution and resource requirements are to changes being made. This helps to avoid adjustments which might unnecessarily degrade the objective achieved during the optimal portfolio selection stage.

In the on-line session, PASS initially applies an optimization model to find an optimal solution, which maximizes the benefit(s) of interest and satisfies any pre-specified limitations such as balancing criteria, resource limitations and interdependence among projects. At the present time NPV and ENPV (Expected NPV) are available, but this can be expanded to a variety of other benefit measures.

Solutions are presented to decision makers on a portfolio matrix display and used as starting points for decision makers to reach satisfactory portfolios through interactions with PASS. A portfolio matrix display style is used since it displays the end product of the selection process, and is more understandable by users. Cooper et al. (1997c) present different types of portfolio matrices that can be used at this stage. PASS also provides decision makers with a Gantt chart that shows project implementation schedule based on the output of the optimization model.

PASS not only supports the intuition of decision makers in the process, but it also eliminates the development of, and direct interaction, with complex models, which are typically developed by decision analysts in advance during off-line sessions. This eliminates a major obstacle that often inhibits managers from using more sophisticated models at the strategic level, and enhances the possibility of system use by higher level managers.

Decision makers, who are active elements in the decision making process, can also use PASS to perform sensitivity analysis in order to examine the robustness of the solution to changes in different variables and parameters. In addition, optimal solutions that are proposed by the system can be modified by adding or dropping different projects to find a more balanced and intuitively satisfactory portfolio. Moreover, PASS allows decision makers to observe the resulting impact of any proposed changes on the optimality of the solution and on the availability of required resources.

During the adjustment stage, PASS prevents decision makers from selecting or de-selecting a project when certain constraints, such as resource limitations or interdependence among projects, are binding the decision maker; the system also provides the user with the necessary feedback in such situations. The final portfolio that decision makers choose, might not be optimal. However, this should not be an important issue as long as decision makers know how far the selected portfolio is from the optimal portfolio initially recommended by the system, and how much of each resource is required if they choose a different portfolio.

6.2 PASS Architecture

The current version of PASS, that supports decision makers in on-line sessions, is made up of four software components. An interface developed with the Delphi®

application development environment provides a user interface through which users can interact with the system. The other two components are commercially available software. Access® provides the database module, which stores data that is keyed in by the user, extracted from other databases, or the results of calculations made by the system's financial, scoring and optimization models. MPL® is used for model definition and it also provides an interface to the solver package Cplex®, that we have selected to handle the 0-1 integer linear model used in PASS. We examined many other competitive products on the market before selecting these software components. We also received trial versions of many of the competing software packages and went through an extensive test and comparison stage before selecting the software packages that were best for PASS. This process is detailed in Appendix 4. Since different pieces of software would interact with each other throughout the process, support of the ODBC standard (see Appendix 3) was a required criterion during the software selection process.

Visual Basic®, ToolBook®, PowerBuilder® and Delphi® were compared for selecting the most appropriate developing environment and Delphi® was selected for the user interface. For the database module, Paradox® and Access® were compared and Access® was selected. For an appropriate optimization model definition software package, we compared AMPLPlus®, MPL®, Lingo®, and XPRESS-MP® and selected MPL®. And finally, for integer linear programming solver packages we compared Cplex©, XA®, XPRESS-MP®, and Lingo®. Since the speed of finding the optimal solution was a major consideration in solver selection, we developed a case example and benchmarked the above solver packages by running case examples in MPS[1] format. After a long period of software adjustment and tuning, Cplex® showed the best results of the solver packages and so it was selected. See Appendix 4 for more details.

Since project evaluation and scoring is performed during the off-line sessions, to provide input for portfolio selection, and also since the optimization model is developed in off-line sessions, we will first discuss the off-line sessions and then the on-line sessions.

6.3 Off-Line Sessions

As depicted in Figure 6.1 in the off-line sessions the decision analyst:

1. Enters the required data into Access® through PASS user interface, selects the appropriate financial model(s) and calculates the required attributes for different projects. Commercial software packages such as Excel® can be used for this purpose, and data can also be imported from other existing databases.
2. Calculates the score for each project based on its quantitative and/or qualitative attributes. Software packages such as spreadsheets can be applied for this purpose. Specialized software packages can be applied as well. For example, Expert Choice® can be used to calculate the relative AHP project scores.
3. Developes or modifies the optimization model, using the MPL® modeling language.

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[1] The MPS format is a de facto standard ASCII medium among most of the commercial LP codes.

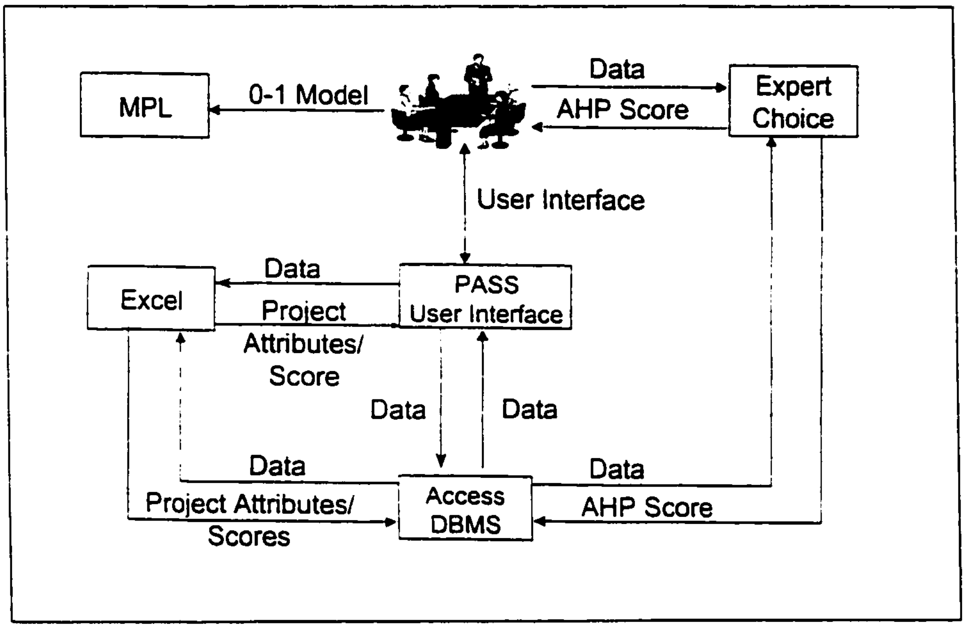

Figure 6.1 Off-line sessions

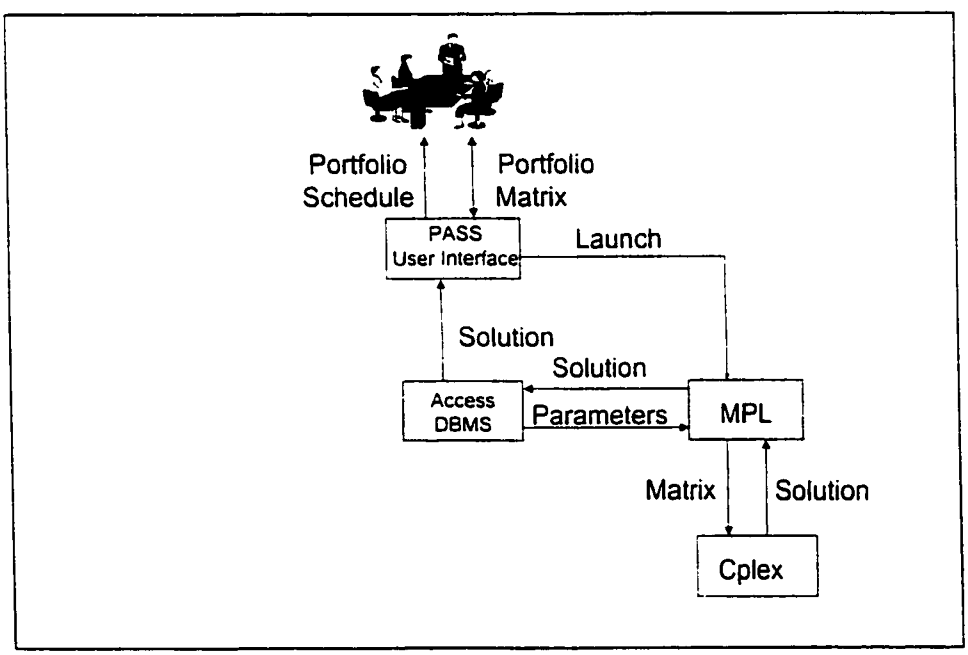

Figure 6.2 On-line sessions

6.4 On-Line Session

Interactions between decision makers and PASS and also among different software packages during the project selection process are depicted in Figure 6.2 and explained below.

1. The decision maker interacts with PASS through its user interface and launches MPL®.
2. MPL® taps into Access® and imports the model's pre-stored parameters to complete the model. Then it creates a standard matrix based on the optimization model and exports it to Cplex® to solve the problem.
3. Cplex® solves the problem, finds the optimal solution, and exports it back to MPL®.
4. MPL® deposits the results into the Access® database.
5. The PASS user interface imports the solution from Access® and presents the optimal results on a portfolio matrix display and the project schedule on a Gantt chart.
6. The decision maker adjusts the portfolio by selecting/de-selecting projects and launches MPL® again. Model parameters that are stored in Access® can also be modified seamlessly through the PASS user interface.
7. Step 2 to 6 can be repeated as often as desired, until the decision maker comes up with a solution which is satisfactory, but not necessarily optimal.

6.5 A Typical PASS Session

On starting the PASS application, the user is presented with the first screen (Figure 6.3). Pressing the Start button will display the main screen of PASS (Figure 6.4).

All of the project information (such as project attributes and resource availability) have already been entered during the off-line sessions and the user can view and edit them by selecting the appropriate option in the View or Edit pull down menu. The user can also change the balancing criteria (Figure 6.5) or Minimum Attractive Rate of Return (Figure 6.6). The user can give a name to the scenario to identify it for future use, and then click the Optimize button to run the model and find the optimal solution. During optimization, PASS launches the optimization software and a box appears that shows the progress of the process (Figure 6.7). A beep announces the end of the optimization process and the box disappears. Now the user can click on the Show button to see the optimal portfolio on a portfolio matrix (Figure 6.8).

The area of each circle is proportional to its benefit calculated in the off-line session. The project's position, in this particular display, on the X-axis represents its Risk Level and its position on the Y-axis shows the Duration (Time to Complete) of the project. Green circles represent selected projects and blank circles with red borders represent other projects. This is consistent with traffic lighting convention and so is intuitive. The selection of colors and boundaries also makes the system usable for color-blind people and understandable on black and white printouts.

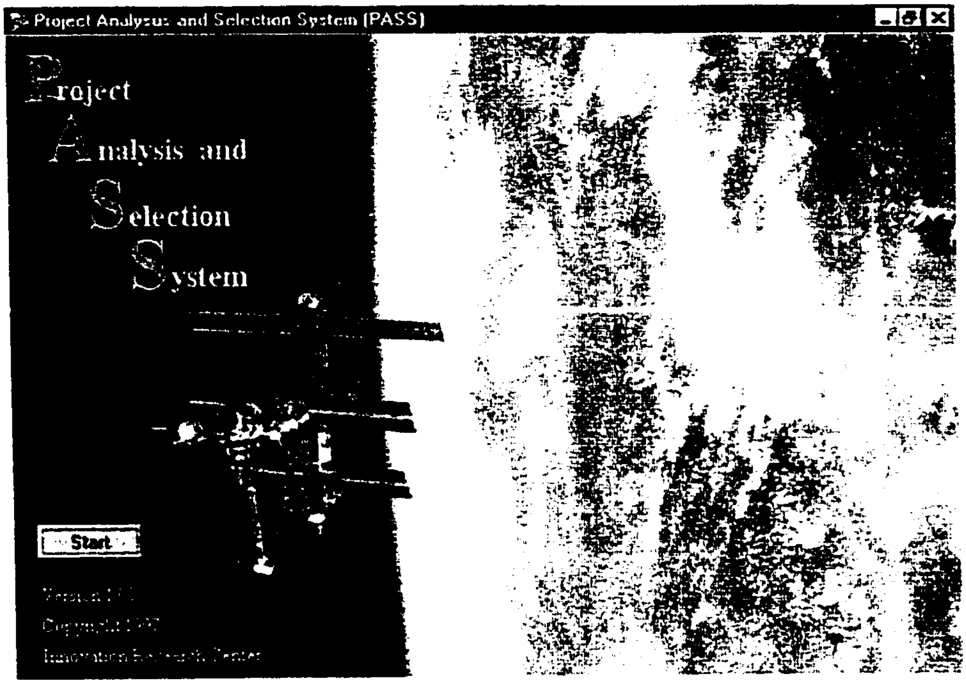

Figure 6.3 PASS first screen

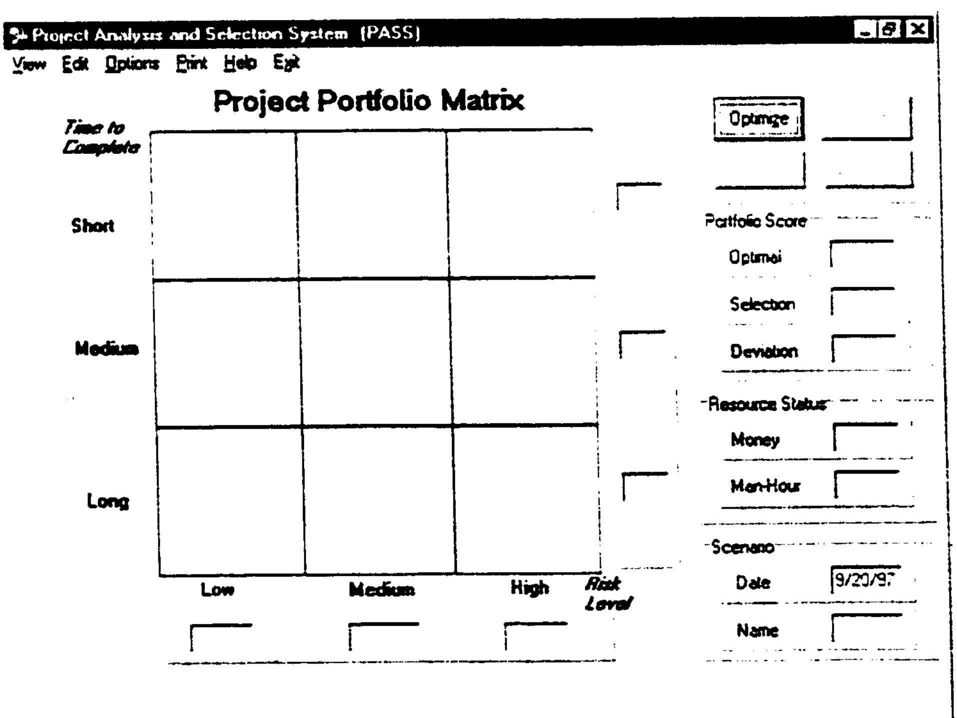

Figure 6.4 PASS main screen

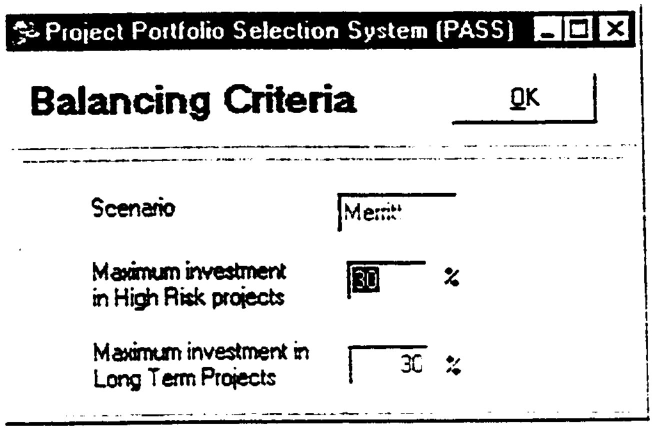

Figure 6.5 Balancing criteria edit panel

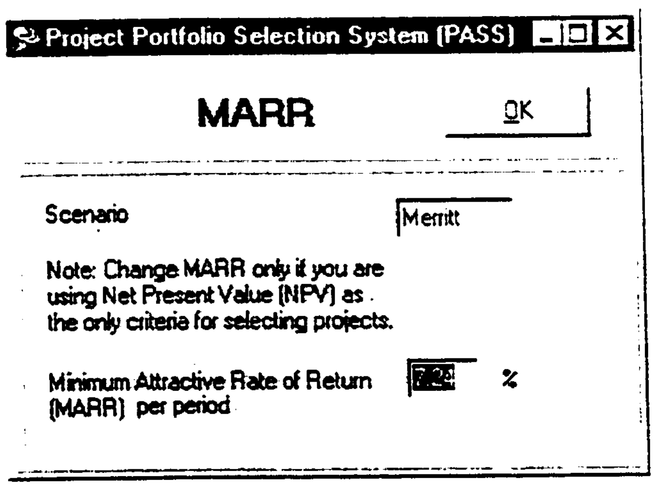

Figure 6.6 MARR edit panel

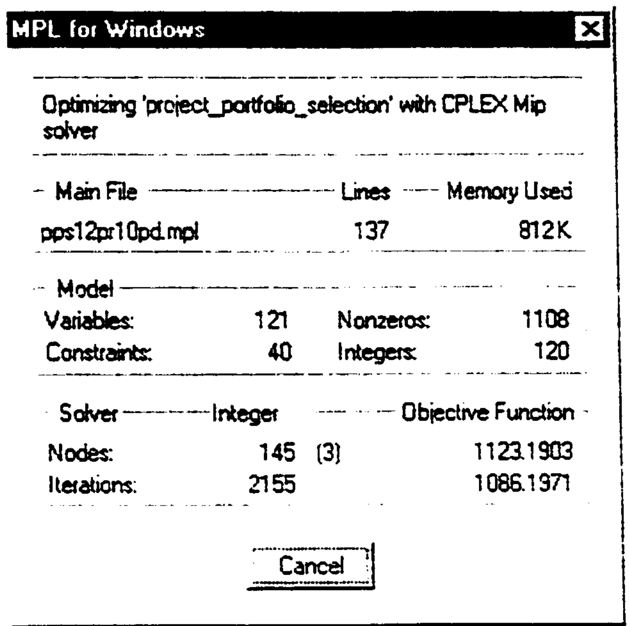

Figure 6.7 Optimization software window

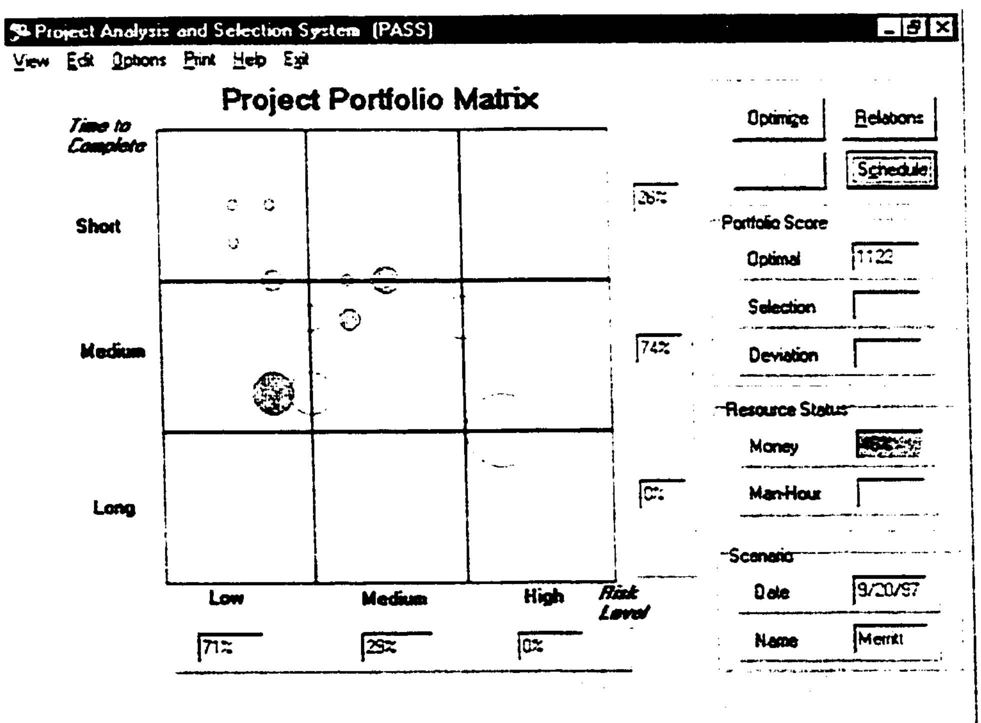

Figure 6.8 Optimal portfolio

More information about each project can be displayed, as a window overlay, by pressing the right mouse button on the relevant circle (Figure 6.9). If the project in focus has predecessor or successor projects the interdependencies will be shown as well on the main display with appropriate arrows.

The user can also see the percent of each resource that would be left if the optimal portfolio were selected. The color of the resource status boxes would be green in this case because no shortage would occur with the optimal portfolio. The percentage of investment in each Risk Level category (Low, Medium, and High) and in each Duration category (Short, Medium, and Long) is also shown. The optimization model not only selects the optimal set of projects but it also schedules them based on periodic resource availability. The user can view the time schedule of the selected portfolio within the planning horizon by clicking on the Schedule button (Figure 6.10). Clicking on the Close button will return the user to the main screen.

The decision maker can use this optimal solution as a starting point and work with PASS towards finding a more satisfactory portfolio. PASS will assist users in this process and will also provide proper feedforward and feedback when necessary. Decision makers can add or drop certain projects by clicking the left mouse button on the projects in the main display. Users can monitor deviations from the optimal result and the changes to resource status on the screen as they select or de-select projects. The more projects the user selects, the more score the portfolio gains. However, resource constraints will not let the users select more projects unless they add the required resources or de-select some of the selected projects.

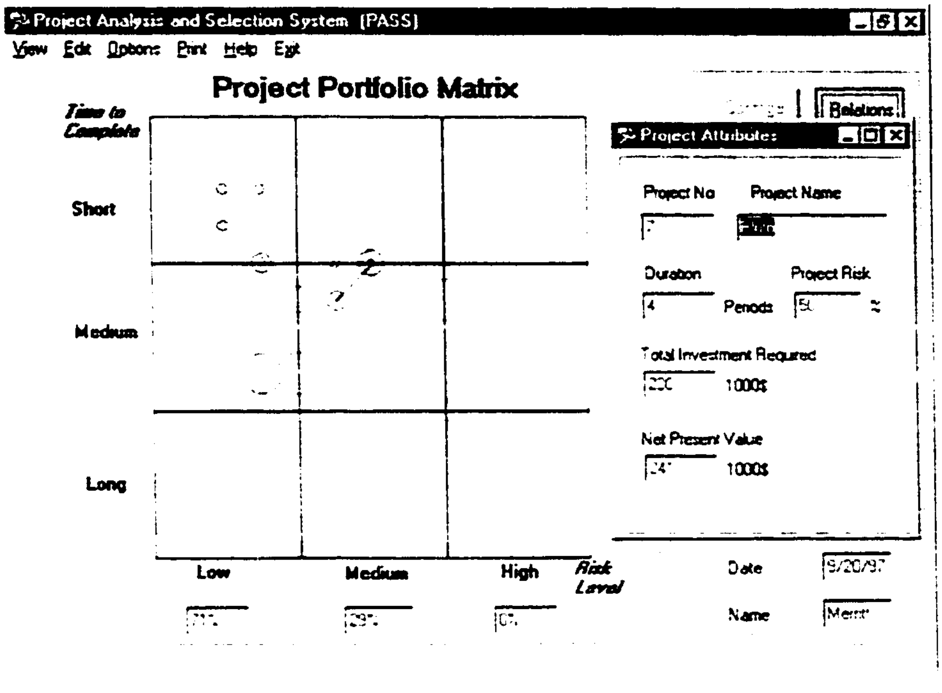

Figure 6.9 Project attributes window

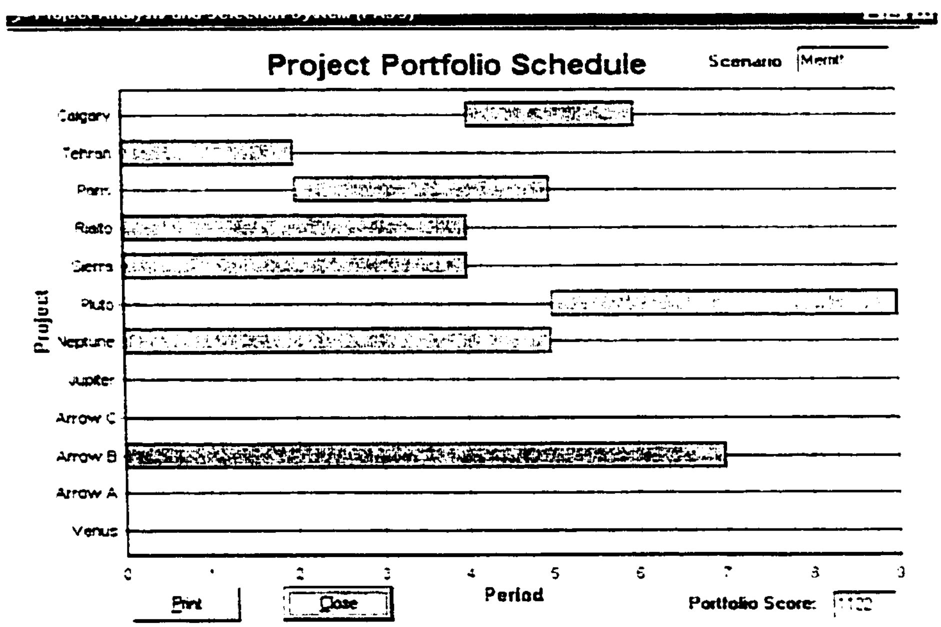

Figure 6.10 Project schedule

A major consideration in selecting or de-selecting a project is its interdependencies with other projects. For example, users cannot select a project with predecessor when its predecessor is not selected: also they cannot de-select a project with a successor when its successor is selected. In such cases PASS will prevent decision makers from making the wrong selection/de-selection and will provide them with the appropriate feedback (Figures 6.11 and 6.12). In order to view all interdependencies among the candidate projects users can click on the Relations Button (Figure 6.13). PASS also prevents selecting a project when its alternative (mutually exclusive project) is selected, and gives an appropriate message (Figure 6.14)

When the user is satisfied with the selected portfolio and there is no resource shortage, a new name can be given to the scenario, and the optimize button pressed. PASS will remind users about the number of projects that they have selected, which will now be treated as mandatory, and included in the optimal portfolio (Figure 6.15). Also, if one of the resources is over-committed with the selected portfolio, PASS will show another message and will not proceed until either the user adds the required resource or de-selects some projects (Figure 6.16).

When the optimization is done the user clicks on the Show button to see the optimal portfolio on the screen. PASS will show a warning message if no optimal solution is found (Figure 6.17). The user can repeat the adjustment process any number of times to reach a more satisfactory solution.

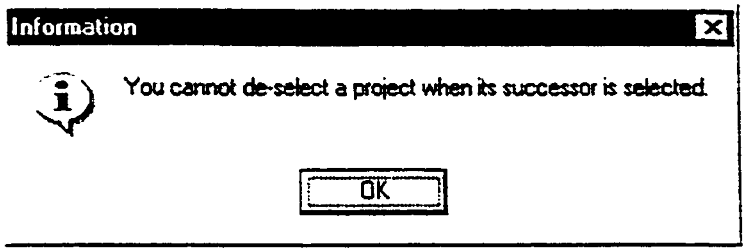

Figure 6.11 De-selection error feedback

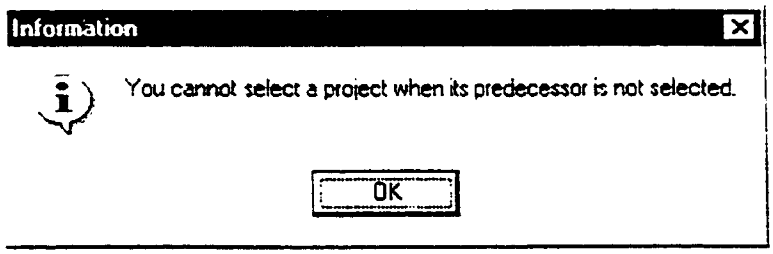

Figure 6.12 Selection error feedback

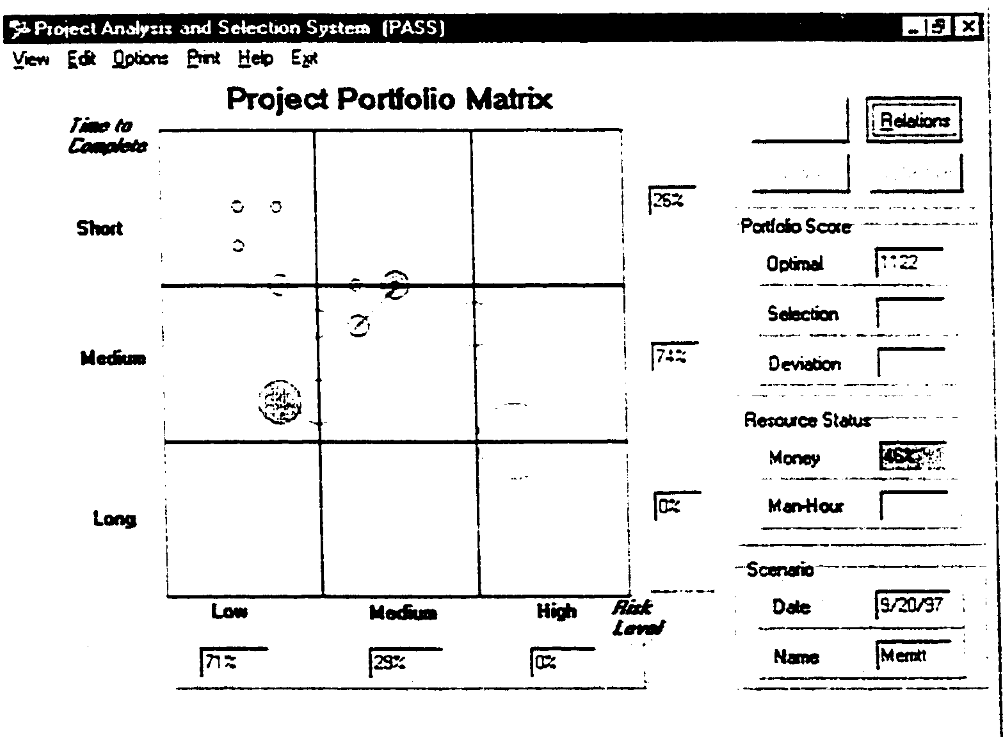

Figure 6.13 Project dependencies

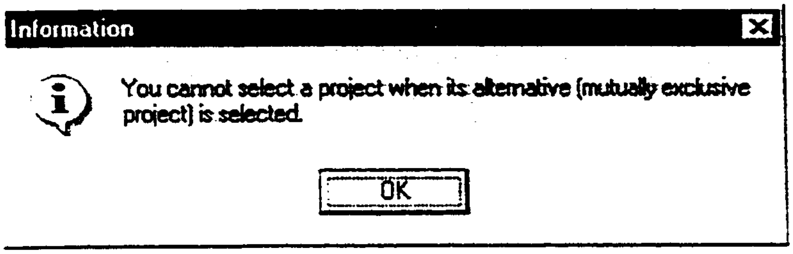

Figure 6.14 Selection error message

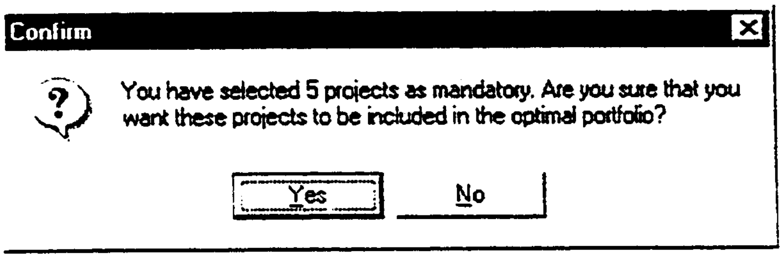

Figure 6.15 Confirmation message

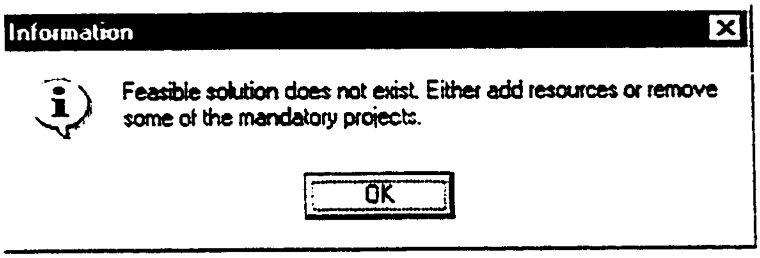

Figure 6.16 Error message

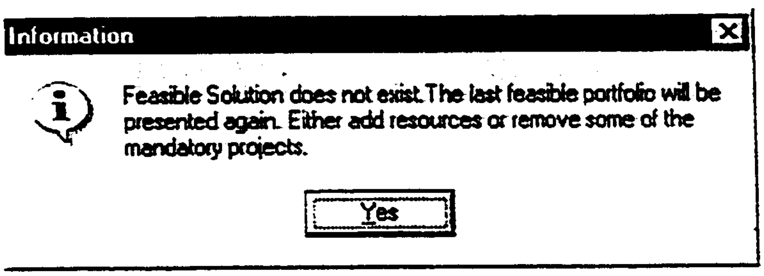

Figure 6.17 Infeasible solution message

It is appropriate to print each scenario and compare the printouts when deciding on the most satisfactory portfolio. If the user presses the Print button all of the required information about the current portfolio will be printed. This includes the portfolio matrix, portfolio schedule, project attributes table, resource allocation table, and resource consumption table. When the user is done with PASS pressing the close button will exit the program.

6.6 Summary

In this chapter we described a prototype decision support system, called Project Analysis and Selection System (PASS), that we have developed to support decision makers throughout the portfolio selection process. PASS is not intended to prescribe a certain portfolio, but rather is intended to find and present an optimal portfolio to decision makers, which they can adjust to obtain a more suitable portfolio based on their intuition, expertise and knowledge. We also described the architecture of PASS and the interactions among its components, and explained a typical PASS session in detail.

Chapter 7

Hypotheses And Experimental Design

7.1 Introduction

When PASS was developed, an important issue was to determine whether the system would be useful, by collecting data on user perceptions of its usefulness and ease of use. A positive perception about usefulness of the system does not necessarily mean that the system helps decision makers in making better decisions. However, if test results show that users do not perceive PASS as a useful tool, even if it really offers better solutions, its perceived usefulness needs to be improved. Users are not likely to use a system unless they perceive it as a useful and easy to use tool (Davis et al., 1989; Moore and Benbasat, 1991). The following hypotheses were developed to test the usefulness of PASS, as well as user perceptions of its usefulness and ease of use.

7.2 Hypotheses

Three hypotheses were investigated in this research. We applied tests of these hypotheses to both small and larger problems. We define small problems as problems with five candidate projects (or less) to be selected over a time horizon of ten periods (or less) and larger problems as problems with more than five projects to be selected and scheduled over at least ten periods. The first hypothesis concerns the improvement of project portfolio decisions when using PASS versus normal manual methods (MM). The second and third hypotheses examine the perceived usefulness and perceived ease of use of PASS. Research suggests that perceived usefulness and perceived ease of use are fundamental determinants of user acceptance (Davis, 1989). Investigation into hypotheses two and three was required because, even if the tests showed significant improvement in solutions obtained using PASS over manual methods, we have only proved that PASS improves project portfolio selection decisions. In optional use situations, which are typical for systems such as PASS, users may avoid using PASS simply because they do not perceive it as a useful and easy to use tool. Even in mandatory use situations or when there is no other alternative but to use PASS (captive situation) perceived usefulness and perceived ease of use can enhance user satisfaction (Adams et al., 1992).

All of the three hypotheses were examined by testing a certain number of sub-hypotheses through analyzing data collected from student subjects during the test on a data sheet (for hypothesis one) or responses to the related questions in a questionnaire (for hypotheses two and three). A sample test data sheet and questionnaire are included in Appendix 1. A detailed explanation of the hypotheses follows.

7.2.1 Hypothesis 1

The use of PASS improves the quality of project portfolio selection decisions.

H_0: PFB ≤ 0.5

H_1: PFB > 0.5

where PFB is the probability of finding a portfolio with PASS which is better than the portfolio found by the manual method (MM).

Related Data: Test Data sheet information (TD-1 to TD-4)

A higher quality decision is defined as selection of a portfolio that: 1) provides more benefits overall, 2) is better balanced, 3) considers all of the different types of interdependencies among projects (selection-dependency[2], time-dependency[3], and mutually exclusiveness), and 4) satisfies resource constraints.

In order to simplify the test cases for the subjects, we assumed the benefit to be net present value (NPV). However, more sophisticated criteria such as analytical hierarchy process (AHP) scores, that combine multiple quantitative and qualitative objectives into one individual score for each project, could be easily handled by PASS. Other criteria such as expected net present value (ENPV), currently available with PASS, could also have been used.

In practical situations, many different resource constraints and project interdependencies might also exist, but again for simplicity we limited the two test cases to a few constraints and only in the larger problem case were interdependencies among projects included.

7.2.2 Hypothesis 2

<u>Users perceive PASS as a useful tool for project portfolio selection.</u>

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[2] e.g., project A is selection-dependent on project B if it cannot be selected unless B is selected.
[3] e.g., project A is time-dependent on project B if it cannot start until B is finished.

This hypothesis deals with the perceived usefulness of PASS and was tested by four sub-hypotheses using responses to the related questions in the questionnaire in Appendix 1. The sub-hypotheses and related questions are described below. A seven point Likert scale was used for measurement in the questionnaire. A score of 4, which has been used in the following sub-hypotheses, indicates the middle point on each scale.

Sub-hypothesis 1 ($H_{2.1}$)

PASS helps to accomplish project portfolio selection more quickly than MM.

H_0: M1 $\leq$ 4

H_1: M1 > 4

where M1 is the estimated median of responses to question 1 in the questionnaire.

Sub-hypothesis 2 ($H_{2.2}$)

PASS improves project portfolio selection decisions.

H_0: M2 $\leq$ 4

H_1: M2 > 4

where M2 is the estimated median of responses to question 2 in the questionnaire.

Sub-hypothesis 3 ($H_{2.3}$)

PASS makes it easier to do project portfolio selection.

H_0: M3 $\leq$ 4

H_1: M3 > 4

where M3 is the estimated median of responses to question 3 in the questionnaire.

Sub-hypothesis 4 ($H_{2.4}$)

Overall, PASS is a useful tool for project portfolio selection.

H_0: M4 $\leq$ 4

H_1: M4 $>$ 4

where M4 is the estimated median of responses to question 4 in the questionnaire.

7.2.3 Hypothesis 3

Users perceive PASS as an easy-to-use tool.

This hypothesis deals with the perceived ease of use of PASS and was tested by six sub-hypotheses using responses to the related questions in the questionnaire in Appendix 1. The sub-hypotheses and related questions are described below:

Sub-hypothesis 1 ($H_{3.1}$)

It was easy to learn PASS.

H_0: M5 $\leq$ 4

H_1: M5 $>$ 4

where M5 is the estimated median of responses to question 5 in the questionnaire.

Sub-hypothesis 2 ($H_{3.2}$)

It was easy to get PASS to do what I wanted to do.

H_0: M6 $\leq$ 4

H_1: M6 > 4

where M6 is the estimated median of responses to question 6 in the questionnaire.

Sub-hypothesis 3 ($H_{3.3}$)

PASS was clear and understandable.

H_0: M7 $\leq$ 4

H_1: M7 > 4

where M7 is the estimated median of responses to question 7 in the questionnaire.

Sub-hypothesis 4 ($H_{3.4}$)

PASS was flexible to interact with.

H_0: M8 $\leq$ 4

H_1: M8 > 4

where M8 is the estimated median of responses to question 8 in the questionnaire.

Sub-hypothesis 5 ($H_{3.5}$)

It would be easy to become skillful at using PASS.

H_0: M9 $\leq$ 4

H_1: M9 > 4

where M9 is the estimated median of responses to question 9 in the questionnaire.

Sub-hypothesis 6 ($H_{3.6}$)

<u>Overall, PASS is easy to use.</u>

H_0: M10 $\leq$ 4

H_1: M10 $>$ 4

where M10 is the estimated median of responses to question 10 in the questionnaire.

7.3 Experimental Design

In order to collect data on the variables of interest during the test, a test data sheet and a questionnaire (Appendix 1) were developed. The test data sheet contained data about the solution that subjects found by using the manual method. The questionnaire contained questions to measure different aspects of user perception of usefulness and ease of use. Davis has developed and validated measurement constructs for perceived usefulness and perceived ease of use (Davis, 1989), and these constructs were validated later by other researchers (Adams et al., 1992). We adapted his questionnaire in our research, with some minor changes. Two items ("increases my productivity" and "enhances my effectiveness") were eliminated because they did not match very well with the decision support application at hand. Also, although it can be argued that flexibility actually reduces ease of use to the extent that it provides users with a great number of decisions to make during interaction with the system (Goodwin, 1987; Silver, 1988) since this item was included in Davis' questionnaire we decided to keep this item. Tables 7.1 and 7.2 compare the questionnaire that we developed to test PASS with the one that was developed and validated by Davis.

The questionnaire contained ten questions (Appendix 1) where user perceptions were measured on a seven point Likert scale in which 1 means "strongly disagree", and 7 means "strongly agree". The participants showed the intensity and direction of their feelings about each item by checking the appropriate box on the scale. The questionnaire also contained open-ended questions to collect participant comments about the system.

Davis Questionnaire	PASS Questionnaire
1. Using CHART-MASTER in my job would enable me to accomplish task more quickly.	1. PASS helps to accomplish project portfolio selection more quickly.
2. Using CHART_MASTER would improve my job performance.	2. PASS improves project portfolio selection decisions.
3. Using CHART_MASTER in my job increases my productivity.	
4. Using CHART_MASTER would enhance my effectiveness on the job.	
5. Using CHART_MASTER would make it easier to do my job.	3. PASS makes it easier to accomplish project portfolio selection.
6. I would find CHART_MASTER useful in my job.	4. Overall, PASS is a useful tool for project portfolio selection.

Table 7.1 Usefulness questions

Davis Questionnaire	PASS Questionnaire
1. Learning to operate CHART_MASTER would be easy for me.	1. It is easy to learn PASS.
2. I would find it easy to get CHART_MASTER do what I want to do.	2. It is easy to get PASS to do what I wanted to do.
3. My interaction with CHART_MASTER would be clear and understandable.	3. PASS is clear and understandable.
4. I would find CHART_MASTER to be flexible to interact with.	4. PASS is flexible to interact with.
5. It would be easy for me to become skillful at using CHART_MASTER.	5. It would be easy for me to become skillful at using PASS.
6. I would find CHART_MASTER easy to use.	6. Overall, PASS is easy to use.

Table 7.2 Ease of Use questions

Two project portfolio selection cases were developed for use in the tests (see appendix 1). The first test case (Acme) represents a small problem in which subject was asked to select a portfolio from a list of 4 candidate projects and schedule them within a 10 period time horizon. The second case (Merritt) represents a larger problem in which the subject was asked to select a portfolio from a list of 12 candidate projects and schedule them within a 10 period time horizon. Since the solution space for project portfolio selection problems is usually huge (2^{40} in the Acme case and 2^{120} in the Merritt case) finding the optimal solution manually can be difficult. As a result, although PASS can easily solve much larger problems, in this experiment we limited the larger problem case to 12 projects, 10 periods, and few constraints to reduce frustration of the subjects when solving the problem. The objective was to have one relatively straightforward portfolio problem (Acme) and one more complex one (Merritt), to compare the time, effort, and quality of manual versus PASS solutions for two quite different problems.

In all cases subjects solved the case manually first, and then solved it with the help of PASS, to avoid biasing the results obtained in the manual part of the test towards the optimal PASS solution. To reduce learning time effects, and also to prepare the subjects for the test, we developed a simple case (ABC) which consisted of three candidate projects that could be selected and scheduled within a 10 period time horizon, with few constraints (Appendix 1). Solving this case with both the manual method and PASS helped the subjects to learn both methods before undertaking their assigned tasks.

Some participants, due to their background or past experience, might have been more familiar with project selection and scheduling problems and the heuristics that could be applied for these kinds of problems than others. To decrease the impact of this potential difference among participants, a sheet was given to each subject which contained some heuristics for manually solving the case (Appendix 1). The use of these heuristics was not mandatory and subjects could use any manual method they found to be useful.

7.4 The Test Procedure

To maintain consistency across the tests the following procedure was followed:

1) The participant read and signed the consent form.
2) The subject quickly browsed through the "PASS Tutorial" (Appendix 1) to become familiar with PASS.
3) The subject read the ABC case (Appendix 1) and solved it manually. A blank Gantt chart, heuristics sheet (Appendix 1), a calculator, spreadsheet software, pencil and eraser were provided for the user. Once the solution was found, the subject was asked to draw the results on a Gantt chart.
4) The subject received the "Instructions for working with PASS" (Appendix 1) and followed the instructions to solve the ABC case with PASS. Subjects could keep working with PASS until they felt they had become sufficiently familiar with it to solve project portfolio selection problems.
5) One of the two cases (Acme or Merritt) was assigned randomly to the subject. They were asked to solve the case manually using the tools that were given to them in Part 3. The subjects who received the Acme case were expected to solve it in about 10 to

20 minutes and those who received the Merritt case, in about 20 to 40 minutes. These timings were not rigidly enforced and participants could keep working on their case as long as they felt comfortable in continuing. Once the final solution was found, subjects were asked to draw their results on a Gantt chart. The data that were recorded in the test data sheet at the end of this stage were:

a) NPV of the solution found, and whether it was optimal (TD-1),

b) whether the balancing criteria were met (TD-2),

c) whether project interdependencies were met (TD-3), and

d) whether the financial constraints were met (TD-4).

6) The subject solved the case with PASS and observed the selected portfolio on the portfolio matrix and the schedule on the Gantt chart.

7) The subjects performed a sensitivity analysis by increasing financial resources by 10%. They also changed the balancing criteria and observed the impact of such changes on the optimal solution. For more details see "Instructions for working with PASS" in Appendix 1.

8) The subjects filled out the questionnaire.

Subjects could ask as many questions as they wanted at any stage during the test, although they were not assisted directly in solving their assigned portfolio problems.

7.5 Summary

In this chapter we explained three hypotheses that were developed to test the usefulness, perceived usefulness and perceived ease of use of PASS. We also described the experiment that was developed to test these hypotheses. The first hypothesis was based on direct measurements, whereas the second and third hypotheses were based on subjects' responses to questions in a questionnaire. Since other researchers have already developed and validated appropriate questionnaires for testing perceived usefulness and perceived ease of use, we adapted their questionnaires in our experiment. We also described the test procedure that was developed to maintain consistency across the tests.

Chapter 8

Experimental Results

8.1 Introduction

A pilot test was conducted with seven students to collect some initial data and to identify and correct potential problems in PASS, the test procedure and questionnaire, and to finalize the hypotheses before embarking on the full-scale test. The pilot test helped us to modify and improve the experimental design and the interface as well as the hypotheses. Due to the small size of the sample in the pilot test, and also since the questionnaire was changed during this test, we did not find significant results on any of the three hypotheses. However, despite the small sample size, the pilot test results were very promising because we found significant results on many of the sub-hypotheses.

A full-scale test was conducted with 26 third and fourth year Commerce undergraduate students. Each student was paid $10 for taking part. One of the cases was given to each subject. The Acme and Merritt cases, were randomly assigned to individual participating students; each case was assigned to 13 subjects. Subjects first solved the case that was assigned to them manually to find a portfolio, from the candidate projects, that maximized the net present value (NPV) of the portfolio while satisfying all of the existing constraints. Information that was required to solve the case such as project characteristics and existing constraints (for example, financial constraints, balancing criteria, and project interdependencies) was provided with the case (Appendix 1). The results of the tests are described below, and subject comments about PASS are presented in Appendix 2.

8.2 Data Consistency Test

The reliability of responses to the questionnaire was evaluated with the Cronbach alpha test (Cronbach, 1951). Reliability assesses the internal consistency of the data; that is, how consistently individuals responded to questions. High Cronbach alphas are usually signs that the measurements are reliable (Straub and Carlson, 1989). The Cronbach alpha was calculated for the data from questionnaire, perceived usefulness and perceived ease of use, using the responses from all 26 subjects. The perceived usefulness Cronbach alpha was 0.67, and for perceived ease of use it was 0.81. Since a reliability score of 0.6 is usually considered acceptable (Nunnally, 1967), the results indicate that the responses to questions that support each of hypotheses 2 and 3 were reliable.

8.3 Data Analysis

The three hypotheses were examined, for small and larger problems respectively by analyzing the data on test data sheets and questionnaire. In order to test each hypothesis, its sub-hypotheses were examined to see how well they supported the main hypothesis.

8.3.1 Hypothesis 1

H_1: The use of PASS improves the quality of project portfolio selection decisions.

Hypothesis 1 was analyzed using quantitative data collected during the test in the test data sheet. Since a yes/no nominal scale was used for measurement, the Binomial test was used.

8.3.1.1 Test Results for the Small Problem

A summary of test results for the manual method is presented in Table 8.1. As this table shows, two subjects found infeasible solutions (the solutions that they found violated at least one of the constraints) and only one subject found the optimal solution. As a result, in 12 out of 13 cases PASS found a better portfolio than the manual method. Figure 8.1 shows the distribution of the feasible solutions found by subjects in comparison with the optimal solution. Five subjects found feasible solutions that were less than 1% below the optimal PASS solution.

The statistical result for Hypothesis 1 for the small problem is presented in Table 8.2. As this table indicates, the Binomial test results showed a highly significant result ($p<0.01$). The null hypothesis was rejected and so we can conclude that for the small problem "The use of PASS improves the quality of project portfolio selection decisions".

8.3.1.2 Test Results for the Larger Problem

A summary of the test results for the manual method is presented in Table 8.3. As this table shows, three subjects found infeasible solutions (their solutions violated at least one of the constraints) and three subjects found the optimal solution. As a result, in 10 out of 13 cases PASS found a better portfolio than the manual method. Figure 8.2 shows the distribution of the feasible solutions found by subjects in comparison with the optimal

Test No.	NPV Found	NPV_{PASS}-NPV_{MM}	Constraint(s) Violated (MM)	PASS Found Better Solution
A1	378	2	N	Y
A2	291	89	N	Y
A3	291	89	N	Y
A4	379	1	N	Y
A5	593	Infeasible	Y	Y
A6	469	Infeasible	Y	Y
A7	379	1	N	Y
A8	380*	0	N	N
A9	376	4	N	Y
A10	361	19	N	Y
A11	280	100	N	Y
A12	374	6	N	Y
A13	373	7	Y	Y
Total (Y)			3	12

Table 8.1 Summary of test results for the small problem (* means optimal)

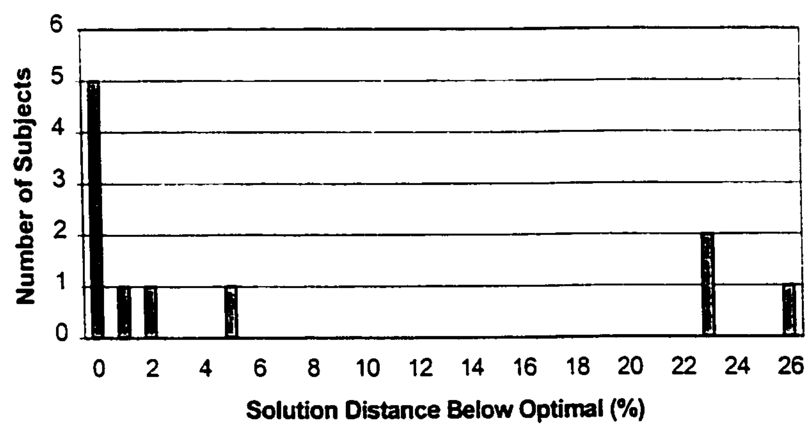


Figure 8.1 Histogram for the manual solutions found in the small problem

Hypothesis	P Value
H_1: The use of PASS improves the quality of project portfolio selection decisions.	0.002

Table 8.2 Statistical analysis of results for Hypothesis 1, for the small problem

Test No.	NPV Found	NPV_{PASS} - NPV_{MM}	Constraint(s) Violated (MM)	PASS Found Better Solution
M1	1048	74	N	Y
M2	1122*	0	N	N
M3	1118	4	N	Y
M4	1094	28	N	Y
M5	1269	Infeasible	Y	Y
M6	978	Infeasible	Y	Y
M7	607	515	N	Y
M8	1113	Infeasible	Y	Y
M9	303	819	N	Y
M10	1122*	0	N	N
M11	1119	3	N	Y
M12	1122*	0	N	N
M13	933	189	N	Y
Total (Y)			3	10

Table 8.3 Summary of test results for the larger problem (* means optimal)

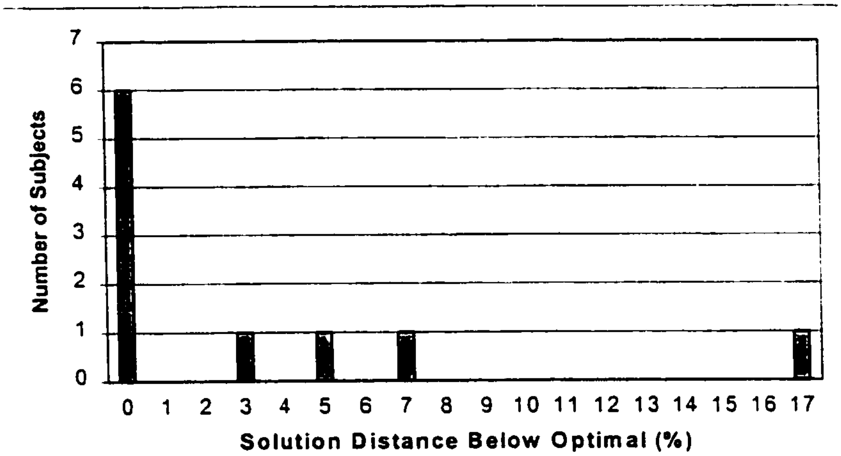


Figure 8.2 Histogram for the manual solutions found in the larger problem

Sub-Hypothesis	P Value
H_1: The use of PASS improves the quality of project portfolio selection decisions.	0.046

Table 8.4 Statistical analysis of results for Hypothesis 1, for the larger problem

solution. Six subjects found feasible solutions that were less than 1% below the optimal PASS solution.

The statistical result for Hypotheses 1 for the larger problem is presented in Table 8.4. As this table indicates, the Binomial test results showed a significant result ($p<0.05$). The null hypothesis was rejected and so we can conclude that for the larger problem "The use of PASS improves the quality of project portfolio selection decisions".

Since solving problems without violating the constraints would seem to be less difficult in smaller problems, we expected more subjects to find an optimal or close to optimal solution in the small problem case. This did not happen, but to obtain an appropriate interpretation of these results would require additional experiments with a spectrum of problem sizes and constraint numbers and values. This was beyond the scope of our study.

The results of our test are limited to the two types of case problems that we developed and so cannot be generalized to all types of project portfolio selection problems with different size and complexities. However, PASS always finds the optimal solution in a very short time. It should be noted that it takes some time to adjust the optimization model (change the constraints and input parameters) to the situation at hand each time that PASS is going to be used. However, as mentioned before, this should be done in off-line sessions by experts, so decision makers do not have to spend time on such activities in the on-line session.

Due to human limitations in handling larger and more sophisticated problems we expect even better support for this hypothesis in real world problems, since they are typically larger and more complex than the simplified example cases developed for this experiment. For example, since both of the cases that we developed for the test (Acme and Merritt) were intentionally simplified to prevent subject frustration at the outset, six students in each of the small and large problem cases were able to find a portfolio that was only 2% below the optimal solution. Although these results are acceptable in practical situations (considering that many of the model parameters, such as NPV, are calculated based on estimates that are uncertain in nature), one should notice that real world problems are not as small and simple as the cases developed for this test. As the number of projects or periods increases the solution space grows exponentially (addition of only one project or one time period doubles the solution space), and addition of real world constraints (such as having more than one limited resources, more than one project interdependency, and so on) makes real problems much more complex. As a result we do not expect as many people to find the optimal or close to optimal portfolios in a real environment as they did in this experiment with the simplified cases.

An additional effect in real world situation is the need to re-calculate solutions each time portfolio adjustments are made, so the impact of adjustments can be estimated. The same issue applies when decision makers want to perform sensitivity analysis to investigate the impact of changes in certain parameters (such as balancing criteria) on the solution and on the availability of resources. Clearly this would be impractical if manual calculations had to be re-done at each iteration, because of the long time delays involved.

8.3.2 Hypothesis 2

H_2: Users perceive PASS as a useful tool for project portfolio selection.

This hypothesis was examined by four sub-hypotheses using the answers to questions 1 t o 4, using the Median test.

8.3.2.1 Test Results for the Small Problem

Figure 8.3 shows the histograms of responses to questions 1 to 4. The results of the statistical analysis are presented in Table 8.5. All of the first three sub-hypotheses had very significant results ($p<0.01$). The null hypotheses for these questions were rejected. As a result, we can conclude that for the small problem "Users perceive PASS as a useful tool for project portfolio selection". As the table shows this conclusion is also strongly supported by the results for sub-hypothesis $H_{2.4}$ that claims "Overall, PASS is a useful tool for project portfolio selection".

8.3.2.2 Test Results for the Larger Problem

Figure 8.4 shows the histograms of responses to questions 1 to 4. The statistical analysis of results for these sub-hypotheses is presented in Table 8.6. All of the first three sub-hypotheses had very significant results ($p<0.01$). The null hypotheses for these questions were rejected. As a result, we can conclude that for the larger problem "Users perceive PASS as a useful tool for project portfolio selection". As the table shows this conclusion is also strongly supported by the results for sub-hypothesis $H_{2.4}$ that claims "Overall, PASS is a useful tool for project portfolio selection".

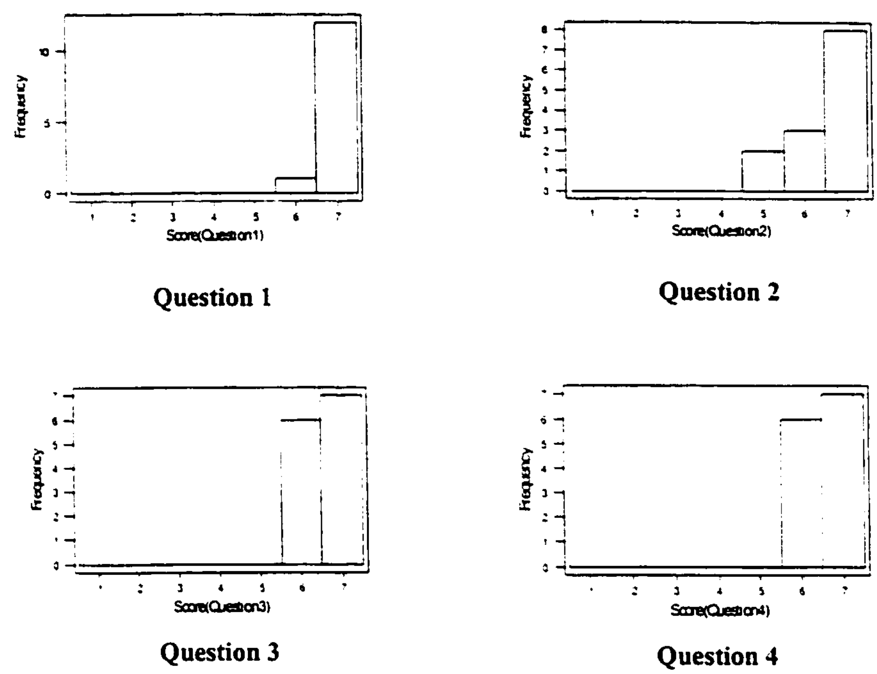
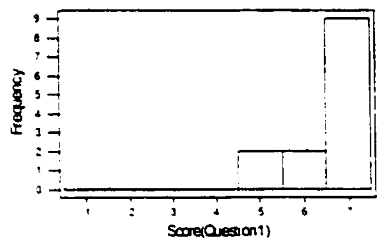


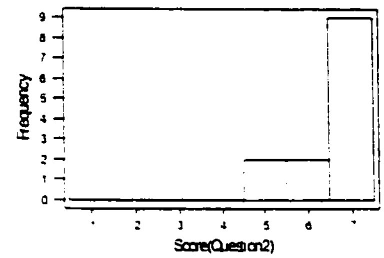
Figure 8.3 Histograms for hypothesis 2 (the small problem)

Sub-Hypotheses	P Value
$H_{2.1}$: PASS helps to accomplish project portfolio selection more quickly	0.000
$H_{2.2}$: PASS improves project portfolio selection decisions	0.000
$H_{2.3}$: PASS makes it easier to do project portfolio selection	0.000
$H_{2.4}$: Overall, PASS is a useful tool for project portfolio selection	0.000

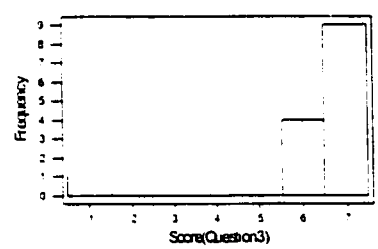
Table 8.5 Statistical analysis of results for sub-hypotheses of hypothesis 2 for the small problem



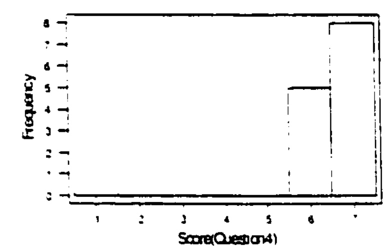
Question 1



Question 2



Question 3



Question 4

Figure 8.4 Histograms for hypothesis 2 (the large problems)

Sub-Hypotheses	P Value
$H_{2.1}$: PASS helps to accomplish project portfolio selection More quickly	0.000
$H_{2.2}$: PASS improves project portfolio selection decisions	0.000
$H_{2.3}$: PASS makes it easier to do project portfolio selection	0.000
$H_{2.4}$: Overall, PASS is a useful tool for project portfolio selection	0.000

Table 8.6 Statistical analysis of results for sub-hypotheses of hypothesis 2 for the larger problem

8.3.3 Hypothesis 3

H_3: Users perceive PASS to be an easy to use tool.

This hypothesis was examined by six sub-hypotheses using the answers to questions 5 to 10, using the Median test.

8.3.3.1 Test Results for the Small Problem

Figure 8.5 shows the histogram of responses to questions 5 to 10 for the small problem. The results of the statistical analysis for these sub-hypotheses are in Table 8.7. All of the first five sub-hypotheses had very significant results ($p<0.01$). The null hypotheses for these questions were rejected. As a result, we can conclude that for the small problem "Users perceive PASS as an easy to use tool for project portfolio selection". As the table shows this conclusion is also highly supported by the results for sub-hypothesis $H_{3.6}$ that claims "Overall, PASS is easy to use".

8.3.3.2 Test Results for the Larger Problem

Figure 8.6 shows the histograms of responses to questions 5 to 10 for the larger problem. The statistical analysis of results for these sub-hypotheses are in Table 8.8. All of the five sub-hypotheses had highly significant results ($p<0.01$). The null hypotheses for these questions were rejected. All of the first five sub-hypotheses had very significant results ($p<0.01$). As a result, we can conclude that for the larger problem "Users perceive PASS as an easy to use tool for project portfolio selection". As the table shows this conclusion is also strongly supported by the results for sub-hypothesis $H_{3.6}$ that claims "Overall, PASS is easy to use".

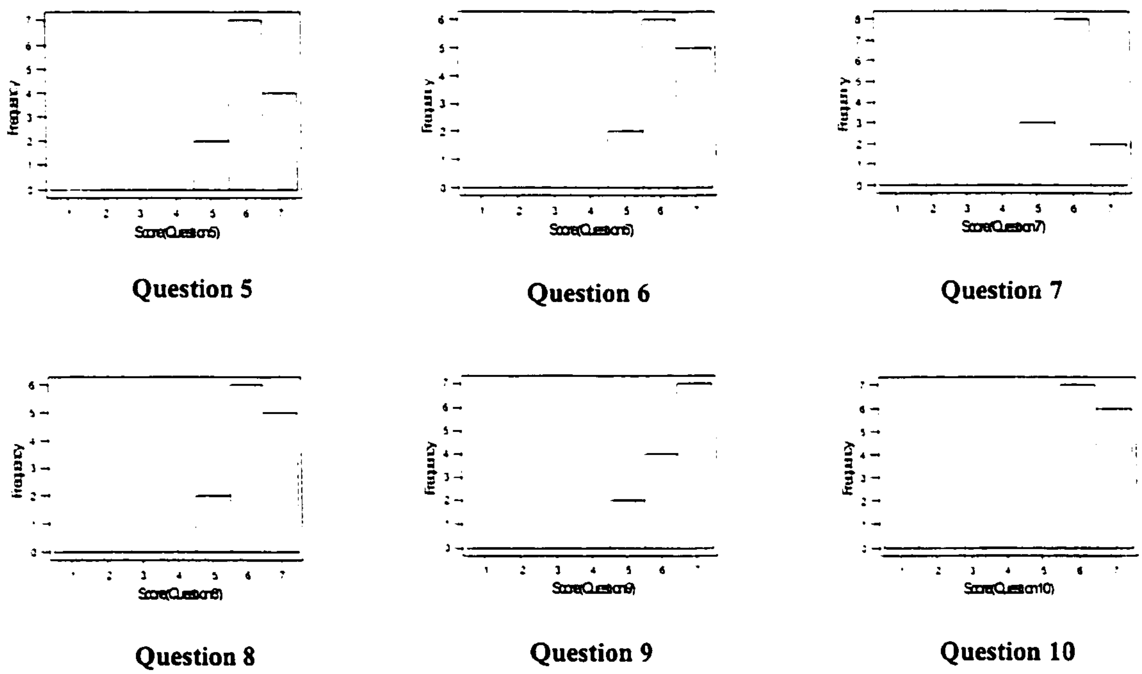
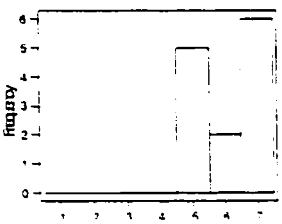


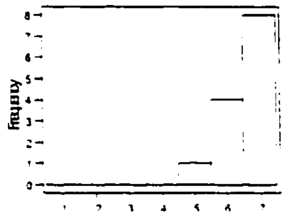
Figure 8.5 Histograms for Hypothesis 3 (the small problem)

Sub-Hypotheses	P Value
$H_{3.1}$: It is easy to learn PASS.	0.000
$H_{3.2}$: It is easy to get PASS to do what I wanted to do.	0.000
$H_{3.3}$: PASS is clear and understandable.	0.000
$H_{3.4}$: PASS is flexible to interact with.	0.000
$H_{3.5}$: It would be easy to become skillful at using PASS.	0.000
$H_{3.6}$: Overall, PASS is easy to use.	0.000

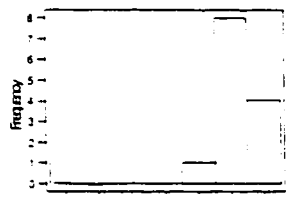
Table 8.7 Statistical analysis of results for sub-hypotheses of hypothesis 3 for the small problem



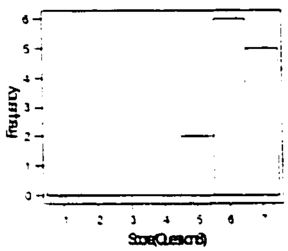
Question 5



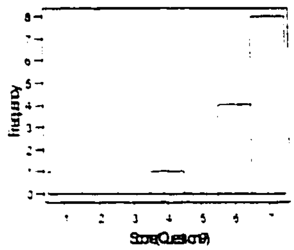
Question 6



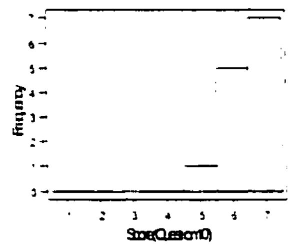
Question 7



Question 8



Question 9



Question 10

Figure 8.6 Histograms tor hypothesis 3 (the larger problem)

Sub-Hypotheses	P Value
$H_{3.1}$: It is easy to learn PASS	0.000
$H_{3.2}$: It is easy to get PASS to do what I wanted to do	0.000
$H_{3.3}$: PASS is clear and understandable	0.000
$H_{3.4}$: PASS is flexible to interact with	0.000
$H_{3.5}$: It would be easy to become skillful at using PASS	0.000
$H_{3.6}$: Overall, PASS is easy to use	0.000

Table 8.8 Statistical analysis of results for sub-hypotheses of hypothesis 3 for the larger problem

8.4 Comments From Subjects

Twenty out of twenty six subjects who participated in the experiment provided us with their comments on the back of the questionnaire. These comments are presented in Appendix 2. Most of the comments show that subjects were enthusiastic about PASS, especially its ease of use. Some of these comments are presented below:

- Very quick and easy compared to manual selection.
- Easy to manipulate and easy to understand.
- Diagrams (matrices/schedules) are very self-explanatory.
- PASS becomes very useful in solving more complicated problems.
- Clear and user-friendly.
- It was very simple and minimized the chance for errors.
- It is extremely easy and efficient to select a project portfolio with PASS.
- Makes performing sensitivity analysis easier and more useful.

Also, some of the respondents provided us with some good ideas, as summarized below, that we will consider in future extension of PASS.

- Add a feature that allows automatically increase or decrease resource availability throughout the planning horizon.
- Add more sophisticated objective functions to PASS.
- Make the messages as short as possible.
- Allow for planning horizons of more than 10 periods.
- Add other dimensions to the portfolio matrix other than risk and time to complete.

- Add the ability to superimpose different scenarios without printing them out.

8.5 Summary

The purpose of this experiment was to test the effectiveness and also the perceived usefulness and perceived ease of use of PASS. We conducted a lab experiment with 26 Commerce students to test three hypotheses that were developed for this purpose. Two different project portfolio selection cases, as samples for small and larger problems, were developed and used in the test. Each case was randomly assigned to 13 subjects. Subjects first solved their cases manually and then with PASS.

The test results were recorded during the test. At the end of the test subjects filled out a questionnaire, which consisted of four questions about their perception of PASS usefulness and six questions about their perception of PASS ease of use. This questionnaire was adapted from a questionnaire that was developed and validated by Davis (1989) for measuring perceived usefulness and perceived ease of use.

The reliability of responses to the questionnaire was evaluated using the Cronbach alpha. The perceived usefulness Cronbach alpha was 0.67, and for perceived ease of use it was 0.81. Since a reliability score of 0.6 is usually considered acceptable, this indicates that the responses to the questions were reliable. The test results, based on the comparison of the solutions found by subjects using a manual method versus PASS, suggest that in both small and larger problems "PASS improves the quality of project portfolio decisions". We define a higher quality decision in project portfolio selection as selecting a portfolio that gains more benefit, is better balanced, and satisfies all of the existing constraints such as project interdependencies and resource limitations.

Although the test results in general suggest that PASS is a useful tool, users will not adopt and use PASS unless they perceive it as a useful and easy to use tool. Our test results strongly supported the hypothesis that "users perceive PASS as a useful tool for project portfolio selection in both small and larger problems". Moreover, the test results strongly supported the hypothesis that "users perceive PASS as an easy to use tool in both small and larger problems". Since perceived usefulness and perceived ease of use are two fundamental determinants of user acceptance these results are very important and show the high potential of using PASS in practical situations.

It should be noted that our test results apply only to the sample problems that were developed for the experiment. In order to generalize the results of our experiment to different types of project portfolio selection problems, one should conduct experiments on a wide variety of problems with different sizes and constraints.

Chapter 9

Feedback From Industry

9.1 Introduction

To examine the potential for applying the proposed framework and the PASS decision support system in practical situations, and also to gain some feedback from industry, we demonstrated PASS for two high tech firms. These companies had heard of our research and had indicated an interest in getting familiar with the framework and with PASS. They wanted to investigate the feasibility of applying the results of our research in their companies.

In these meetings, the managers and analysts in charge of project selection described their existing project selection methods and the major problems that they had to deal with in this process. We presented our portfolio selection framework and demonstrated PASS and its capabilities. The presentation included a demonstration of the 12 project Merritt case and its analysis. In the ensuing discussion, we attempted to determine how our system could help them, and where adaptations were needed to suit it more to their application.

In the following, we will explain the issues that each of these companies raised and then will describe ways in which the framework and PASS could be adapted to address these concerns. Due to the confidentiality of the issues raised in the meetings we will refer to these companies as A and B respectively.

9.2 Company A

The department we met with in Company A was an internal support organization which had about 200 candidate projects. The projects included different categories such as customer-driven and internal projects. These categories have somewhat different objectives but share common resources such as money and workforce. Their current approach is to select projects individually, based on a calculated score. The major problems that they had to deal with and the ways that our approach could address these problems are explained in the following:

1. **Problem:** Large number of projects to be considered.

Solution: Developing a set of guidelines based on the company's strategy (in the form of a checklist) and applying the pre-screening stage of the framework could help to eliminate a number of projects that are not in line with the company's objectives, at the outset. Also, applying the screening stage of the framework by defining certain hurdles for the projects (such as a requirement for a minimum ROR , say 10%, for each project to pass the screening stage) would help to eliminate more projects. Care should be taken in this screening stage, as explained in detail in chapter 3, to avoid elimination of projects which may otherwise be very promising.

2. **Problem:** Since projects share scarce resources, and since a balance is required in terms of some dimensions (such as time to complete and so on), the company requires a method to deal with the problem as a portfolio selection problem, and not simply a project selection problem.

Solution: This is the whole point of developing the framework. Applying the proposed framework would assure that projects are treated as a portfolio and not on an individual basis.

3. **Problem:** There are some mandatory projects, assigned to the company by headquarters, where the department has no choice in the selection. The budget required for these projects is allocated by the head office and so financial constraints are not binding in such projects. However, these projects consume other scarce resources such as work-force, which many other projects need as well.

Solution: Our framework handles mandatory projects and PASS takes their consumption of scarce resources into consideration.

4. **Problem:** The candidate projects belong to more than one category (customer requests, internal projects, and so on) and so they should be evaluated with different sets of criteria. However, the budget assigned to the projects is not split among the different categories. This makes the prioritization process very difficult.

Solution: One possible solution to this problem is the use of AHP for scoring the projects. The use of AHP would allow the company to explicitly identify and weight the criteria and sub-criteria for project selection in a hierarchical structure for the different categories and score the projects accordingly. Then PASS could be used to find a portfolio that maximizes the AHP score of the portfolio and satisfies existing constraints.

5. **Problem:** Financial resources are not the only limitation that is binding. The department has a certain number of experts in different areas who are available only for a certain amount of time in each month (work force limitation). The problem is more

sophisticated in this company because some of these experts can work in more than one area of expertise. This interdependence among scarce resources is a major source of problems for project selection.

Solution: Adding certain constraints to the optimization model can solve this problem. For example, suppose the company has three types of experts as indicated below:

Expertise A: Can only perform job 1

Expertise B: Can only perform job 2

Expertise C: Can perform both jobs 1 and 2

Each of these types of expertise can be considered as a scarce resource in the model. One more constraint should be added to the model which handles resource interdependencies. For example, if the company has only 100 hours per month available from each type of the above-mentioned expertise then the following sets of constraints would address this issue:

1. $\sum_{i=1}^{N}\sum_{j=1}^{k} RA(i,k+1-j) * X_{i,j} \leq 200$ for k=1,...T

2. $\sum_{i=1}^{N}\sum_{j=1}^{k} RB(i,k+1-j) * X_{i,j} \leq 200$ for k=1,...T

3. $\sum_{i=1 i=j=1}^{n}\sum^{k} (RA(i,k+1-j) * X_{i,j} + RB(i) * X_{i,k+1-j}) \leq 300$ for k=1,...T

where RA(i,k+1-j), RB(i,k+1-j) are respectively the amount of expertise A and B, required by project i in period k, N is the total number of projects being considered, and T is the last period in the planning horizon. $X_{i,j}$, that is the decision variable, is 1 if project i is selected to start in period j and is 0 otherwise. For more details see section 4.2.

9.3 Company B

This company has two departments that select project portfolios: new product research and development portfolios respectively. Each department may have about twelve projects underway at any time. The major problems that they have to deal with, and the ways that our approach could address these problems, are explained in the following:

1. **Problem:** The company wishes to balance the portfolio in terms of the two categories of projects that are included in the portfolio.

Solution: Adding a constraint (similar to the ones that are already included in the model to handle portfolio balance in terms of risk and duration) would assure that the required balance exists in the proposed portfolio. Some changes in the PASS interface are required as well, to enable users to view the projects on an appropriate portfolio matrix that includes project categories. If decision makers want to view the balance status of the portfolio on more than two dimensions, appropriate portfolio matrix displays that cater to the needs of the company can be developed and added to the PASS user interface.

2. **Problem:** Mandatory projects and ongoing projects must be selected in the portfolio, and ongoing projects should start at period zero.

Solution: The current version of PASS handles mandatory projects. As for ongoing projects, adding the following constraint to the optimization model in PASS would assure that such projects would not be interrupted.

$$\sum_{j=1}^{T} X_{i1} = 1 \qquad \text{for} \quad i \in S_0$$

where S_o is the set of ongoing projects and T is the last period in the planning horizon. A modification is also needed in the PASS interface to support this change by identifying both mandatory and ongoing projects.

3. Problem: Delivery time is a major consideration in scheduling the selected projects and the company may want to establish completion dates for certain projects.

Solution: Adding the following set of constraints to the optimization model would assure that such projects, if selected, would be scheduled for completion before the due date.

$$\sum_{j=1}^{L_i} jX_{ij} + D_i \leq L_i + 1 \qquad \text{for } i \in S_f$$

where S_f is the set of projects that should be finished before a certain time (L_i), and D_i is the duration of project i. $X_{i,j}$, that is the decision variable, is 1 if project i is selected to start in period j and is 0 otherwise.

9.4 Miscellaneous Suggestions

In addition to the above-mentioned problems, some interesting comments and issues were raised in the meeting with company B that are explained in the following:

a) Since Company B does not have a large number of projects in either portfolio, they think that even the portfolio matrix part of PASS, without applying the optimization model, would be a very useful tool for them in the initial stages of project portfolio selection. For example, they believe that the marketing manager in the initial stages of the selection process could use the PASS portfolio matrix display, without running the optimization model, to see the impact of selection/deselecting projects on the objective function, balancing, and resource availability. This may help in developing a preliminary suggestion for a suitable portfolio.

b) Company B requires three major different types of expertise to accomplish its projects. Although workforce is not a scarce resource in company B (because of the possibility of outsourcing) they believe that they can use their existing workforce resources more efficiently by considering the existing workforces as scarce resources and using PASS for selecting the portfolio. The portfolio suggested by PASS is not necessarily the final solution and in most cases would serve as starting point toward finding a more appropriate portfolio. That is, sensitivity analysis would assist in determining when and how much outsourcing was required.

c) The following modifications were suggested by company B to improve the PASS interface:

c.1- Replace period numbers with year, month, quarter, etc. as a selectable option in the Gantt display schedule.

c.2- Identify mandatory and ongoing projects on the matrix display.

c.3- Add an option that would leave the inter-project relation arrows displayed. This could make the selection/deselection process easier for decision makers.

c.4- Show the names of more than one project in the display at one time. This could help decision makers to do the selection/deselection process more conveniently.

c.5- Show special projects such as mandatory projects with different icons, and add a legend to the screen to explain each icon.

9.5 Summary

In order to examine the potential for applying the proposed framework and PASS in practical situations we held separate meetings with two high-tech companies who wanted to investigate the feasibility of applying our framework and PASS for project portfolio selection in their companies. In these meetings we presented our portfolio selection framework and demonstrated PASS and its capabilities. Company officials raised their major concerns in project portfolio selection process and we explained the way our approach would address those issues. These meetings were very useful and promising in assisting us in future extensions to PASS. Company officials were very supportive and enthusiastic about using the proposed framework and PASS.

Chapter 10

Conclusions And Future Research

In this chapter we will summarize the dissertation and point out the contributions of this thesis. Then we will suggest some additional research that can improve and extend our work.

10.1 Conclusions

In this thesis, we proposed a framework for project portfolio selection. The proposed framework combines methods that are well grounded in theory and those that are easy to understand and applies them in a logical order. It also allows a choice of techniques to decision makers. The proposed framework addresses all of the major difficulties associated with project portfolio selection that we discussed in the first chapter. The *Pre-Screening* and *Screening* stages help to reduce the number of candidate projects to a more manageable size. The *Individual Project Analysis* stage helps to address multiple and qualitative objectives. The *Optimization* stage handles resource and resource flow limitations, project interdependencies, mutually exclusive projects, mandatory and on-going projects, portfolio balancing, and portfolio scheduling. This stage becomes more important as the size and complexity of problem increases. As we explained before, due to human limitations it is impossible, in real world problems that are large and more complex, to search through the whole solution space in order to find the best solution. Although optimization models that will be applied in this stage are the only available method (with sound theoretical support), to address most important project portfolio selection issues, there are some factors, such as the decision maker's intuition and experience, that cannot be appropriately represented by such models. Moreover, these models are not flexible and there are uncertainties associated with the data that they use. In order to address such limitations, the proposed framework includes a *Portfolio Adjustment* stage which allows decision makers to apply their intuition and experience to the solution proposed by the optimization model, through a friendly interface, to find a more satisfactory solution. To deal with uncertainty in the input data, decision makers can perform sensitivity analysis at this stage to investigate robustness of the solution by observing the impact of parameter changes on the proposed portfolio.

Since our approach is not intended to prescribe a certain portfolio, but rather to support decision makers in finding a more satisfactory portfolio, based on their expertise and knowledge, we developed a decision support system, PASS, to support decision makers during the portfolio selection process. PASS initially provides decision makers with an optimized portfolio that maximizes the score to be realized from a portfolio, while recognizing limits on available resources and interdependencies among projects. Then it allows decision makers to interact with the system and perform sensitivity analysis, by changing certain parameters and variables to examine the robustness of the solution. PASS also allows decision makers to adjust the optimal solution based on their experience and knowledge by selecting or deselecting certain projects, and observing the impact of changes on the optimality of the solution and availability of the required resources. The adjustment process continues until decision makers come up with a portfolio they believe is more satisfactory.

We examined the impact of the proposed approach on the quality of portfolio selection in a lab setting. Before embarking on a full-scale test, we conducted a pilot test on seven Ph.D. candidates. This pilot test helped us to improve the experimental design and tools as well as the hypotheses. Due to the small sample size in the pilot test, and also since the questionnaire was changed during the test, we did not get significant results on any of the three hypotheses. We expected significant results for all of the three hypotheses in the full-scale test.

The full-scale test was conducted with 26 undergraduate Commerce students. The test results suggest that in both small and larger problem PASS improves the quality of project portfolio selection decisions. The test results also strongly indicate that in both small and larger problem users perceive PASS as a "useful" and "easy to use" tool for project portfolio selection. Since perceived usefulness and perceived ease of use are two fundamental determinants of user acceptance these results are very important and show the high potential of using PASS in practical situations. We also presented PASS to two high-tech firms who wanted to investigate the feasibility of applying it in their project portfolio selection process. The company officials found PASS a very useful tool and provided us with some useful comments.

10.2 Research Contributions

The major contributions of this research are:

10.2.1 Project Portfolio Selection Framework

A framework was proposed for project portfolio selection that takes advantage of the best characteristics of existing methods and provides a process which is simplified, flexible, and adaptable.

10.2.2 Optimal Portfolio Selection Model

A 0-1 integer linear programming model that addresses most of the important issues in optimal project portfolio selection. The proposed model not only selects an optimal portfolio but it also schedules projects based on available resources in each individual period. The model also handles time-dependent availability and consumption of resources, which frequently occurs in real world applications.

10.2.3. Prototype DSS (PASS)

A prototype of a useful and easy to use decision support system, called PASS, was designed and developed that supports decision makers in the portfolio selection process. PASS usefulness, perceived usefulness and perceived ease of use were supported by a lab test that we conducted on student subjects.

10.3 Future Research

In the following, we introduce additional research than can extend our work.

1. Since the techniques that can be used to evaluate individual projects and to select a project portfolio depends on the type of projects at hand and the characteristics of the organization, research is required to find the most appropriate techniques that can be applied in each situation.
2. Determining which modeling techniques are preferred by decision makers, and how to simplify some of the more useful techniques to make them more acceptable is another related topic for research.
3. Determining the features and components of the framework and PASS that contribute to the enhancement of decision quality is of great interest. For example, one could eliminate the screening stage from the process and examine the impact of the imposed change on output quality.
4. The optimal solution recommended by the zero-one ILP model, though very useful, should be treated with caution because the input variable and parameter values are difficult to estimate. The total score of a portfolio is also not necessarily the sum of individual project scores, as some interactions might exist between different projects that could make linear assumption unrealistic. Research is required to investigate the impact of our assumptions of linear objective functions and linear additive value functions (Evans and Fairbairn, 1989).
5. Improvement in the accuracy of input data, such as cost estimates, for the model is a very important area for development. New methodologies must be developed for

more accurate estimation (Evans and Fairbairn, 1989). Examining the impact of the accuracy of input data on the solution is another related topic for further research.

6. The consequences of projects are not certain and there are different risks, such as technological and marketing risks, associated with each project (for more discussion on uncertainty and risk see McFarlan, 1981; Riggs et al., 1994; Hottenstein and Dean, 1991; and Rousel et al., 1991). The approach that is presented in this paper takes uncertainty and risk into consideration during the scoring and balancing steps but it assumes that the levels of these factors for each project are already determined. However, measurement of risk is a challenging task and research is required to find suitable methods for evaluating project risks.
7. Depending on the type of application at hand and decision maker preferences about the items that should be balanced in the selected portfolio, different types of portfolio matrix displays can be provided. The DSS should help decision makers to select or develop a matrix that matches their needs. Research is also required to find the most appropriate portfolio matrices to use in the adjustment stage of the process.
8. Decision makers, interact with the system through a graphical user interface (GUI), so determining the most suitable methods for displaying system output results as well as major project characteristics is an important issue. User friendliness of the interfaces is a major concern in the development of a DSS. However, there are other important issues that should be taken into consideration as well. These issues may at times conflict with the user friendliness of the system. For example, although the use of circles to represent certain aspects of a project, such as its score, seems to be very

suitable, some researchers contend that circles cause decision makers to overvalue or undervalue the amounts that are represented (Cleveland and McGill, 1984). They suggest that the use of framed rectangles, instead of circles, is more suitable and can result in a more accurate judgment of the magnitude of the aspect that is being represented (Baird, 1970; Baird and Noma, 1978). Research should be conducted to examine this issue.

9. In many situations, a group of decision makers makes portfolio selection decisions. Since people may often disagree on creation items (for example, they might give different weights to a certain criteria), the question that quickly arises is how to resolve the conflict. The DSS should provide support for reaching a consensus within the group. Research is required into extending the concept we have developed into a group decision support system (GDSS).

10. The suggested approach is intended to enhance the quality of project portfolio selection decisions in practical situations. Research is required to examine the effect of the proposed approach on the quality of decisions that are made by decision makers in real environments.

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Appendix 1

Test Material

PASS Questionnaire - Usefulness and Ease of Use

Test No: Subject: Case: Acme [ ] Merritt [ ] Date:

For each of the following, rate PASS on the degree to which it best answers the following statements:

	Strongly Disagree 1	2	3	4	5	6	Strongly Agree 7
1. PASS helps to accomplish project portfolio selection more quickly	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
2. PASS improves project portfolio selection decisions	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
3. PASS makes it easier to accomplish project portfolio selection	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
4. Overall, PASS is a useful tool for project portfolio selection	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
5. It is easy to learn PASS	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
6. It is easy to get PASS to do what I wanted to do	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
7. PASS is clear and understandable	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
8. PASS is flexible to interact with.	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
9. It would be easy for me to become skillful at using PASS	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
10. Overall, PASS is easy to use	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

Please write your comments about PASS on the back of this questionnaire:

Test Datasheet

Test No: **Subject:** **Case: Acme ☐ Merritt ☐** **Date:**

Manual Method

1. Net Present Value (NPV) of the solution found:

   Was it optimal? Yes ☐ No ☐

2. Were the balancing criteria met? Yes ☐ No ☐

   If no, which one was not met?

3. Were all of the project interdependencies constraints met? Yes ☐ No ☐

   If no, which one was not met?

4. Was the financial constraint met? Yes ☐ No ☐

Comments:

Test Timetable

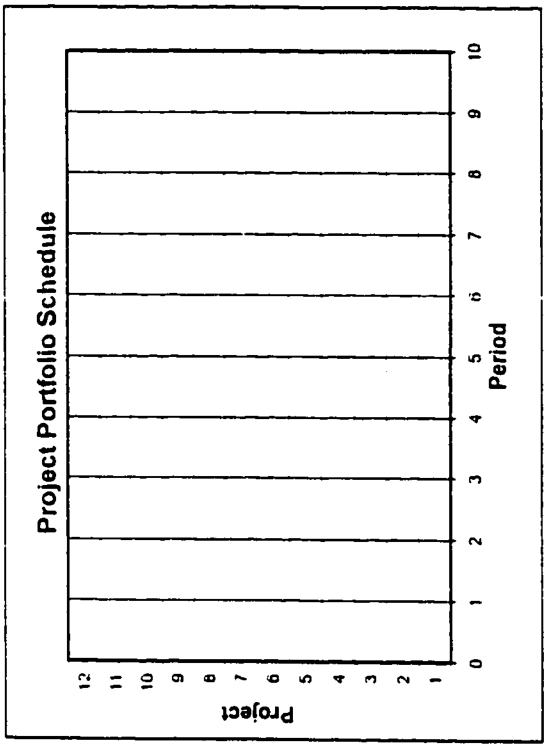
Subject: **Case:** **Acme** ☐ **Merritt** ☐ **Test No:** **Date:**

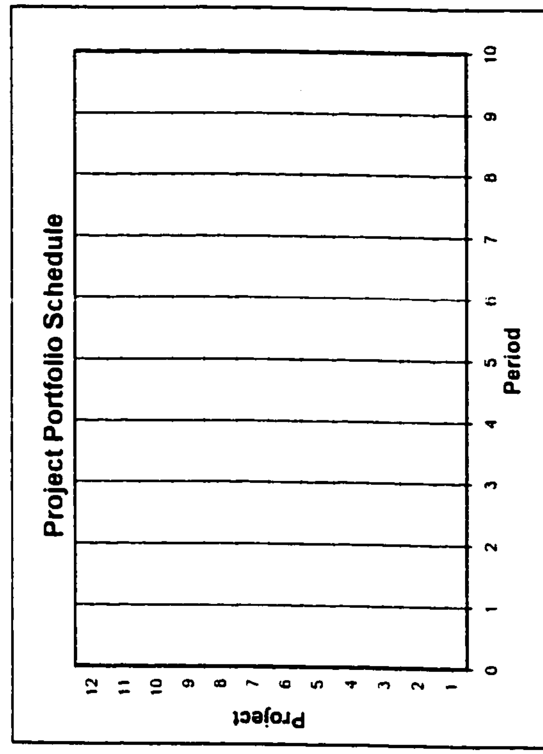
ACME Case:

Description	*Planned Time*	*Start*	*End*	*Actual Time*
Introduction	10			
Exercise with ABC Case (manual)	10			
Exercise with ABC Case (with PASS)	10			
ACME Case (manual)	10-20			
ACME Case (with PASS)	10			
Questionnaires	10			
Total	60-70			

Merritt Case:

Description	*Planned Time*	*Start*	*End*	*Actual Time*
Introduction	10			
Exercise with ABC Case (manual)	10			
Exercise with ABC Case (with PASS)	10			
Merritt Case (manual)	20-40			
Merritt Case (with PASS)	10			
Questionnaires	10			
Total	70-90			


Project Portfolio Schedule
Project
1 2 3 4 5 6 7 8 9 10 11 12
Period
0 1 2 3 4 5 6 7 8 9 10


Project Portfolio Schedule
Project
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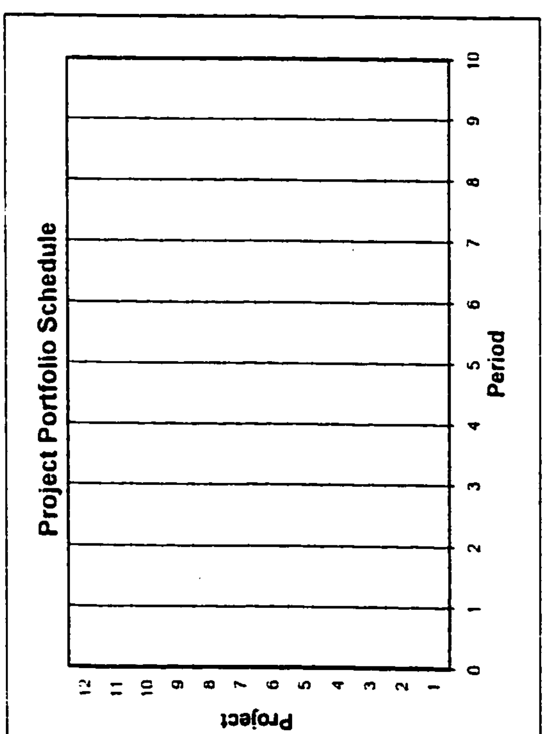
Period
0 1 2 3 4 5 6 7 8 9 10


Project Portfolio Schedule
Project
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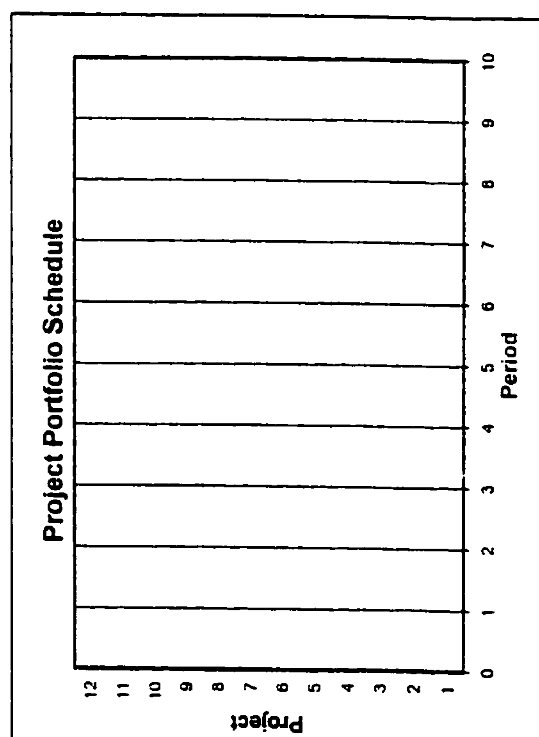
Period
0 1 2 3 4 5 6 7 8 9 10


Project Portfolio Schedule
Project
1 2 3 4 5 6 7 8 9 10 11 12
Period
0 1 2 3 4 5 6 7 8 9 10

Some Heuristics for Solving the Case

Since the solution space for project portfolio selection problems is usually huge (2^{40} in the ACME case and 2^{120} in the Merritt case) finding the optimal solution manually is usually difficult. However, the following heuristics will help to you to reduce the solution space and find the optimal solution faster. These heuristics are just to help you and so there is no obligation to use them. Use any of these heuristics or all of them only if you find them useful.

1. Screen out as many projects as you can. To do that, check the attributes of each project (e.g., resource consumption, risk, and duration) and make sure that the project is not contradicting any constraint stated in the case. Eliminate from further consideration the projects that do not have any chance of selection. This could reduce the solution space drastically and make the case easier to handle.
2. Select the projects with larger NPVs first
3. Schedule to start projects as early as you can. The later a project starts the less its contribution to the total NPV would be (due to the correction factor that is being applied)
4. If you have "mutually exclusive" projects in your "case" select the one that has the larger NPV first.

Good Luck!

Instructions for Working with PASS

1. Click on the PASS icon to run the application.
2. Click OK on both of the login messages that pop up; do not enter any password or user id.
3. Click the Start button to start working with PASS. For more information on how to work with PASS you can click on Help/Tutorial at any time during the session.
4. Type the name of the case that you are solving with a version number "1" beside it (ABC-1, Acme-1, or Merritt-1) in the Scenario box on the bottom right corner of the screen.
5. Use View in pull down menu to view "Project Attributes" and use Edit to change the information if necessary.
6. View "Resource Availability" and Edit the information if necessary.
7. View "Resource Consumption" and Edit the information if necessary.
8. View "Project Dependencies" and Edit the information if necessary.
9. Go to Options/Balancing Criteria and make the required changes according to the case you are solving.
10. Go to Options/MARR and change the MARR according to the case.
11. Click on the "Optimize" button to have PASS find the optimal solution.
12. Click on the "Show" button to see the selected projects in the optimal portfolio.
13. Click on the "Relations" button and ***hold the left mouse button down*** to view the relations.
14. Click on the "Schedule" button to see the portfolio schedule.
15. Print the "portfolio matrix" and "schedule" of the solution found.
16. Try to find a better portfolio through direct interaction with PASS by selecting/de-selecting certain projects through clicking the left mouse button on the appropriate circles. Note that you can view the information and dependencies of each individual project by ***holding the right mouse button down*** on it at any time.
17. Perform *sensitivity analysis* by testing the impact of increasing resources availability on the outcome. For this test assume that you have 10% more money available in

each period. Go to Edit/Resource Availability option and make the required modifications. Check the changes through View/ Resource Availability option.

18. Change the version number in the Scenario box to "2" (ABC-2, Acme-2, or Merritt-2) on the bottom right corner of the screen.
19. Run the model again (by clicking on the Optimize button) to find the new optimal solution based on the imposed change.
20. Click on the "Schedule" button to see the portfolio schedule.
21. Print the "portfolio matrix" and "schedule" of the solution found.
22. Now, perform another *sensitivity analysis* to check the impact of taking more risk (for this test investing up to a maximum of 35% of your investment in high risk projects) on the outcome. To do that Go to Options/Balancing Criteria and change the "Maximum investment in high risk projects to 35%. (If you are doing the Merritt case increase the "Maximum investment in long term projects" to 35% as well)
23. Change the version number in the Scenario box to "3" (ABC-3, Acme-3, or Merritt-3) on the bottom right corner of the screen.
24. Run the model again (by clicking on the Optimize button) to find the new optimal solution based on the changed resource availability.
25. Click on the "Schedule" button to see the portfolio schedule.
26. Print the "portfolio matrix" and "schedule" of the solution found.
27. Compare the optimal result of the selected portfolios and the project schedules in the three different scenarios.

ABC Inc. Portfolio Analysis Case

ABC Inc. is a company, which develops, manufactures, and markets a variety of industrial products. Every six months the management committee at ABC Inc. reviews proposals to develop and market new or enhanced products, and selects projects they think will have the greatest long-term benefit to the company's bottom line.

Before a project proposal is considered seriously, it must undergo a careful feasibility study to estimate the cost to develop the product, the costs needed to install production capacity or convert existing capacity to produce the product, and the estimated sales and related costs over the life of the product. This is converted into a cash flow analysis, which is used to estimate the net present value (NPV) of the project. That is, using the estimated net cash flows (inflows minus outflows) in each period, the present value is calculated as the discounted sum of future net cash flows over the product's life. This is simply defined as

NPV = Sum over all periods (Net cash flow in period i divided by (1+rate)**n)

Another parameter which is used by the committee is an estimate of the project risk, which is a function of the likelihood that the end-product will not meet specifications after being developed, and the likelihood that the estimated market demand will not materialize. The company doesn't want to undertake too many high risk projects (risk more than 0.70) at any one time because too many project failures may jeopardize the company's viability. The committee limits such projects to no more than 30% of the total investment to be committed to new projects.

At the current meeting ABC Inc. management has provided a budget to finance new projects in the coming five years, at a maximum of $350,000 in each six-month period. They will select and schedule projects which will maximize the total NPV (calculated as of now) available from among the potential projects, using their specified minimum attractive rate of return (M.A.R.R.) rate of 7.24% per half-year (equivalent to 15% per year). Selected projects, which cannot begin immediately, will be scheduled so as to maximize total NPV over the next five years. Once projects are started, they will not be re-considered again, but will be completed unless there are changes to estimated costs or they are judged to be failures at some time in the future. General rules for selecting projects: 1) no project can be selected more than once, 2) projects selected must be able to be completed by the end of the ten period plan, and 3) projects, once started, cannot be interrupted.

Following are brief descriptions of the three projects which have been proposed. A financial analysis for each project has been done, in order to calculate the Net Present Value of each project, based on R&D and Capital investments and Net Sales (Sales - production - distribution - marketing & sales costs) over the lifespan of the project (in six month increments). The NPV, risk estimates, and estimates of the semi-annual investments required over the life of the project are given for each project. In addition, a table is given at the beginning for translating the NPV of a project started at some future date into its current NPV, so proper comparisons can be made among projects. Obviously, the total amount required from the project portfolio selected cannot exceed the budgeted amount of $350K per six month time period. The object is to select and schedule the projects in order to maximize the total NPV (projected to the current time) across the projects selected. All amounts are given in $1000s.

Net Present Value Discount Factor

Use discount factors from the table below to apply a discount to the project NPV when the project is scheduled to start at the end of the time period (in six month increments) indicated. These factors are based on a six-monthly discount rate (M.A.R.R. or Minimum Attractive Rate of Return) of 7.24% (15.0% annual equivalent).

Starting Period	Factor
0	1.000
1	0.932
2	0.870
3	0.811
4	0.756
5	0.705
6	0.657
7	0.613
8	0.572
9	0.533

Discount factor The present value of $1 which will be received after n years, when the period discount rate is "rate", is defined as

$$1/(1+rate)^n$$

Project A

Project A is a modification of an existing product with small investment requirement. The overall risk of this project is 0.2 and total investment estimate is $230.

Period	Total Investment
1	25
2	75
3	70
4	60
Totals	230

The Net Present Value of the Delta project is estimated at $241.

Project B

The project B is a product that the company is familiar with and so the overall risk of this project is 0.40 (that it will fail to perform in the marketplace). Project B needs a considerable investment estimated at $1600.

Period	Total Investment
1	150
2	400
3	500
4	350
5	200
Totals	1600

The Net Present Value of this project is estimated at $533.

Project C

This is a long-term project with its overall risk estimated at 0.80. Project C depends on Project A, since it is a major add-on to project A. Project C cannot be undertaken unless and until Project A has been completed. The total estimated investment is $1700K, spread over 7 periods as indicated in the table spreadsheet.

Period	Total Investment
1	150
2	250
3	350
4	350
5	300
6	175
7	125
Totals	1700

The Net Present Value of this project is estimated at $548.

ABC Case solution

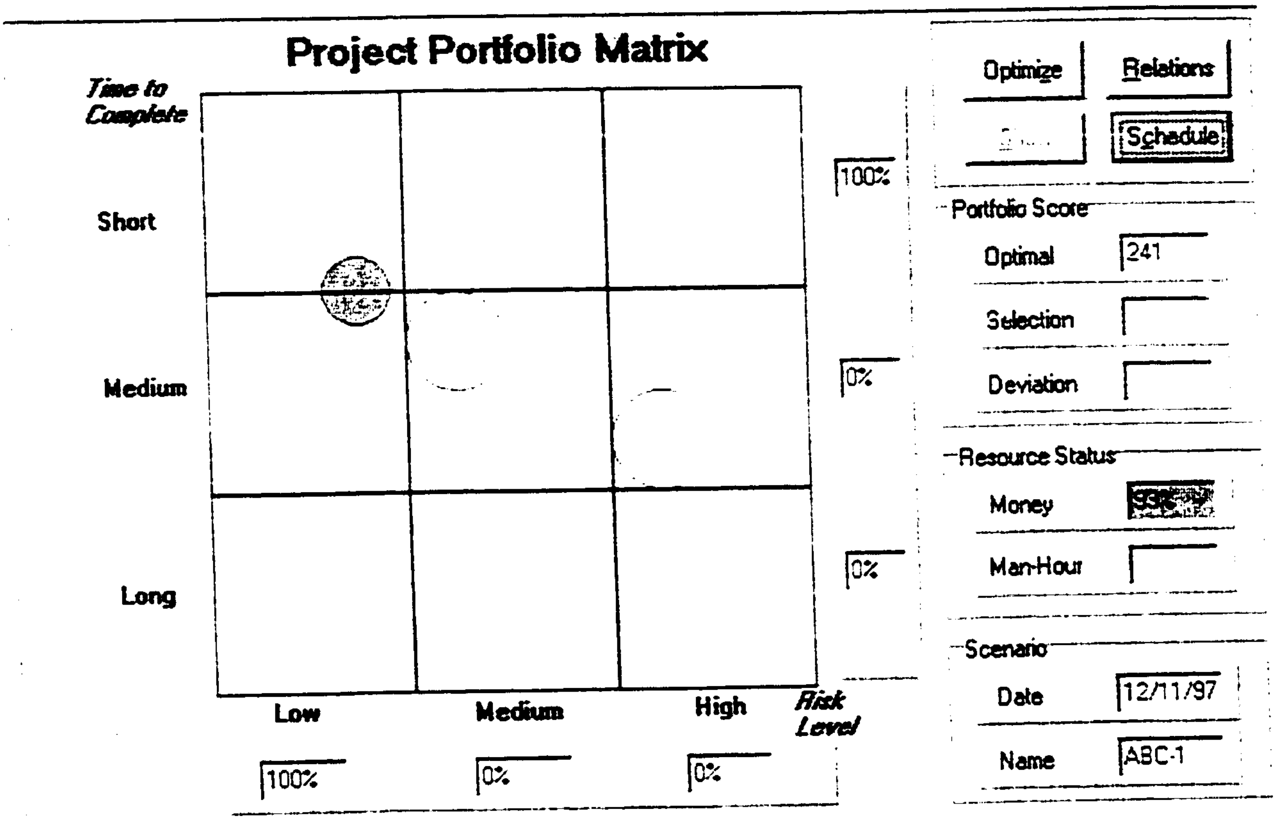


Figure A1.1 Scenario ABC-1 portfolio matrix

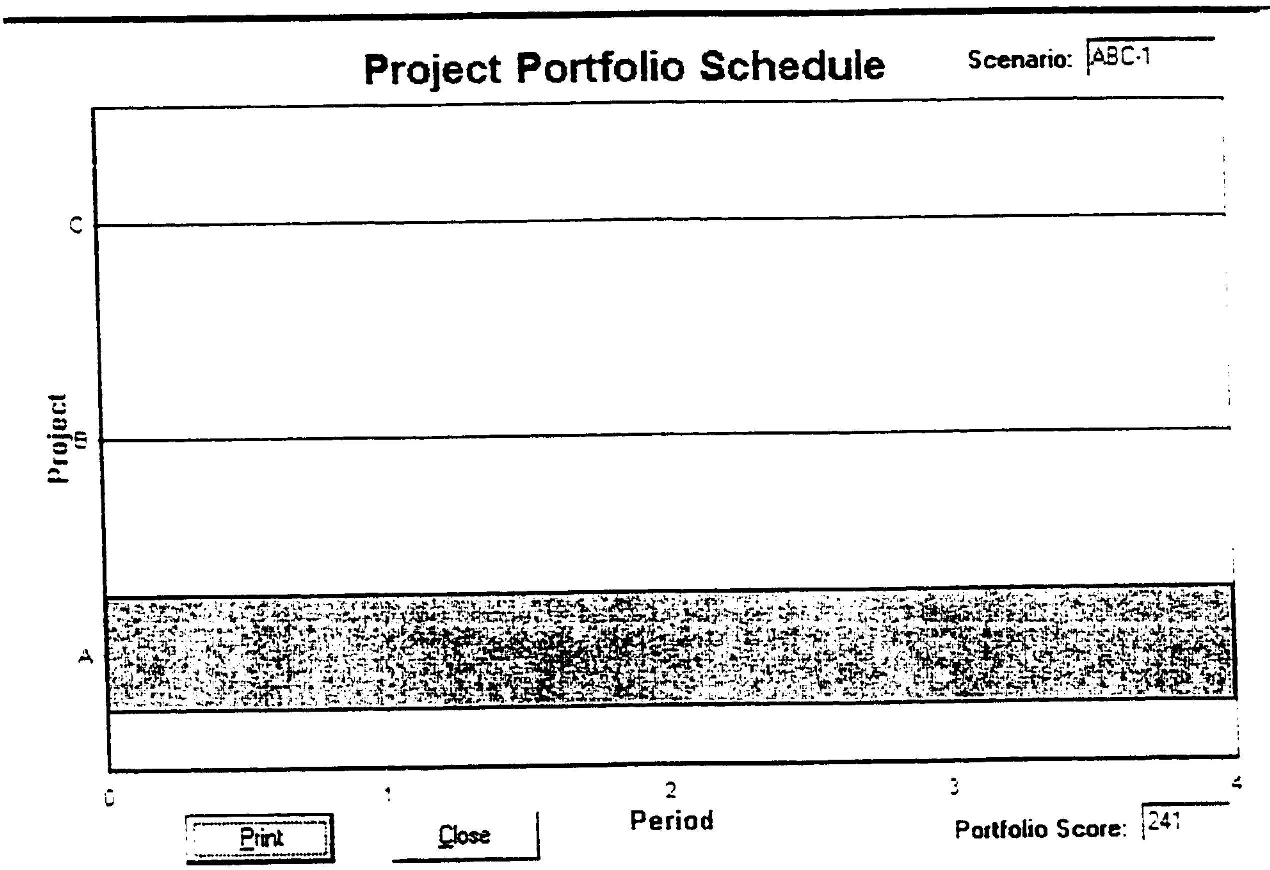


Figure A1.2 Scenario ABC-1 Gantt chart

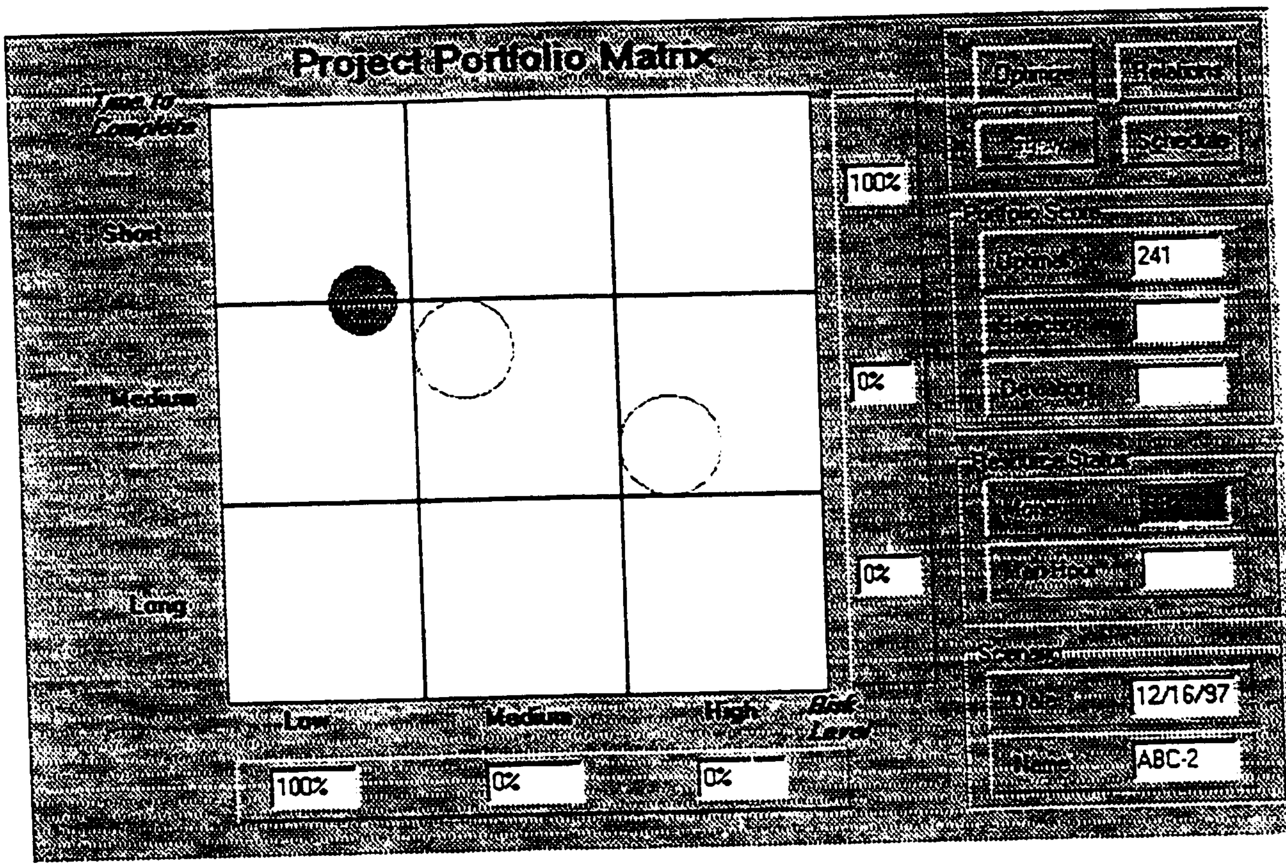


Figure A1.3 Scenario ABC-2 portfolio matrix

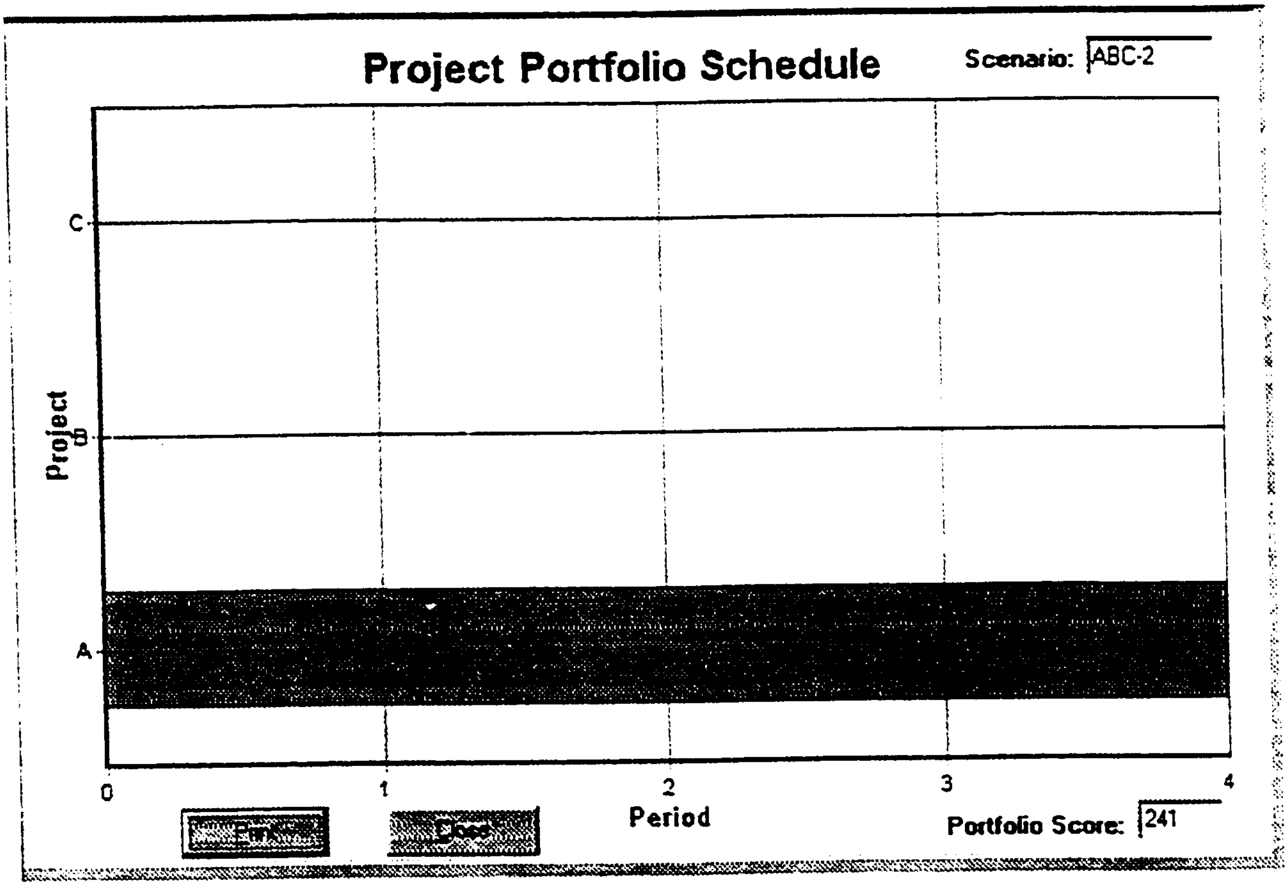


Figure A1.4 Scenario ABC-2 Gantt chart

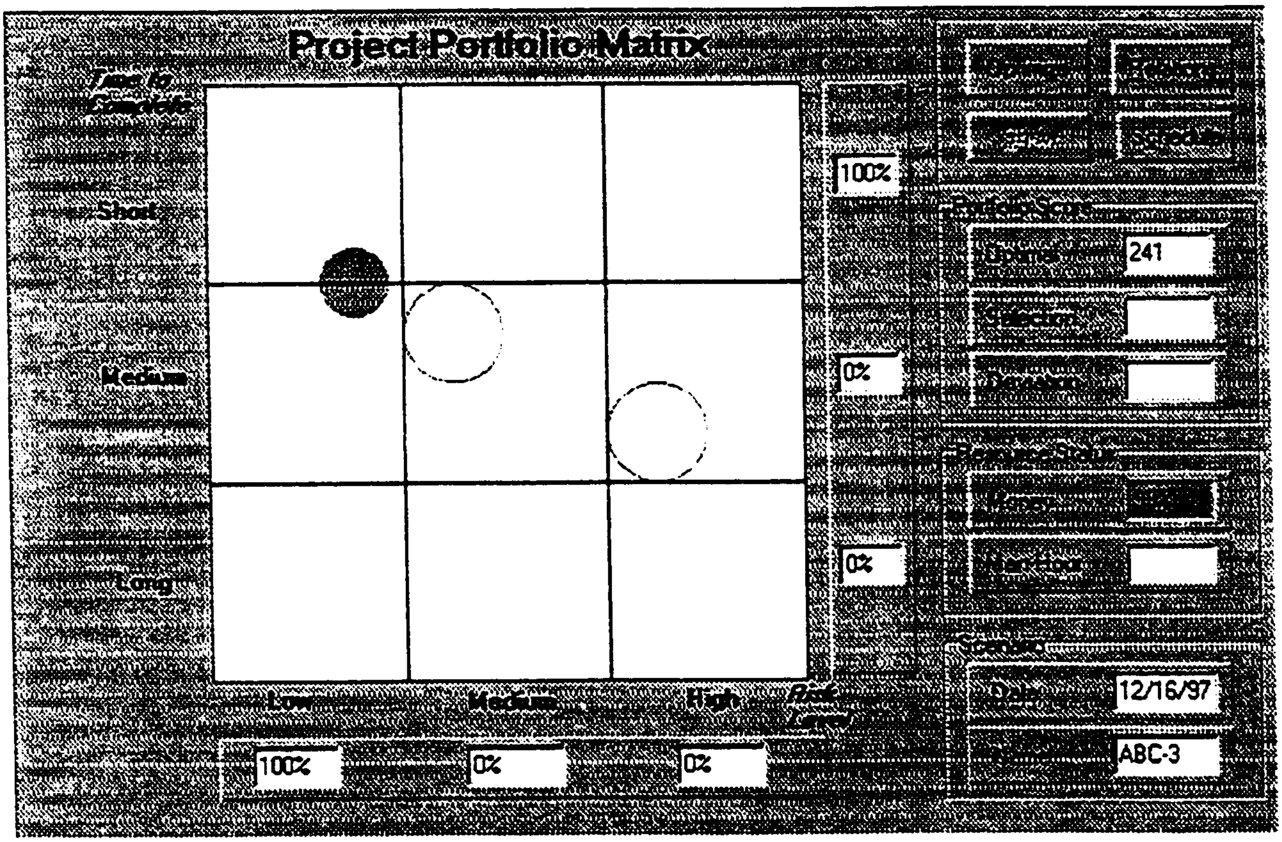


Figure A1.5 Scenario ABC-3 portfolio matrix

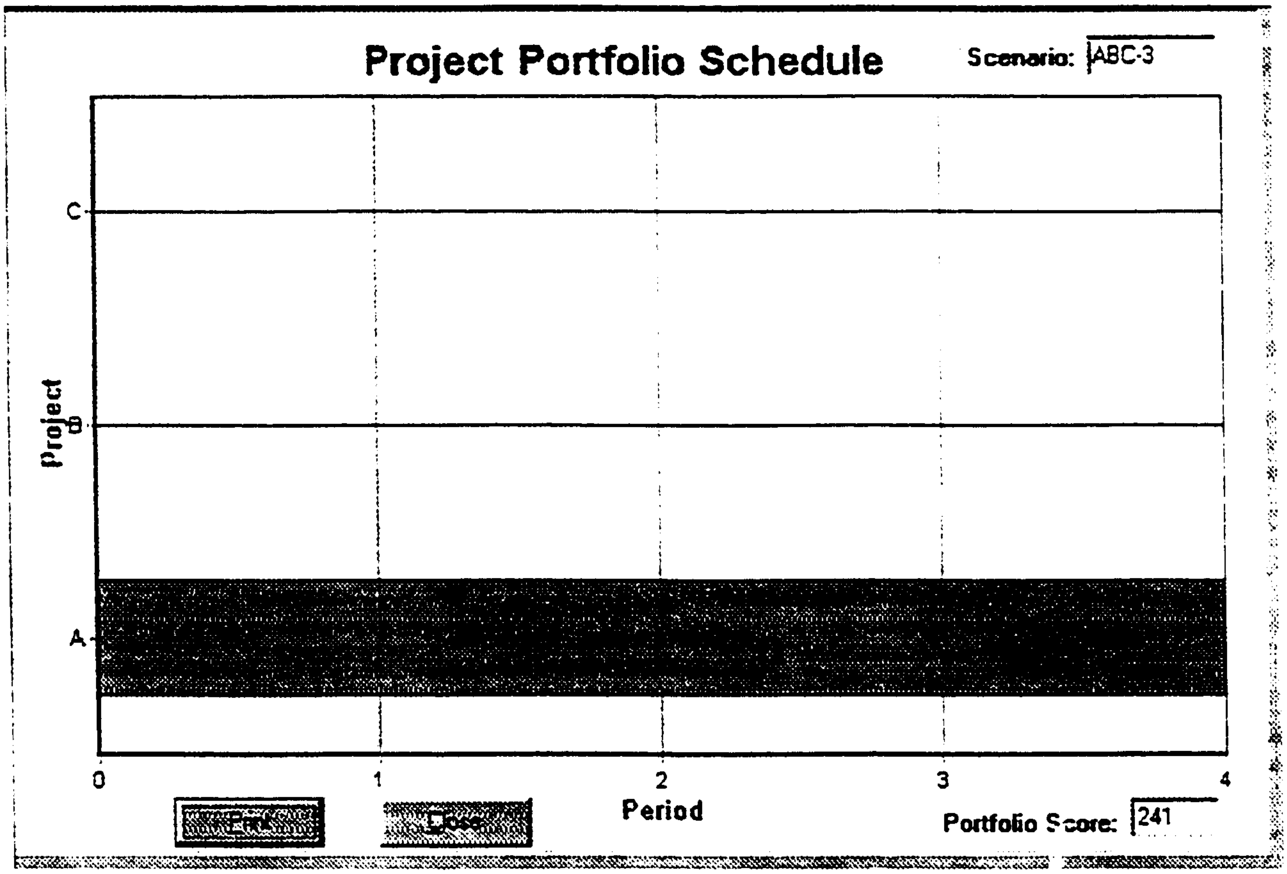


Figure A1.6 Scenario ABC-3 Gantt chart

Acme Electronic Products Portfolio Analysis Case

Acme Electronic Products is a company which develops, manufactures, and markets a variety of advanced electronic industrial products. Every six months the management committee at Acme reviews proposals to develop and market new or enhanced products, and selects projects they think will have the greatest long term benefit to the company's bottom line.

Before a project proposal is considered seriously, it must undergo a careful feasibility study to estimate the cost to develop the product, the costs needed to install production capacity or convert existing capacity to produce the product, and the estimated sales and related costs over the life of the product. This is converted into a cash flow analysis, which is used to estimate the net present value (NPV) of the project. That is, using the estimated net cash flows (inflows minus outflows) in each period, the present value is calculated as the discounted sum of future net cash flows over the product's life. If the discount rate is defined as "rate", and n is the period, then the NPV is defined as

NPV = Sum over all periods (Net cash flow in period n divided by (1+rate)**n)

Another parameter which is used by the committee is an estimate of the project risk, which is a function of the likelihood that the end-product will not meet specifications after being developed, and the likelihood that the estimated market demand will not materialize. The company doesn't want to undertake too many high risk projects (risk more than 0.70) at any one time because too many project failures may jeopardize the company's viability. The committee limits such projects to no more than 30% of the **total investment** to be committed to new projects.

At the current meeting Acme management has provided a budget to finance new projects in the coming five years, at a maximum of $350,000 in each six month period. They will select and schedule projects which will maximize the total NPV (calculated as of now) available from among the potential projects, using their specified minimum attractive rate of return (M.A.R.R.) rate of 7.24% per half-year (equivalent to 15% per year). Selected projects which cannot begin immediately will be scheduled so as to maximize total NPV over the next five years. Once projects are started, they will not be re-considered again, but will be completed unless there are changes to estimated costs or they are judged to be failures at some time in the future. General rules for selecting projects: 1) no project can be selected more than once, 2) projects selected must be able to be completed by the end of the ten period plan, and 3) projects, once started, cannot be interrupted.

Following are brief descriptions of the four projects which have been proposed. A financial analysis for each project has been done, in order to calculate the Net Present Value of each project, based on R&D and Capital investments and Net Sales (Sales - production - distribution - marketing & sales costs) over the lifespan of the project (in six month increments). The NPV, risk estimates, and estimates of the semi-annual investments required over the life of the project are given for each project in an attached table. In addition, a table is given at the beginning for translating the NPV of a project started at some future date into its current NPV, so proper comparisons can be made among projects. Obviously, the total amount required from the project portfolio selected cannot exceed the budgeted amount of $350K per six month time period. The object is to select and schedule the projects in order to maximize the total NPV (projected to the current time) across the projects selected. All amounts are given in $1000s.

Net Present Value Discount Factor

Use discount factors from the table below to apply a discount to the project NPV when the project is scheduled to start at the end of the time period (in six month increments) indicated. These factors are based on a six-monthly discount rate (M.A.R.R. or Minimum Attractive Rate of Return) of 7.24% (15.0% annual equivalent).

Starting Period	Factor
0	1.000
1	0.932
2	0.870
3	0.811
4	0.756
5	0.705
6	0.657
7	0.613
8	0.572
9	0.533

<u>Discount factor</u> The present value of $1 which will be received after n years, when the period discount rate is "rate", is defined as

$$1/(1+\text{rate})^n$$

Alpha Project

This is a long term project which will use advanced technology with which Acme has little familiarity, to open up new territory for the company. As a consequence, the overall risk is estimated at 0.75. The total estimated investment is $995K, spread over R&D and capital for production facilities as indicated in the table spreadsheet. If the product is a success, it should lead to an entirely new family of products. The Net Present Value of this project is estimated at $469.37.

Beta Project

This project would be undertaken as a development project for MaxSpan, another electronics company, using technology with which Acme is familiar. Total investmet by Acme is $1000. This is a shared risk project. The risk is 0.4 (medium risk), that the product developed will fail to meet MaxSpan's specifications. The Net Present Value of the Beta project is estimated at $187.75.

Gamma Project

The Gamma project is a variation on an existing Acme product, and can therefore be completed in a relatively short time, with overall risk of 0.1 (that it will fail to perform in the marketplace), and a small capital investment in production facilities. Total investment is estimated at $475. The Net Present Value of this project is estimated at $114.12.

Delta Project

Delta is also a modification of an existing product, with slightly higher investment required than Gamma, but with the same overall risk of 0.3. Total investment estimate is $550. The Net Present Value of the Delta project is estimated at $135.55.

Summary of the Acme Electronic Products Four Project Case				
		Total		
Project	Name	Investment	NPV	Risk
1	Alpha	995	469	0.75
2	Beta	1000	188	0.4
3	Gamma	475	114	0.1
4	Delta	550	136	0.3
	Investment Requirements			
Period	Alpha	Beta	Gamma	Delta
1	110	150	50	100
2	180	300	175	330
3	200	300	250	120
4	125	250		
5	165			
6	115			
7	100			

Acme Case Solution

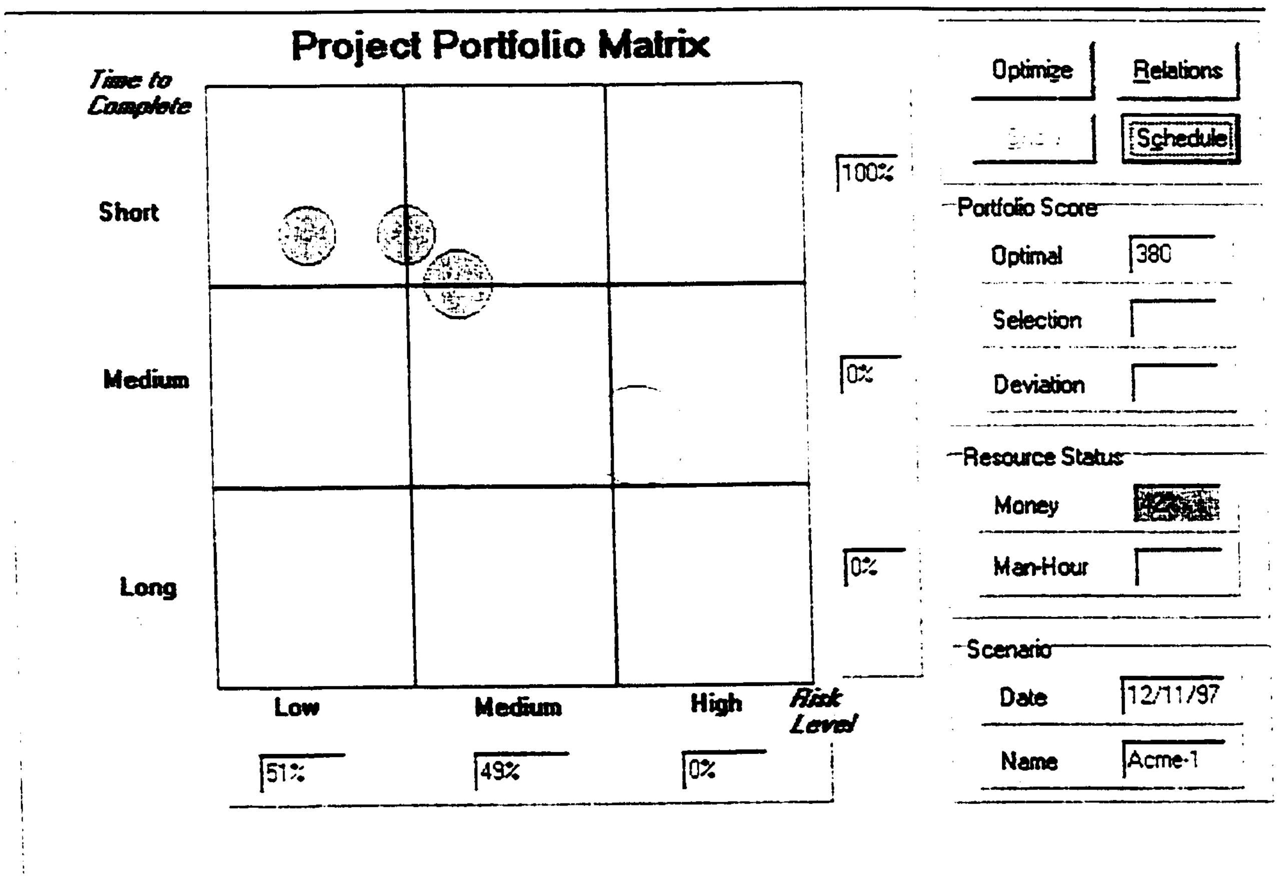


Figure A1.7 Scenario Acme-1 portfolio matrix

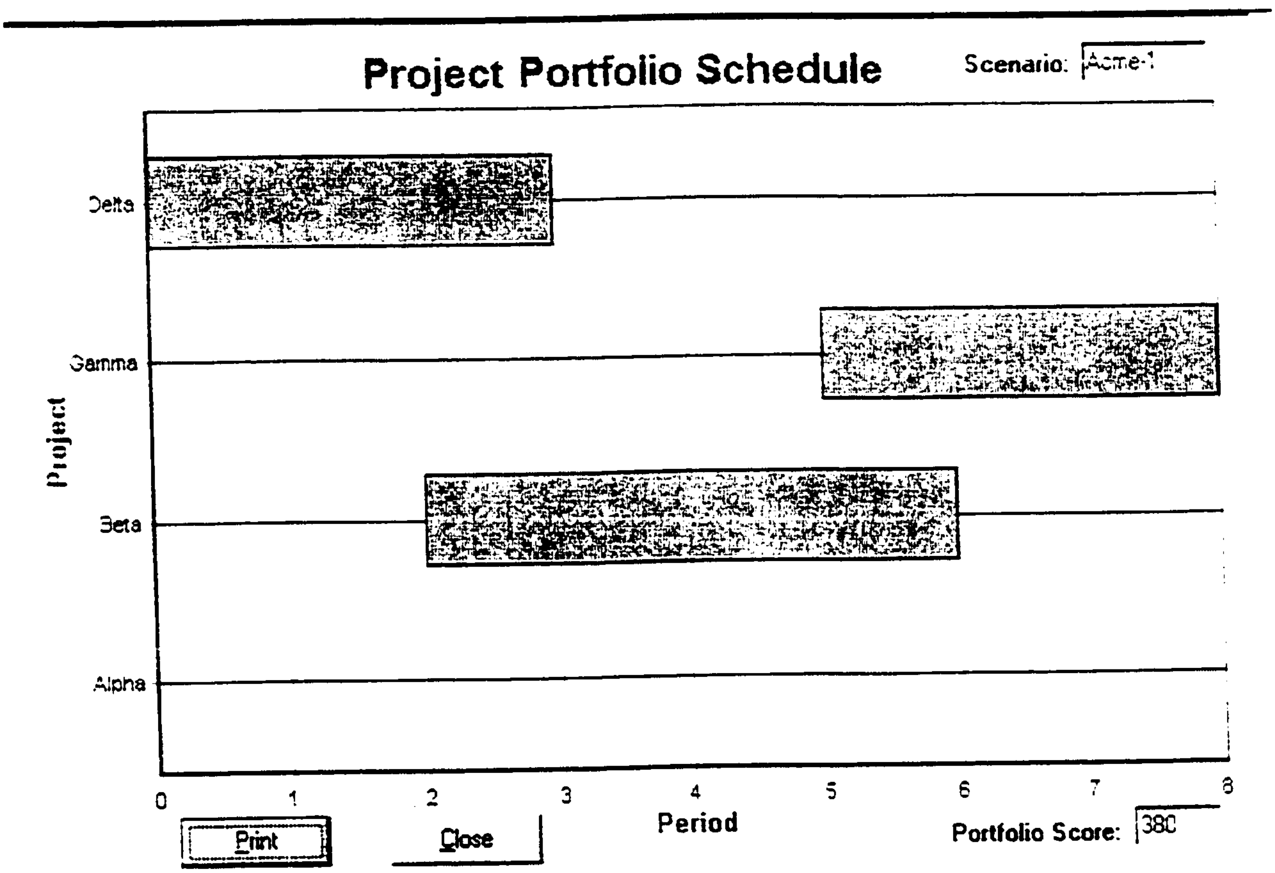


Figure A1.8 Scenario Acme-1 Gantt chart

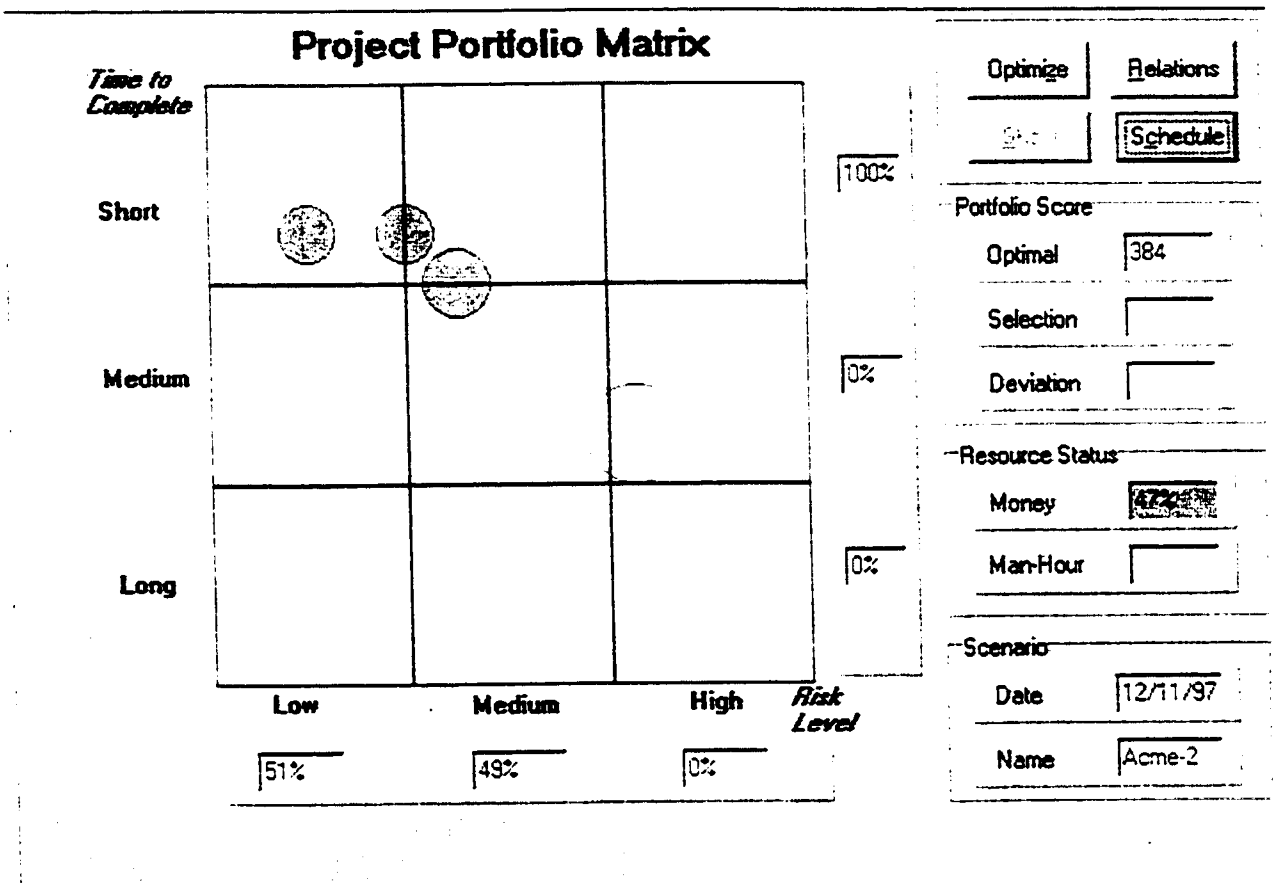


Figure A1.9 Scenario Acme-2 portfolio matrix

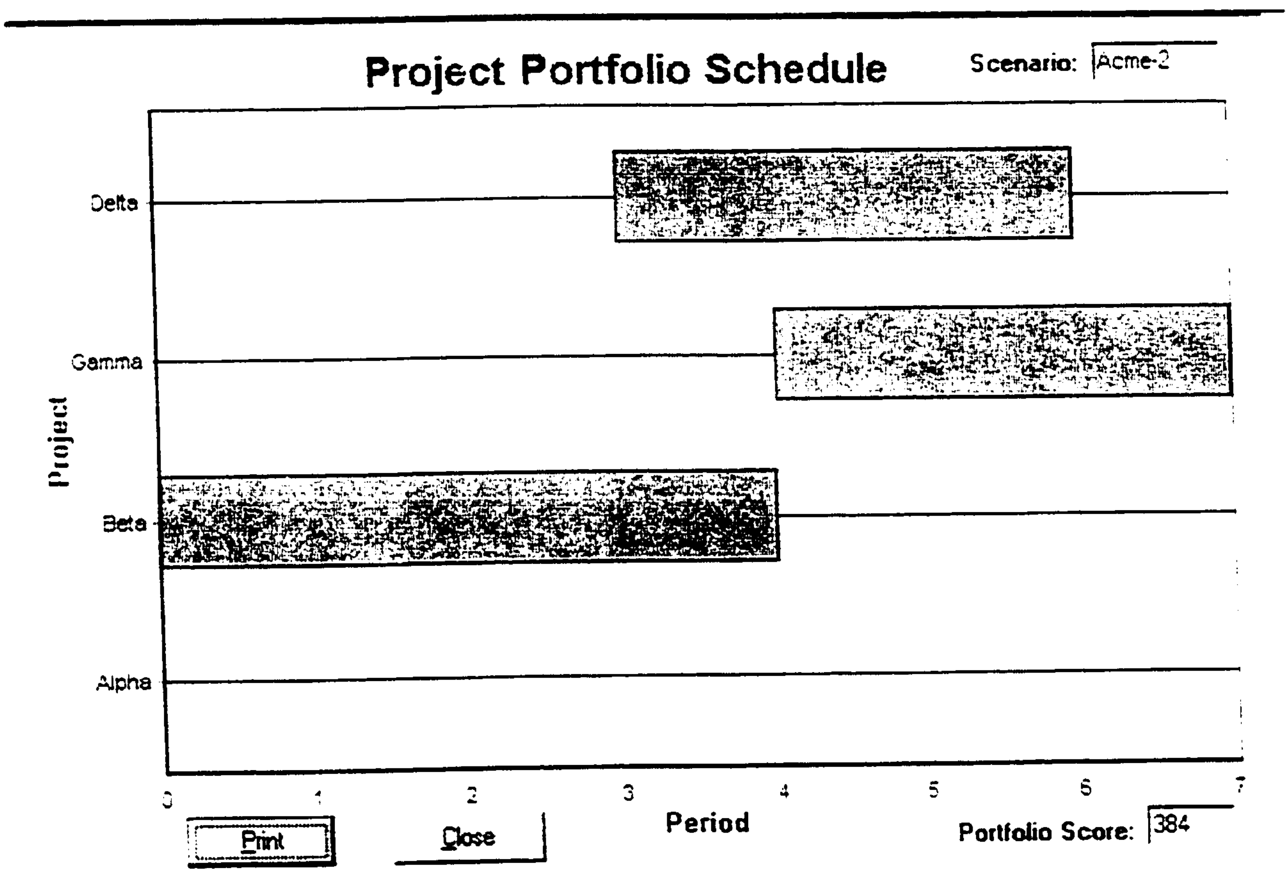


Figure A1.10 Scenario Acme-2 Gantt chart

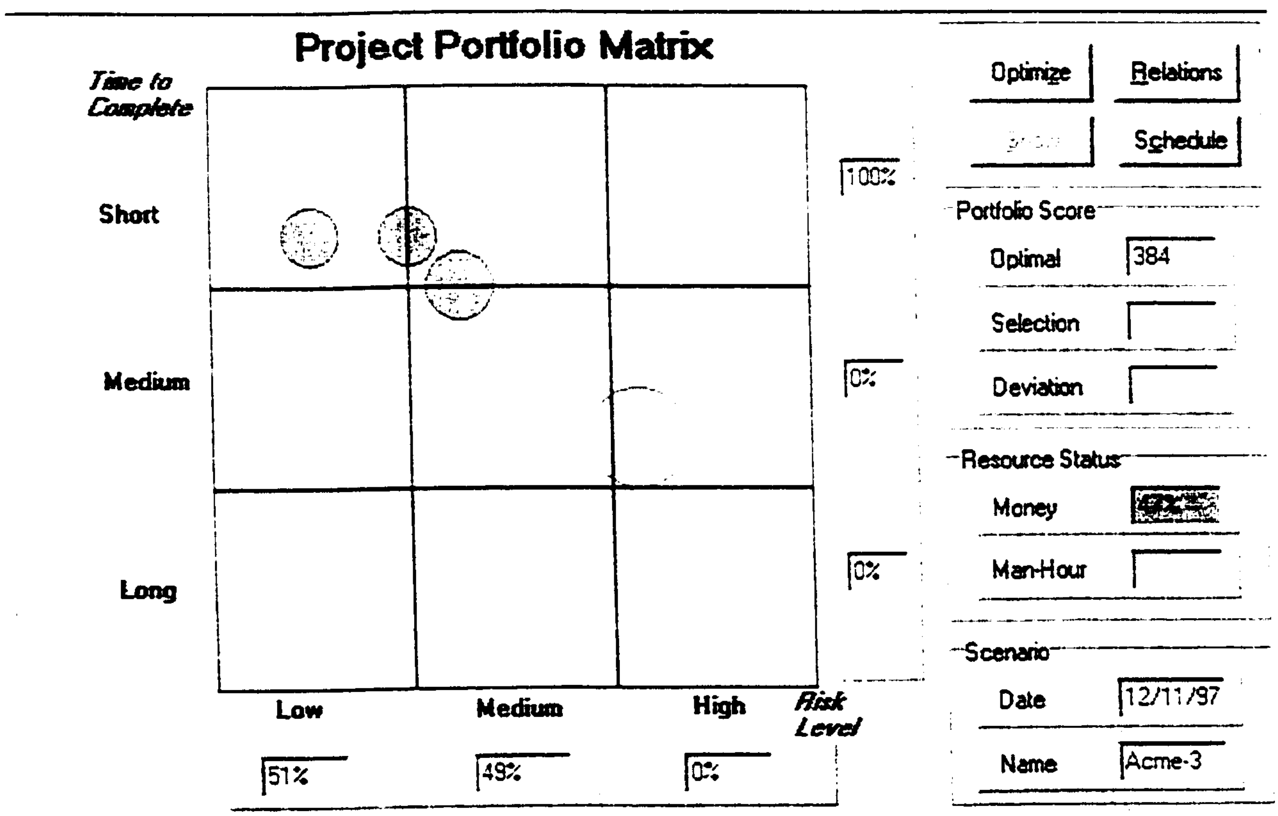


Figure A1.11 Scenario Acme3 portfolio matrix

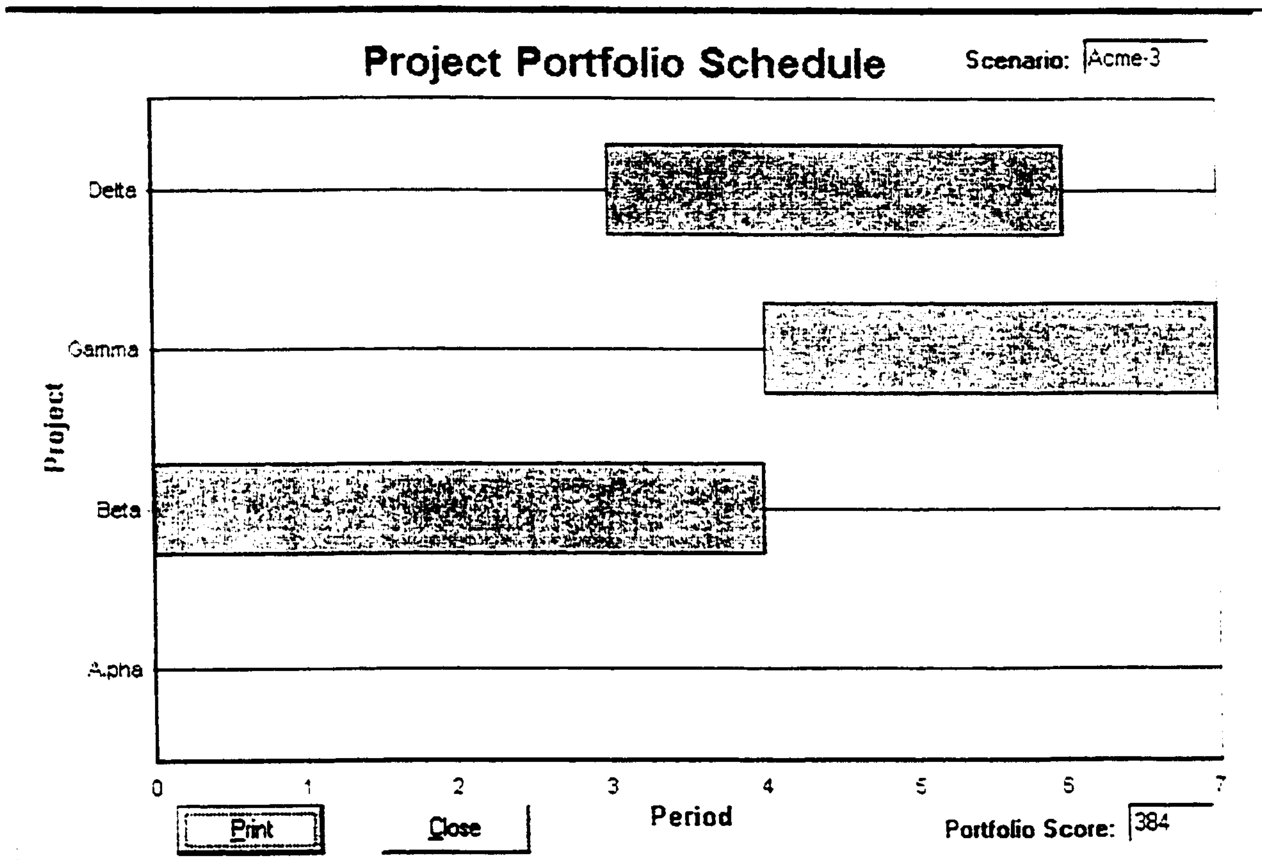


Figure A1.12 Scenario Acme3 Gantt chart

Merritt Corporation Portfolio Analysis Case

Merritt Corporation is a telecommunications manufacturing company which develops, manufactures, and markets a variety of advanced telecommunications products. Every six months the management committee at Merritt reviews proposals to develop and market new or enhanced products, and selects projects that will have the greatest benefit to the bottom line.

Before a project proposal is considered seriously, it must undergo a careful feasibility study to estimate the cost to develop the product, the costs needed to install production capacity or convert existing capacity to produce the product, and the estimated sales and related costs over the life of the product. This is converted into a cash flow analysis, which is used to estimate the net present value (NPV) of the project. That is, using the estimated net cash flows (inflows minus outflows) in each period, the present value is calculated as the discounted sum of future net cash flows over the product's life. If the discount rate is defined as "rate", and n is the period, then the NPV is defined as

NPV = Sum over all periods (Net cash flow in period n divided by (1+rate)**n)

The committee also considers project risk, which is a function of the likelihood that the end-product will not meet specifications after being developed, and the likelihood that the estimated market demand will not materialize. The company doesn't want to undertake too many high risk projects (risk 0.70 or more) at any one time because too many project failures may jeopardize the company's viability. The committee limits such projects to no more than 30% of the **total investment** to be committed to new projects. For the same reason, they limit long term (eight time periods or more) projects to no more than 25% of the **total investment**.

At the current meeting Merritt management has provided a budget to finance new projects in the coming five years, at a maximum of $500,000 in each six month period. They will select and schedule projects which will maximize the total NPV (calculated as of now) available from among the potential projects, using their specified minimum attractive rate of return (M.A.R.R.) rate of 7.24% per half-year (equivalent to 15% per year). Selected projects which cannot begin immediately will be scheduled so as to maximize total NPV over the next five years. Once projects are started, they will not be re-considered, but will be completed unless there are changes to estimated costs or if they are judged to be failures at some time in the future. General rules for selecting projects: 1) no project can be selected more than once, 2) projects selected must be able to be completed by the end of the ten period plan, and 3) projects, once started, cannot be interrupted.

Following are brief descriptions of the twelve projects which have been proposed. A financial analysis for each project has been done, in order to calculate the Net Present Value of each project, based on R&D and Capital investments and Net Sales (Sales - production - distribution - marketing & sales costs) over the lifespan of the project (in six month increments). The NPV, risk estimates, and estimates of the semi-annual investments required over the life of the project are given for each project in the table on page 3. In addition, a table is given on page 2 for translating the NPV of a project starting at some future date into its current NPV, so proper comparisons can be made among projects. Obviously, the total amount required from the project portfolio selected cannot exceed the budgeted amount of $500K in each six month time period. The object is to select and schedule the projects in order to maximize the total NPV (projected to the current time) across the projects selected. All amounts are given in $1000s.

Net Present Value Discount Factor

Use discount factors from the table below to apply a discount to the project NPV when the project is scheduled to start at the end of the time period (in six month increments) indicated. These factors are based on a six-monthly discount rate (M.A.R.R. or Minimum Attractive Rate of Return) of 7.24% (15.0% annual equivalent).

Starting Period	Factor
0	1.000
1	0.932
2	0.870
3	0.811
4	0.756
5	0.705
6	0.657
7	0.613
8	0.572
9	0.533

Discount factor The present value of $1 which will be received after n years, when the period discount rate is "rate", is defined as

$$1/(1+\text{rate})^n$$

Brief Project Descriptions

Venus Project

This is a long term project which will use advanced technology with which Acme has little familiarity, to open up new territory for the company. As a consequence, the overall risk is estimated at 0.8. The total estimated investment is $1320, allocated over time as shown in the foregoing table. If the product is a success, it should lead to an entirely new family of products. The Net Present Value of this project is estimated at $1626.

ArrowA, ArrowB, and ArrowC Projects

ArrowA, ArrowB, and ArrowC are really alternative approaches to the same project. The proponents of the Arrow project have left to the committee the decision on which alternative (if any) should be chosen from these three. ArrowA is an alternative which can be done faster but which will have lower quality than the other alternatives. ArrowB would take longer, would have higher quality, and potentially should do better in the marketplace. ArrowC is similar to ArrowB, but would have more functionality which may or may not do well in the marketplace. The NPVs estimated for these alternatives are $237, $584, and $548, respectively. The total investment estimates are 1400, 1500, and 1700 respectively, while the associated risks are 0.3, 0.2, and 0.3 respectively.

Jupiter Project

Jupiter is a high risk (risk = 0.7) project, with an estimated NPV of $533 and total investment requirement of $1600.

Neptune and Pluto Projects

Neptune is a standalone project, with risk estimated at 0.4, NPV at $115, and investment requirement of $500. Pluto depends on Neptune, since it is a major add-on to Neptune. Pluto cannot be undertaken unless and until Neptune has been completed. Hence, if Neptune is not selected, Pluto cannot be selected either. The risk with Pluto is 0.5, its NPV is $241, and its investment requirements are $230.

Sierra, Rialto, Paris, Tehran, and Calgary Projects

These five projects are modifications of existing products. Their risks are 0.2, 0.4, 0.1, 0.2, 0.1 respectively. Their NPVs are $94, $71, $37, $38, and $24 respectively. The total investments required for each project are $140, $70, $105, $70, and $100 respectively.

Summary of the Merritt Corporation's Twelve Project Case

Project	Name	Total Investment	NPV	Risk
1	Venus	1320	1626	0.8
2	ArrowA	1400	237	0.3
3	ArrowB	1500	584	0.2
4	ArrowC	1700	548	0.3
5	Jupiter	1600	533	0.7
6	Neptune	500	115	0.4
7	Pluto	230	241	0.5
8	Sierra	140	94	0.2
9	Rialto	70	71	0.4
10	Paris	105	37	0.1
11	Tehran	70	38	0.2
12	Calgary	100	24	0.1

Investment Requirements

Period	Venus	ArrowA	ArrowB	ArrowC	Jupiter	Neptune	Pluto
1	90	200	150	150	150	50	25
2	160	350	200	250	400	125	75
3	220	350	300	350	500	125	70
4	220	300	300	350	350	100	60
5	150	200	300	300	200	100	0
6	160	0	150	175	0	0	0
7	200	0	100	125	0	0	0
8	120	0	0	0	0	0	0

Period	Sierra	Rialto	Paris	Tehran	Calgary
1	25	10	15	15	20
2	50	30	40	55	80
3	35	20	50	0	0
4	30	10	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0

Merritt Case Solution

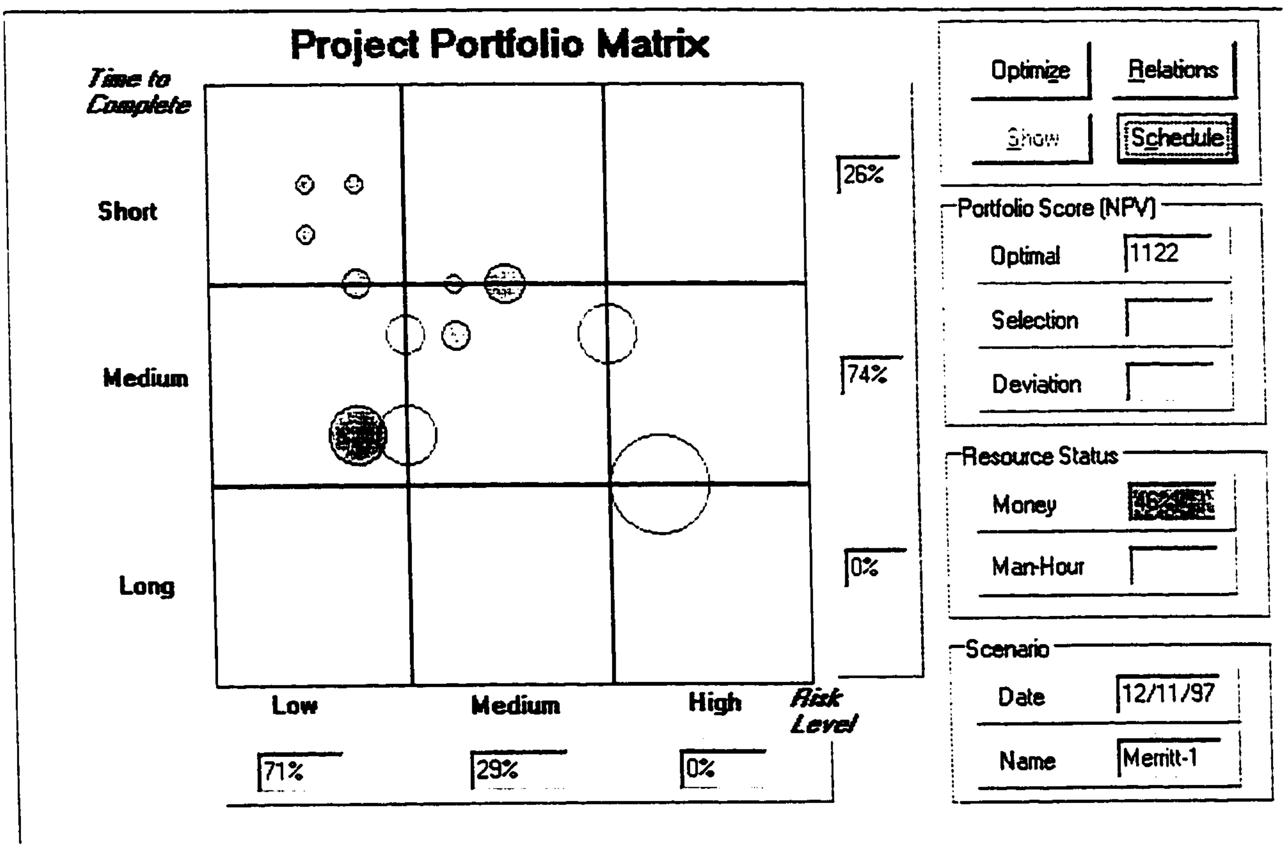


Figure A1.13 Scenario Merritt-1 portfolio matrix

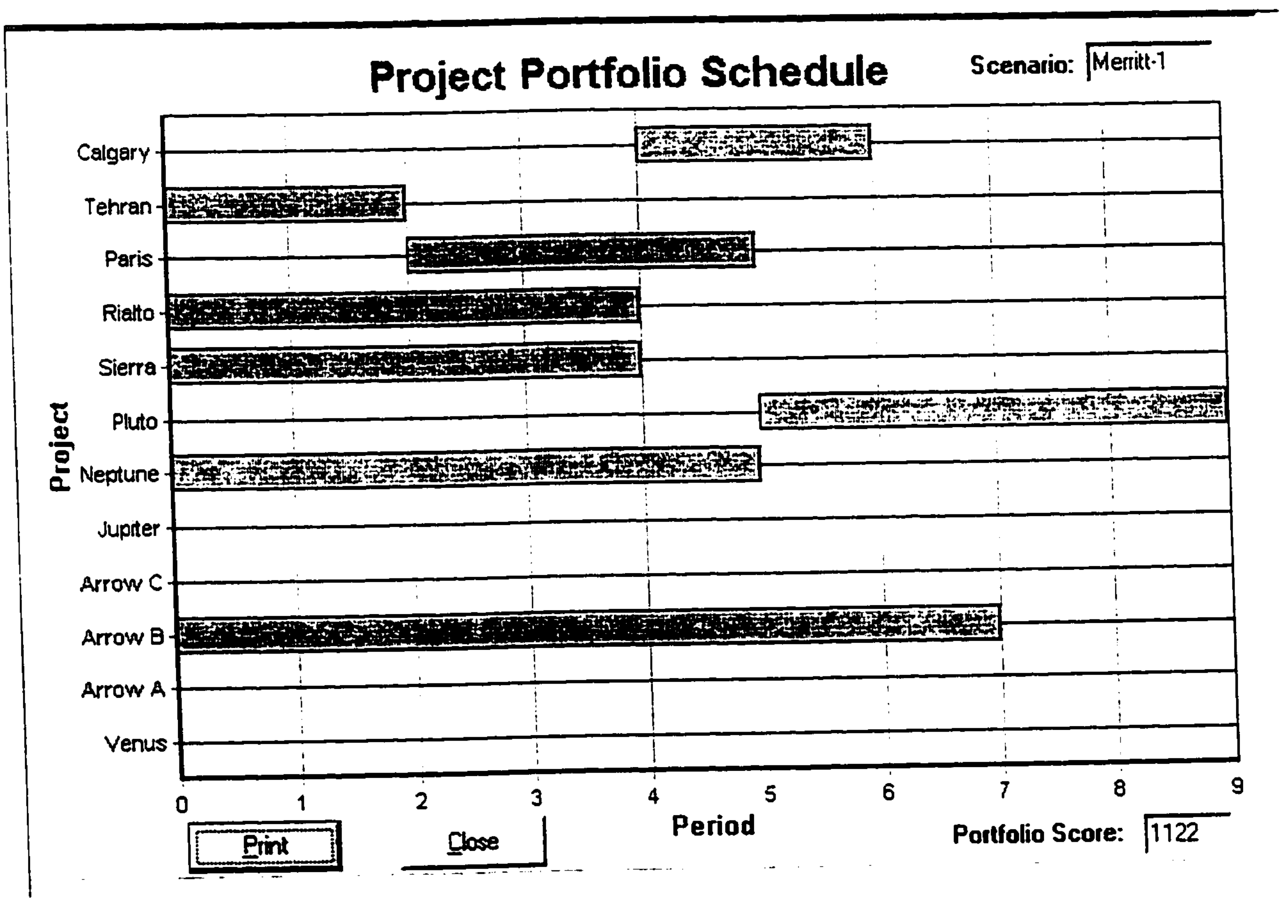


Figure A1.14 Scenario Merritt-1 Gantt chart

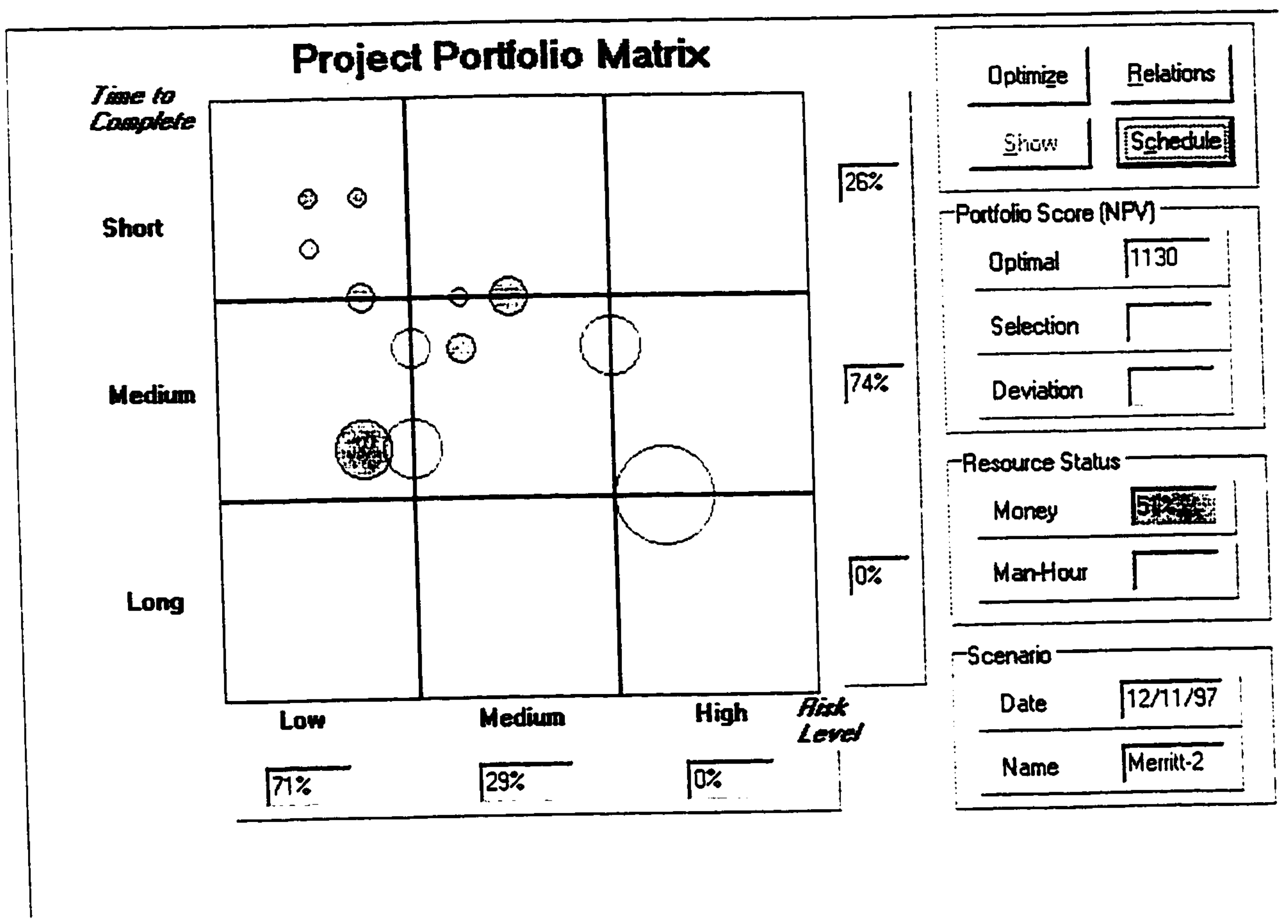


Figure A1.15 Scenario Merrit-2 portfolio matrix

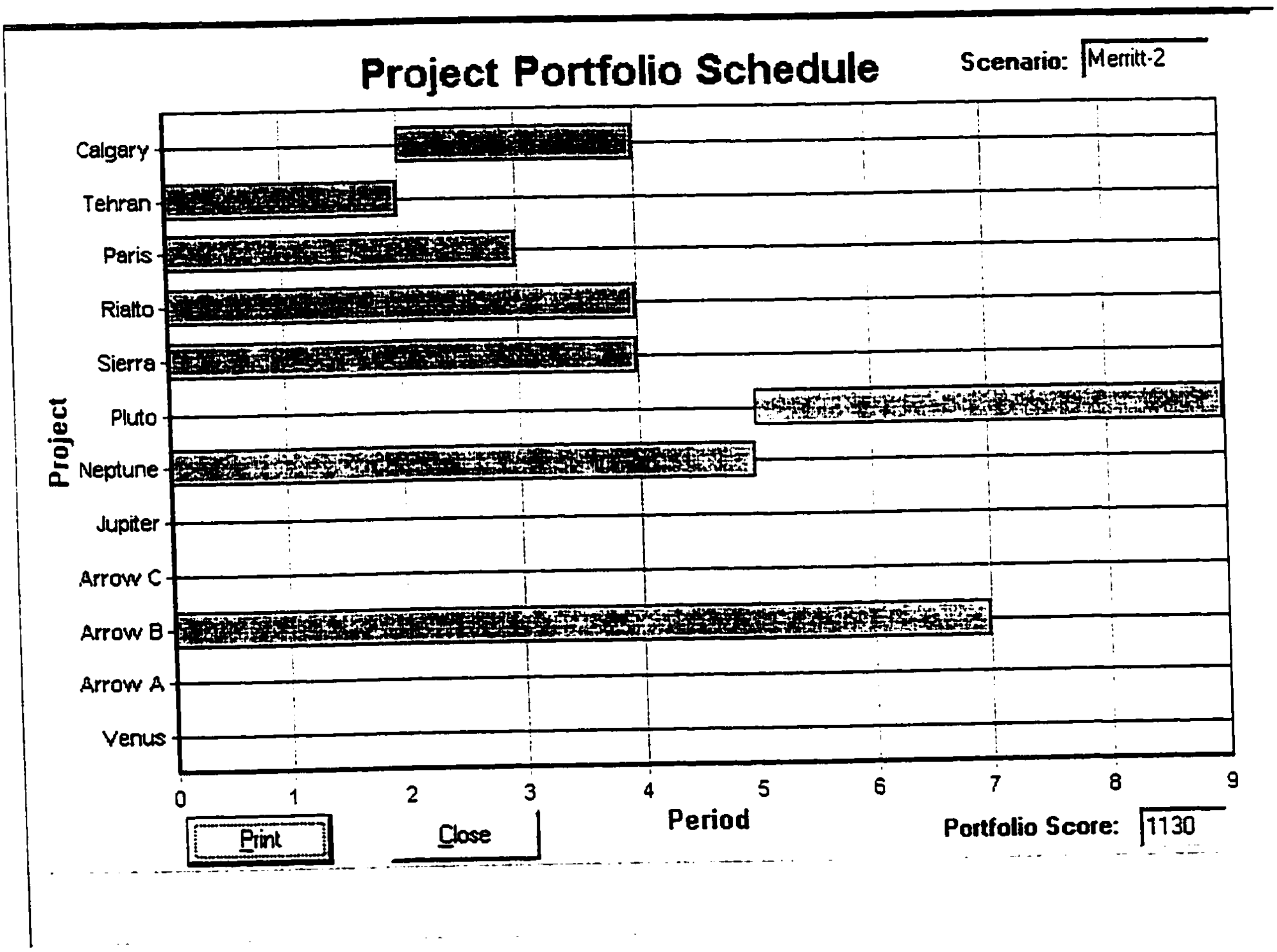


Figure A1.16 Scenario Merritt-2 Gantt chart

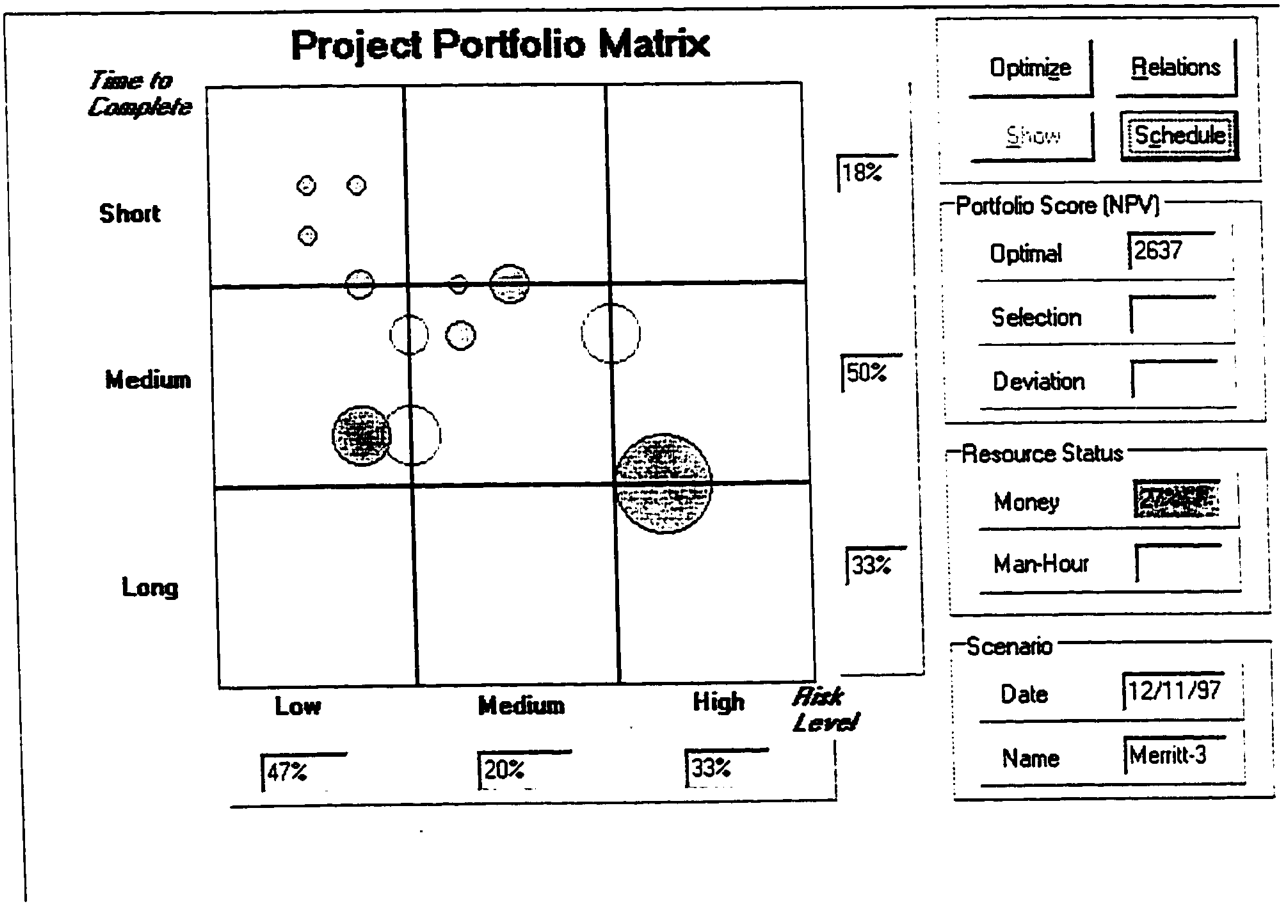


Figure A1.17 Scenario Merritt-3 portfolio matrix

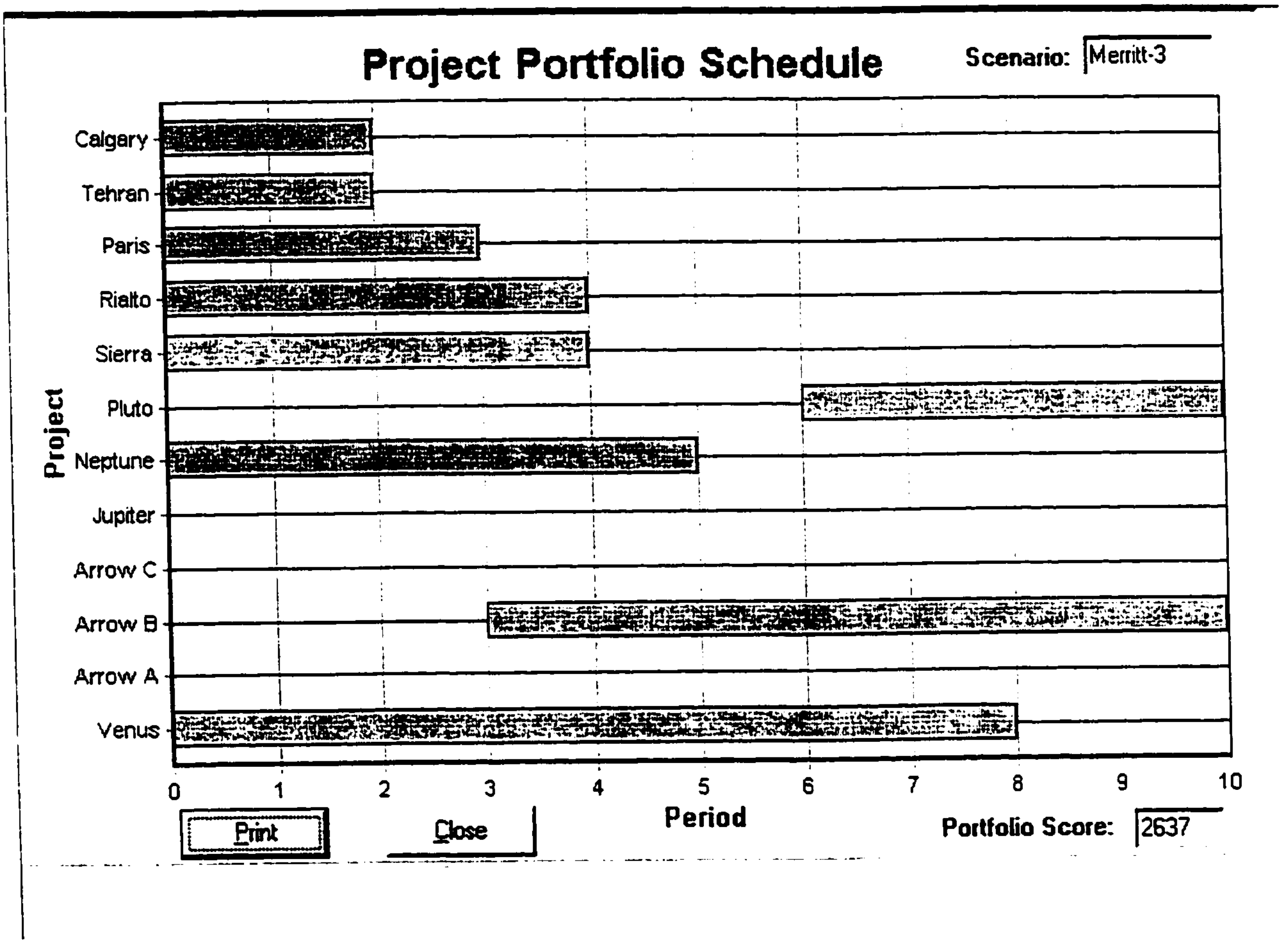


Figure A1.18 Scenario Merritt-3 portfolio matrix

Appendix 2

Comments From PASS Experiment Participants

Codes: A: Acme M: Merritt

Subject: A1

- it wasn't clear that "Portfolio Score-Optimal" was the overall NPV, maybe add a dollar sign
- When it was necessary to change the budget per period from 350 to 385 it would have been nice to have a tool that would change them all at once

Otherwise I think it is a great tool. Maybe I'll be using it one day.

Subject No: A3

- Overall, very east to use for basic portfolio selection, user friendly screens and well presented. Very quick and easy compared to manual selection

Subject No: A4

- Easy to use for those familiar with Win95, but others?

Subject No: A5

- PASS was much quicker than manually coming to a decision. It's easy to manipulate and quite easy to understand. The diagrams (matrixes/schedules) are very self-exploratory.

Subject No: A6

- Generally quite easy to use. However, making the Edit/Resource Availability come under the View/Resource Availability would improve speed and friendliness even more. Also maybe a feature in this command that allows you to automatically increase the money resource over the period range rather than having them enter it manually all the time.

Subject No: A7

- The problems I solved were fairly simple but it is obvious that PASS becomes very useful in solving more complicated problems. It was more precise in the NPV of different portfolio selection, which is important for manager to precisely evaluate portfolio selection.
- The flexibility of the application is useful to integrate the person's thoughts on a maximizing portfolio.

Subject No: A8

- You might consider allowing the program to accept "Enter" as an equivalent to using the mouse to press O..K.

Subject No: A9

- When using computer I don't like to read long messages. Keeping important on screen messages short helps, and all on screen text.

Subject No: A10

- Easy to operate, often basic understanding is established
- Clear and user friendly
- Printouts are useful and handy for comparisons, and potentially handy for presentations
- Changes are easily made-without complications.

Subject No: A11

- Overall, PASS is a useful and friendly tool for making decision about investment on any project. However, it would be more useful if more than 10 period horizon is added.

Subject No: A12

- I liked the fact that it was very user friendly and the fact that icons were properly labeled.

Subject No: M2

The idea is good, but the problems in my opinion are more complex in the reality, and therefore it is difficult to define a project only by risk and NPV.

Subject No: M4

- I found PASS very simple to use and minimized the chance for error

- No obvious changes need to be made since I had a limited time to experiment with PASS

Subject No: M6

- O.K. buttons could be accessed by Enter instead of mouse click
- The increase to resource availability was tedious. Either a spreadsheet or highlight value and click on a button
- A graphing capability with values to be chosen by the user (NPV vs. Risk)
- The ability to superimpose merritt-1 to 3 without printing them out. We could use different colors

Subject No: M7

- Once you have used PASS and know all the functions, it is extremely easy and efficient to select a project portfolio using this program. Requirements for resources and other constraints could be changed easily while the optimal project portfolio would still be found in a very short period of time.
- PASS would be improved by adding other dimensions so as to cater for even further considerations/requirements that companies or individuals may have.

Subject No: M8

- PASS is very user friendly while it allows you to make many changes; you always see the results. Overall I would recommend it.

Subject No: M9

- PASS seems to be a smooth program that does assist in making NPV decisions
- It is user friendly and easily understood.

Subject No: M10

- Very user friendly

Subject No: M11

- By understanding the way the system works, it is easy to see how it may be used to make sophisticated decisions. It allows you to manipulate variables to determine the variability in outcome. That is something that would require more human hours and the program allows you to obtain results within seconds.

Subject No: M12

- Fairly easy to use for someone who is comfortable using computers
- Makes performing sensitivity analysis easier and more useful
- Percentage of risk levels on he X-axis is of little use.

Appendix 3

ODBC Theory Of Operation

A3.1 What Is ODBC*?

The ODBC (Open DataBase Connectivity) standard originated at Microsoft® to provide software drivers in application packages and programming languages for access to data from databases supporting this standard. Since different pieces of software interact with each other in PASS, by storing and retrieving data in a common ODBC database, support of the ODBC standard was pre-requisite for consideration during the software selection process.

The ODBC interface allows applications to access data in database management systems (DBMS) using Structured Query Language (SQL) as a standard for accessing data. Since SQL is a language used by nearly every commercially available DBMS for the retrieval and manipulation of data, the ODBC interface permits maximum *interoperability*- a single application can access different database management systems. For example, an application could access DB2® on an AS/400®, manipulate ACCESS® or Paradox® files on a PC, or bTrieve® files on a laptop. It can also access files that might not even be considered as databases, like Excel® spreadsheets or ASCII data. This allows developing an application without targeting a specific DBMS, as depicted in Figure A3.1. Users can then add database drivers that link the application to their choice of database management systems.

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* The material in this appendix has been adapted from sources listed in section A3.3.

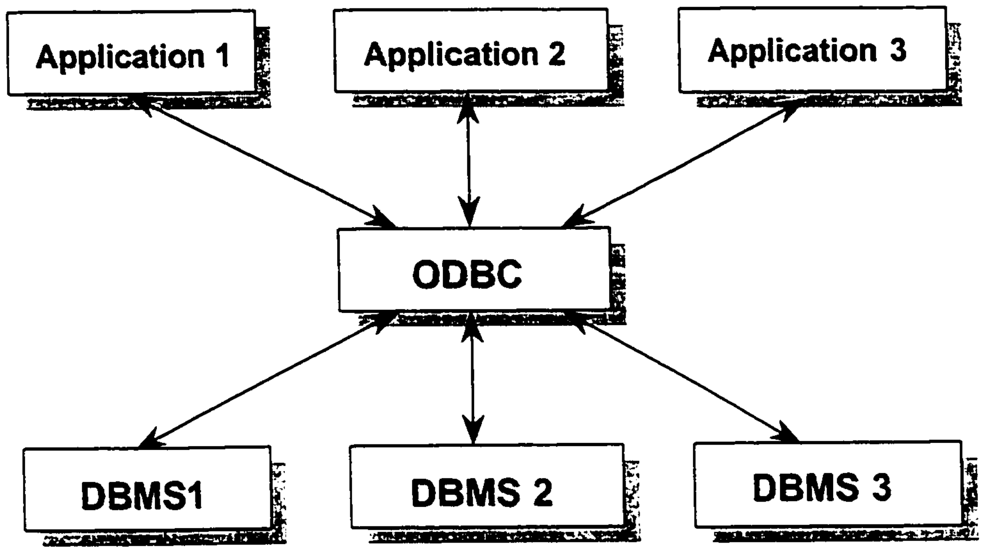

Figure A3.1- Accessing multiple DBMSs with ODBC

(Adapted from "Inside ODBC", Microsoft Press)

A3.2 ODBC Components

The ODBC architecture has four components (Figure A3.2):

Application- Performs processing and calls ODBC functions to submit SQL statements and retrieve results,

Driver Manager- Loads drivers on behalf of an application,

Driver- Processes ODBC function calls, submits SQL requests to a specific data source, and returns results to the application. If necessary, the driver modifies an application's request so that the request conforms to syntax supported by the associated DBMS,

Data Source- Consists of the data the user wants to access and its associated operating system, the DBMS and its network platform (if any). The driver manager and driver appear to an application as one unit that processes ODBC function calls.

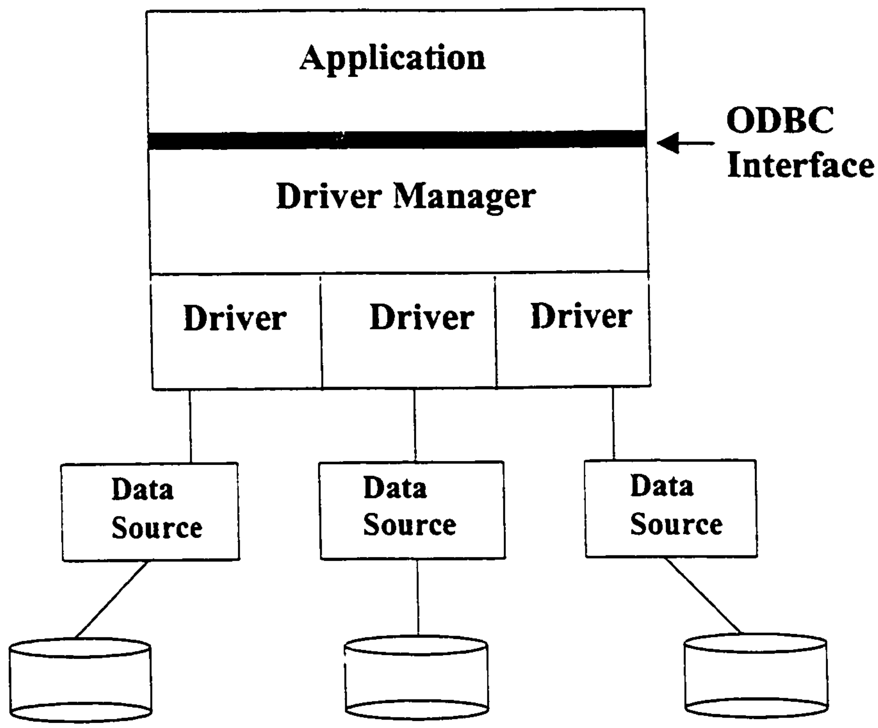

Figure A3.2- ODBC components

A3.2.1 Application

An application using the ODBC interface performs the following tasks:

- Requests a connection, or session, with a data source.
- Sends SQL requests to the data source.
- Defines storage areas and data formats for the results of SQL requests.
- Requests results.
- Processes errors.

- Reports results back to a user, if necessary.
- Requests commit or rollback operations for transaction control.
- Terminates the connection to the data source.

A3.2.2 Driver Manager

The Driver Manager, is a dynamic-link library (DLL) with an import library. The primary purpose of the Driver Manager is to load drivers. The Driver Manager also performs the following:

- Uses the ODBC.INI file or registry to map a data source name to a specific driver dynamic-link library (DLL).
- Processes several ODBC initialization calls.
- Provides entry points to ODBC functions for each driver.
- Provides parameter validation and sequence validation for ODBC calls.

A3.2.3 Driver

A Driver is a DLL that implements ODBC function calls and interacts with a data source. A Driver Manager loads a driver when the application calls the SQL *BrowseConnect*, *SQLConnect*, or *SQLDriverConnect* function. A Driver performs the following tasks in response to ODBC function calls from an application:

- Establishes a connection to a data source.
- Submits a request to a data source.
- Translates data to or from other formats, if requested by the application.

- Returns results to the application.
- Formats errors into standard error codes and returns them to the application.
- Declares and manipulates cursors if necessary.
- Initiates transactions if the data source requires explicit transaction initiation.

A3.2.4 Data Source

A Data Source is a specific instance of a combination of a DBMS product and any remote operating system and network necessary to access it.

A3.3 ODBC Bibliography

Kyler, Geiger (1995), *Inside ODBC*, Microsoft Press.

Microsoft (1992), *ODBC 2.0*, Microsoft Press.

Gryphon, Robert (1995), *Using ODBC*, Indianapolis; Que.

Appendix 4

Software Selection For PASS

A4.1 Introduction

As any other decision support system, PASS consists of three major components: user interface, database, and model base. Selection of the most appropriate software for each component is a very important and tedious task that can make the difference between success and failure in constructing such a DSS. Many different software packages were evaluated during the software selection process for PASS. In the following, we describe the results of our evaluation and explain how the most appropriate software packages were selected for each component.

A4.2 Selection Of User-Interface Software

ToolBook® was used to develop the first versions of the PASS prototype, since this development environment is relatively easy to use and learn. However, as the prototype grew bigger we faced memory shortages and long run time problems. As a result, we decided to select a more appropriate programming environment to develop the full-scale PASS user-interface. Since we wanted to develop a PC-based DSS that works under the Windows 95® environment and interacts with other software modules on-line, we limited our choices to interface development environments that work under Windows 95® and support the ODBC standard (see Appendix 3). A review of the market and consultation with experts in the field showed that Visual Basic®, PowerBuilder® and Delphi® are the best software packages available for this type of application. Although any of these packages could do the job, we selected Delphi® because it had a major advantage in its integrated native code compiler that speeds up program execution, in comparison with other packages.

A4.3 Selection Of DBMS Software

We initially considered using a spreadsheet such as Excel® for our database module because spreadsheets can support simple financial models that are required for individual project evaluation, as well as graphing features for creating graphics such as Gantt charts for showing portfolio schedules. However, since the solver and modeling packages we planned to use could not establish good on-line connections with spreadsheet packages, and also due to some other spreadsheet limitations when they are used for databases, we chose a DBMS for this purpose. Since individual project evaluation was performed in off-line sessions, the integration of Excel® spreadsheet calculations into PASS was not essential. The latest version of Delphi® (Version 3.0) supports rich graphs such as Gantt charts and so we did not need Excel® for the on-line session. We therefore eliminated it from the integrated PASS system.

We investigated Paradox® and Access®, two DBMS that work under Windows 95®, support the ODBC standard, and are market leaders. Earlier versions of the prototype database were developed with Paradox®. However, Access® is a more widely recognized package, and fewer problems should result in future development of the associated ODBC standard. For example, the 32 bit ODBC standard was introduced during our work, and this solved some major problems with the 16 bit ODBC, such as establishing simultaneous connections with more than one data source. This was handled simply by upgrading our Access® software to the 32 bit version.

A4.4 Selection Of Modeling And Solver Software

An optimization model can be developed using different tools called "modeling" software. The core software that actually computes the optimal solution to the mathematical model is called "solver" software. There is a wide variety of modeling and solver software available in the market place. Selecting the right tool for the job can greatly simplify the work and help to arrive at a better solution in less time. Determining the most appropriate modeling and solver software to be included in PASS was a very time consuming and challenging task in our research. The major issues that were considered at this stage included:

- The size of the problem in terms of the number of variables and constraints.
- The type of problem being addressed: continuous vs. discrete, linear vs. non-linear.
- The mathematical technique used in the solver: simplex, branch and bound, etc.
- The environment and the user-friendliness of interfaces offered to the user: modeling language, input formats, operating systems etc.

In addition to the above issues, since we wanted to integrate the modeling and solver software into PASS there were some other considerations:

- The modeling and solver software should work under the Windows95® environment.
- The software should support the ODBC standard, to allow on-line interaction with other software modules in the DSS such as the DBMS.

- Run-time was one of the most important criteria because decision-makers are the main users of PASS and long run times (more than a few minutes) would make the system frustrating to use and prevent easy interaction with the system. This is an important aspect of any decision support system.

In order to come up with the most appropriate software for this purpose we evaluated different types of software programs as explained in the following.

A 4.4.1 Spreadsheets

Spreadsheets have several advantages for building and solving optimization models. The learning time is very low and the user can create, modify, format, audit and solve the models easily. Since the Excel® spreadsheet package was readily available we first tried this software by developing and solving a limited version of project portfolio selection problems with it. Excel® was a good option for small problems but as the models became larger it became more and more difficult to use this package as a modeling and solver tool. When such a model has hundreds of formulas copied into different cells on the spreadsheet, it becomes increasingly difficult to find errors. It is also hard for users to understand the model and extend it. Further difficulty arises with spreadsheets when the dimensions of the model begin to change, since spreadsheet models are often constrained by a two dimensional layout and are difficult to modify or to accommodate additional dimensions. The other problem was that Excel® could handle up to 200 variables, which is very low for project portfolio selection problems. For example, to select a portfolio from only 12 candidate projects and schedule the selected projects in 10 periods, the optimization model requires 240 variables. As a result, we decided to eliminate spreadsheets from our choice of modeling and solver packages. We found that Excel® and other spreadsheet software are good tools, but mainly for educational purposes and small problems.

A4.4.2 Specialized 0-1 ILP solver

In order to find specialized solver software, first we tried to obtain a package that applies "implicit enumeration" (a specialized algorithm for zero-one linear integer problems) to solve the zero-one problem more efficiently. Our search on the internet, review of solver surveys in journals (especially the June and October 1995 issues of ORMS), market investigation, and consultation with experts in the field showed that, although there are some isolated software programs such as OPBDP[4] available for this purpose, there is no commercially available software that works under Windows® and applies the implicit enumeration algorithm.

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[4] OPBDP is an implementation in C++ of an implicit enumeration algorithm for solving (non) linear 0-1 optimization problems with integer coefficients. The binary files of the executable OPBDP are provided for SunOS®, Solaris®, and Linux® architectures on the Internet. More information about this software can be downloaded from ftp://ftp.mpi-sb.mpg.de/pub/guide/staff/barth/opbdp/opbdp.html.
For more information on other codes available to solve LP problems see: http://www.mcs.anl.gov/home/otc/Guide/faq/linear-programming-faq.html.

A4.4.3 Lingo®

The student version of Lingo®, that supports 200 variables and 100 constraints, and was the first specialized optimization software that we tried for this purpose. Lingo® is based on the Lindo® solver, and was useful for validating the 0-1 integer linear programming model we developed. However, this software is basically an educational package and lacks the major features we required, such as ODBC support (see Appendix 3), and so was eliminated from further consideration.

A4.4.4 SAS®

SAS® was another package that we considered for modeling. It was eliminated from further consideration because our investigation and consultation with the experts showed that this software: 1) is a general-purpose package and is not regarded as professional optimization software, 2) requires some programming for matrix generation, and 3) is not as fast as specialized solver software such as Cplex® and XA®.

A4.4.5 The Final Rivals

Three solver software packages remained for further investigation as solver software module for PASS: 1) Cplex®, 2) XA®, and 3) Xpress-MP®. All of these packages work on the Windows 95® platform, support the ODBC standard, and therefore satisfied the minimum requirements to be embedded in PASS. We obtained a trial version of each of these solver packages from their vendors in order to do the comparison tests. Cplex® can be coupled with different modeling software packages that are used for developing the model and which also act as an interface between the user and the solver. MPL® and AMPLPlus® are the best-known packages on the market for this purpose. We obtained trial versions of both (MPL®+Cplex®,and AMPLPlus®+Cplex®) packages from their vendors.

Learning the required languages to define models for each solver package, and also learning how to work with all of the above-mentioned software was a very time consuming task. However, a review of the literature showed that creating an MPS[5] problem format could ease the model preparation problem. The MPS format is named after an early IBM LP product, which has emerged as a de facto standard ASCII medium among most of the commercial LP codes. Using the model that was developed with Lingo®, we created an MPS format of the problem. This served as an input to the trial version of each of the software packages.

Although the AMPLPlus® vendor was very helpful and ran our MPS formatted files (that we sent to the vendor through the Internet) on the stand-alone version of Cplex®, this software was eliminated from further consideration because it didn't accept MPS formatted files as input and so could not be benchmarked on our machine. Other reasons for rejection: 1) AMPLPlus® didn't have any major advantages, for our purpose, over the other software packages at hand, 2) we found MPL® easier to learn and its user interface more friendly than AMPLPlus®, and 3) MPL® was coupled with the latest

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[5] For more information on MPS format files see *Advanced Linear Programming*, by Bruce A. Murtagh and *Computer Solutions of Linear Programs*, by J.L. Nazareth.

version of Cplex® (version 4) by its vendor, whereas AMPLPlus® was coupled with version 3 at that time.

All of the three remaining candidate packages satisfied the requirements mentioned before, so we decided to test them in terms of their run times. We developed an example problem in which a project portfolio was to be selected from twelve projects and scheduled within five periods, subject to certain constraints. A Pentium® 166 MHz with 32 MB of RAM, running Windows 95®, was used to conduct the test.

A4.4.6 Xpress-MP®

First, we tested a particular version of our problem both with Cplex® and Express-MP®. We tuned the software by setting the proper options on both packages with the guidance of their vendors, to make run times as low as possible. It took 684 seconds for Express-MP® to find the optimal solution whereas Cplex® solved it in 25 seconds. Another problem with Xpress-MP® was that it combined modeling and solver software in one package. This was a disadvantage to us because we preferred to have more flexibility in terms of the selection of solver and model definition software. Both Cplex® and XA® offer such flexibility. For example, one can use MPL® or AMPLPlus® as modeling tool with the Cplex® solver software. This is a major advantage, especially for later extensions of PASS. For example, we can replace the modeling software (MPL) later on with a customized and more user-friendly interface that we can develop with the Delphi® programming environment. As a result of these shortcomings Xpress-MP® was eliminated from the competition.

A4.4.7 Cplex®

In order to compare Cplex® and XA®, the remaining solver packages, first we tuned these packages to reduce their run times as much as possible. This is a major consideration and has a great impact on the run time. Table A4.1 compares the run times of different versions of the problem on Cplex®, with Lingo®. With the default settings, Cplex® could not solve some versions of the problem (for example, versions 8 and 9) after about two hours. However. after the appropriate tuning, in close co-operation with the vendors and also after a lot of trial and error cycles, the run times dropped drastically.

Table A4.2 compares the run times on different versions of the problem when using the default setting versus the "Strong Branching" setting. The problem versions are sorted based on resource availability. For example, in version 1 there are only 100 units of resource available in each of the five periods whereas in version 34 this number is 1250 units. As an example in the table, in version number 20 the run time dropped from more than two hours for the default setting to 28 seconds when using strong branching.

Although adopting the Strong Branching strategy for Cplex® dropped the run time drastically, we noticed that in certain versions of the problem (such as versions 25 and 26) the run time was above ten minutes. This is too high if the software is going to be embedded in a decision support system. To find the best software to handle problems in reasonably low times we concentrated on the worst versions of our problem (the ones with maximum run times).

Table A4.1- Comparison of WinLingo and Cplex run time

Date: Nov. 8, 1996

Prepared by: Fereidoun Ghasemzadeh

Row	Problem (Version)	WinLingo		Cplex		Objective Function	Comments On Cplex Solution
		Iterations	Run Time	Iterations	Run Time		
1	N12j5p1r(Ver1.1)	794	0:16	85486	2:09	220	
2	N12j5p3r(Ver1.2)	681	0:04	9992	0:17	220	
3	N12j5p1r(Ver2.1)	24195	1:17	356323	9:54	360	
4	N12j5p3r(Ver2.2)	24011	0:32	112368	3:39	360	
5	N12j5p1r(Ver3.1)	382682	21:24	545243	13:34	410	
6	N12j5p3r(Ver3.2)	147988	9:18	667411	21:53	410	
7	N12j5p1r(Ver5.1)	87446	4:50	787737	17:38	580	
8	N12j5p3r(Ver5.2)	31461	1:59	2768510	1:50:48	580	500000 node exceeded,Optimal solution not found
9	N12j5p1r(Ver8.1)	264902	13:22	5104710	2:05:07	690	500000 node exceeded,Optimal solution not found
10	N12j5p3r(Ver8.2)	137208	8:48	26482	3:44	530	
11	M12j5p3r(Ver1)	66351	3:40	370364	9:17	530	

Date: Nov. 28, 1996 Prepared by: Fereidoun Ghasemzadeh

Row	Problem (Version)	Cplex (Default)		Cplex (Strg Brng)		Objective Function
		Iteration	un Time	Iteration	Run Time	
1	fgh11	85486	2:09	98	0:02	220
2	fgh151			98	0:02	220
3	fgh12	9992	0:17	95	0:02	220
4	fgh21	356323	9:54	513	0:14	360
5	fgh251			1822	0:37	360
6	fgh22	112368	3:39	513	0:14	360
7	fgh31	545243	13:34	3836	1:34	410
8	fgh351			3540	1:29	410
9	fgh32	667411	21:53	3836	1:34	410
10	fgh41			1652	0:52	520
11	fgh451			2630	0:54	520
12	fgh42			1652	0:52	520
13	fgh451			2630	0:54	520
14	fgh51	787737	17:38	551	0:16	580
15	fgh551			2704	1:02	580
16	fgh61			949	0:32	620
17	fgh651			5949	2:29	620
18	fgh71			655	0:21	670
19	fgh751			8316	3:39	670
20	fgh81	5104710	2:05:07	810	0:28	690
21	fgh851			3074	1:48	690
22	fgh82	26482	3:44	810	0:28	690
23	fgh91			10194	5:00	730
24	fgh951			21301	9:11	730
25	fgh971			31572	12:40	730
26	fgh981			34513	14:24	730
27	fgh92			10194	4:57	730
28	fgh101			1967	1:01	750
29	fgh1051			5857	2:49	750
30	fgh102			1967	1:01	750
31	fgh111			5250	2:28	750
32	fgh1151			9662	4:01	750
33	fgh121			420	0:14	780
34	fgh1251			864	0:25	780
35	M12j5p3r(Ver1)	370364	9:17	409	0:14	530

Important Note: In all runs with strong branching, in "Computational Options", Use Advanced Basis is unchecked.

Table A4.2 Cplex® run times for different versions of the problem

Our tests revealed an interesting pattern in the run times of different versions of the problem (Figure A4.1). As the figure shows, the run times are lower when resources are either low or very high. The run time is highest for versions 23 to 27 where the amount of resource is neither low nor too high. Our interpretation for this trend is that, when resources are very low, many branches (in the branch and bound algorithm that is used by Cplex®) will be infeasible and so eliminated from further consideration by the solver. On the other hand, when the amount of resources is high, more optimal solutions should exist and so the solver will find the first optimal solution faster. We decided to check our interpretation by counting the number of optimal solutions for each version of the problem and drawing the relevant curve on Figure A4.1 based on that. However, we found that no commercially available software counts the number of optimal solutions, and solvers invariably stop when they find the first optimal solution.

The trend presented in Figure A4.1 was an important finding in our test, and since bringing the run time down was a major issue for us, we decided to concentrate on the versions of the problem that had the maximum run times (versions 21 to 26). Since we required run times of less than about one minute, although the Cplex® results were significantly improved with adoption of the Strong Branching strategy, run times were not satisfactory yet. In order to solve this problem we decided to change the settings so Cplex® would use "heuristics" in finding the optimal solution, but still allowed the solver to find a solution that was within 10% of the optimal solution. Since solvers usually find an optimal or close-to-optimal solution in earlier stages of the optimization process, and then spend the remaining run time on proving the optimality of the solution or finding the

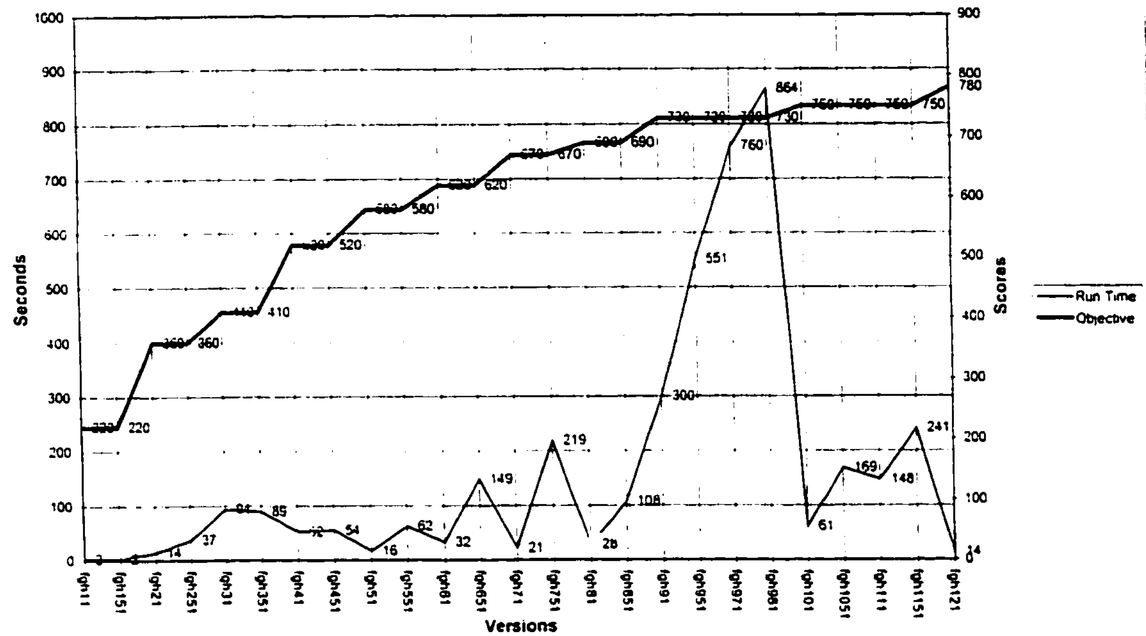

Figure A4.1 Cplex® run times

optimal, instead of close-to-optimal solution, this strategy reduced the run time significantly. The results of this experiment are presented in Table A4.3. Here, the maximum run times were decreased from about 13 and 14 minutes to about 3 and 1 minutes respectively. These run times were close to what seemed to be suitable for a DSS. However, this strategy had a major disadvantage due to the fact that the solutions were not necessarily optimal and we only knew that they were within 10% of the optimal solution.

A4.4.8 Run Time Repeatability

One of the most interesting and serious problems that we encountered during the tuning stage was the amazingly different run times in Cplex® for the same model in different runs although all of the factors (machine used, model parameters, machine work load, software settings, and so on) were intact from one run to the other. For example, on a certain version of the model, using Cplex® with its Strong Branching option we obtained the results presented in Table A4.4.

Unpredictability of run times was a serious problem for DSS and it took a lot of effort and communication with the vendor to fix this problem. An MPS format of the model was sent to the vendor (through the Internet) and they ran the model on the standalone version of Cplex® that runs outside the MPL® environment. The vendors ran the model on six different platforms:

1. Pentium® Windows 95®
2. Pentium® Unix® (Linux®)

Date: Dec 17, 1996

Prepared by: Fereidoun Ghasemzadeh

Row	Problem (Version)	Cplex (SB)		Objective Function	Cplex (SB+HR+10%)	
		Iterations	Run Time		Iterations	Run Time
1	fgh11	98	0:02	220		
2	fgh151	98	0:02	220		
3	fgh21	513	0:14	360		
4	fgh251	1822	0:37	360		
5	fgh31	3836	1:34	410		
6	fgh351	3540	1:29	410		
7	fgh41	1652	0:52	520		
8	fgh451	2630	0:54	520		
9	fgh451	2630	0:54	520		
10	fgh51	551	0:16	580		
11	fgh551	2704	1:02	580		
12	fgh61	949	0:32	620		
13	fgh651	5949	2:29	620	1662	0:59
14	fgh71	655	0:21	670	554	0:19
15	fgh751	8316	3:39	670	3732	1:53
16	fgh81	810	0:28	690	574	0:16
17	fgh851	3074	1:48	690	1448	0:37
18	fgh91	10194	5:00	730	833	0:33
19	fgh951	21301	9:11	730	2738	1:39
20	fgh971	31572	12:40	730	4908	2:55
21	fgh981	34513	14:24	730	1429	0:56
22	fgh101	1967	1:01	750	1012	0:35
23	fgh1051	5857	2:49	750	631	0:22
24	fgh111	5250	2:28	750	351	0:10
25	fgh1151	9662	4:01	750	2979	1:41
26	fgh121	420	0:14	780		
27	fgh1251	864	0:25	780		
28	M12j5p3r(Ver1)	409	0:14	530		

Important Note: All runs with strong branching, and in "Computational Options", "Use Advanced Basis" is unchecked.
SB = Strong Branching
HR = Heuristics
10% = Within 10% of optimal solution

Table A4.3 Cplex® run times with different strategies

Run Time (Min:Sec)	Iterations	Objective Value
53:14	97166	690
02:52	5042	690
14:37	27330	690
28:21	50581	690

Table A4.4 Cplex® results with strong branching for problem fgh81

3. DEC Alpha NT®

4. DEC Alpha Unix®

5. HP Unix®

6. Sun Ultrasparc Unix®

The vendor made repeated runs on each machine, and in some cases ran multiple copies of Cplex® simultaneously to simulate a loaded machine. Although the solution paths differed from one machine to the other, no instance of different solution path (and different run times as a result) was observed. According to the vendor it was consistent with their prior experience with their Branch and Bound implementation, and Strong Branching in particular: the algorithm is deterministic and will not vary from run to run (the only exception being when running on a parallel processor computer). The existence of multiple optima should have no impact on this observation, because when ties are broken they always will be broken the same way on the same machine. It should be noted that not only non-trivial LP models take different solution paths on different machines, but also on the same machine we will see this behaviour when we recompile using a new version of a compiler. That is because in any computer-intensive program, such as Cplex®, there are many things that go inside the compiler and system libraries, that can affect round-off errors that occur during execution. A tiny change in round-off error may cause ties to be broken differently, and different solution paths taken as a result.

The result of Cplex® vendor's tests of the same model on different platforms is presented in Table A4.5. The MPL® vendor who ran the model with Cplex® through MPL® reported the same number of iterations when the problem was the same and the option settings were unchanged. We also asked the AMPLPlus® vendor to do the test for us (using the stand-alone version of Cplex®) and they came up with repeatable run times as well. This was promising in one sense because it showed that we can expect repeatable run times but the problem was still there still there because vendors couldn't provide us with a reasonable explanation of the problem. We were still getting random run times in different runs and, given the importance of the issue, we could not ignore it.

Platform	Iterations	Run Time (Sec)
Pentium® Windows 95®	507	44
Pentium® Unix® (Linux®)	512	6
DEC Alpha NT®	389	5
DEC Alpha Unix®	653	16
HP Unix®	507	26
Sun Ultrasparc Unix®	653	6

Table A4.5 Run time on different platforms for problem fgh81

Further tests, trial and errors and consultations with experts showed that one possible explanation for this problem is that when the LP relaxation of an MIP (Mixed Integer Programming- the algorithm applied by Cplex® to solve 0-1 problems) has alternate optima, then starting the branch-and bond algorithm from a different basis will almost certainly cause a different tree to be built.

Finally, we searched through the MPL® documentation and found that it has an option called "Use Advance Basis". This option allows the advance basis from the previous optimization to be used as the starting point for the next optimization. The default for this option on MPL® was "on". We turned this option off and ran the model several times. The run times repeated in all tests and the unrepeatable run time problem never happened again. It was a big advance in our study because no matter how low the run time is, when it is random one does not know how long it will take to find the optimal solution the next time that the model is run. This is not acceptable for a DSS and if we could not solve this problem it could damage the whole idea of using DSS for project portfolio selection.

A4.4.9 XA®

Once the unrepeatable run time problem was solved with Cplex®, the long run time problem remained. Since we couldn't improve the run times on Cplex® with the existing model, we started to test XA® solver software. XA® had eight different strategies and we found that strategies 6 and 8 gave better run times. Table A4.6 shows

Date: Dec 17, 1996 Prepared by: Fereidoun Ghasemzadeh

Row	Problem (Version)	Cplex (SB)		Objective	XA (Strategy 8)		Objective	XA (Strategy 6)		Objective
		Iterations	Run Time	Function	Iterations	Run Time	Function	Iterations	Run Time	Function
1	fgh11	98	0:02	220	1858	0:05	220	3446	0:10	220
2	fgh151	98	0:02	220						
3	fgh21	513	0:14	360	4953	0:16	360	8977	0:34	360
4	fgh251	1822	0:37	360						
5	fgh31	3836	1:34	410	10465	0:36	410	15871	0:49	410
6	fgh351	3540	1:29	410						
7	fgh41	1652	0:52	520						
8	fgh451	2630	0:54	520						
9	fgh451	2630	0:54	520						
10	fgh51	551	0:16	580						
11	fgh551	2704	1:02	580						
12	fgh61	949	0:32	620						
13	fgh651	5949	2:29	620	57432	3:12	600	620		620
14	fgh71	655	0:21	670	31809	1:51	670	670		670
15	fgh751	8316	3:39	670	94028	5:22	620	670		670
16	fgh81	810	0:28	690	48150	2:46	690	690		690
17	fgh851	3074	1:48	690	53646	3:10	690	690		690
18	fgh91	10194	5:00	730	52535	2:34	730	730	7:45	730
19	fgh951	21301	9:11	730	158990	7:47	700	730		730
20	fgh971	31572	12:40	730	186789	8:41	730	730		730
21	fgh981	34513	14:24	730	178085	8:05	730	730	37:23	730
22	fgh101	1967	1:01	750	10923	0:32	750	750		750
23	fgh1051	5857	2:49	750	31839	1:38	750	750		750
24	fgh111	5250	2:28	750	47918	2:13	750	750		750
25	fgh1151	9662	4:01	750	55773	2:39	750	750		750
26	fgh121	420	0:14	780						
27	fgh1251	864	0:25	780						
28	M12j5p3r(Ver1)	409	0:14	530						

Important Note: All Colex runs with strong branching, and in "Computational Options", "Use Advanced Basis" is unchecked.
SB = Strong Branching
HR = Heuristics
10% = Within 10% of optimal solution

Table A4.6 Cplex® versus XA® run times

XA® run times versus Cplex® using its "Strong Branching" strategy. It should be noted that we were working with Cplex® through the MPL interface, whereas a standalone version of XA® was used directly (without any interface such as MPL® or AMPLPlus®), as supplied by the vendors. As Table A4.6 shows, some run times were improved with XA® but they were still far from satisfactory for PASS. XA® showed mixed results for run time compared to Cplex® (it showed better run times in some versions and worse run times in the others). Since Cplex® was already coupled with a suitable user interface (MPL®), whereas XA® didn't come with a pre-developed user interface, we decided to eliminate XA® and continue our test with Cplex®, through the MPL user interface.

A4.4.10 Final Solver Selection

In some stages of our research we considered the elimination of the modeling software, to establish a direct connection between PASS and the solver (Cplex® or XA®). However, we found that developing a modeling tool with Delphi® that would do a job comparable to MPL is a big job. This interface must help the user to develop the model, allow the establishment of an ODBC connection with the DBMS to input model parameters, combine the data with the model, convert it into a matrix format that is understandable by Cplex®, export the matrix to Cplex® and import the results from Cplex®. Moreover, such customized software should allow for making different types of adjustment to speed up the optimization process. Since software packages that can perform these functions are already available on the market we decided to use MPL® instead.

Since we had examined carefully Cplex®, the most powerful commercial solver software on the market, it seemed that either we must accept a close-to-optimal solution with run times of about 2 to 3 minutes, or accept run times of about 10 minutes. None of these were satisfactory, so we chose to review the literature to see if there was a solution to this problem.

Further literature review showed that, in contrast to linear programming, in integer programming formulating a "good" model is of crucial importance to solving the model efficiently. Knowing the importance of this issue and its potential impact on run time we decided to restructure the models we were using. Finally, we managed to change the model structure and cut the number of variables in half for problems we had been solving. The number of variables in the example model was reduced from 120 to 60 by reformulating it. The older formulation of the model is presented in Ghasemzadeh et al. (1996), and the new formulation is presented in chapter 4 of this thesis.

As the solution space increases exponentially in zero-one problems (introduction of a new variable doubles the solution space) we expected significant improvement in the run times due to this drastic change in the number of variables. Testing the new formulation showed a significant improvement in the run times, and all versions of the problem were solved and optimal solutions found in less than 30 seconds. For our example problem of 12 projects and 5 periods this was a very reasonable run time and so we selected Cplex® as the solver and MPL® as the modeling software for PASS.