PROJECT PORTFOLIO SELECTION TECHNIQUES: A REVIEW AND A SUGGESTED INTEGRATED APPROACH

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ABSTRACT

Project portfolio selection is an important issue for many firms. Tools for project portfolio selection and management are a widely recognized need in research, development, production, and marketing activities for manufacturing firms and in other sectors such as engineering, construction, and software development. They are also used in the public sector, in government, health care, and the military. Such a diversity of applications has generated many differing methods for portfolio selection. The objective of this paper is to review a sample of these methods and to suggest an approach which builds on the strengths of existing methods to develop an integrated strategy that can be used to support managers in making critical decisions concerning project portfolio selection. The strategy allows flexibility in the selection of the methods to suit the culture and environment of the particular organization. It is a three stage approach which includes in the first or *Pre-Process* stage, before project considerations begin, the choice of models and model structures suitable to the organizational environment. A second component of the first stage is *Pre-Screening* to eliminate clearly infeasible projects and reduce task complexity. The second or *Process* stage includes *Individual Project Evaluation* calculations, *Screening* to eliminate projects which do not meet certain specified criteria, and finally integrated considerations of the remaining projects in *Portfolio Selection*. The final or *Post-Process* stage provides portfolio balancing or adjustment under the direct control of the decision makers, using sensitivity analysis with possible iterations back to the portfolio selection process.

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1. Introduction

In its broadest sense, a *project* can be defined as "a complex effort, usually less than three years in duration, made up of interrelated tasks, performed by various organizations, with a well-defined objective, schedule, and budget." A *program* is "a long-term undertaking which is usually made up of more than one project." A *task* is "a short-term effort (a few weeks to a few months) performed by one organization, which may combine with other tasks to form a project." The foregoing definitions are from Archibald (1992). A *project portfolio* is a group of projects, and/or it could also be projects in one or more programs, that are carried out under the sponsorship and/or management of an organization. Hence these projects must compete for scarce resources (people, finances, time, etc.) available from the sponsor, since it is rare that there are enough resources to carry out every project that may be proposed and which meets the organization's minimum requirements for certain criteria such as potential profitability, etc. This results in a need to select among available projects in order to meet the organization's objectives in some optimal manner, however that may be defined.

Project portfolio selection and the associated activity of managing selected projects throughout their life cycles are important activities in many organizations (Martino 1995; Cooper 1993; Meredith and Mantel 1995). There is much evidence indicating that these organizations are making serious but widely divergent efforts to estimate, evaluate, and choose project portfolios optimally (Dos Santos, 1989; Cooper, Edgett, & Kleinschmidt 1995). In fact, it has been suggested (Roussel, Saad, & Erikson 1991) that project portfolio analysis and planning will grow in the 1990s to become the powerful tool that business portfolio planning became in the 1970s and 1980s. Some of the criteria that are addressed in the process of portfolio selection include the organization's objectives and priorities, financial benefits, intangible benefits, availability of resources, and risk levels (Schniederjans and Santhanam, 1993).

In order to discuss project portfolios, we must first understand the generic properties of projects. The attributes that characterize projects include (based on Meredith & Mantel 1995):

1) Life cycle. From an initial beginning, a project may progress through a series of more-or-less well-defined phases through a buildup in size and resource consumption, and then begin to decline after a peak activity and finally to terminate. The generic definition of project phases includes: Concept, Definition, Design, Development/Manufacture, Application/Installation, and Post Completion (Archibald 1992). The actual activities carried out within each phase will differ, depending upon the general class or type of project. Project classes include (Archibald 1992):

a) Commercial and government projects under contract for products or services (e.g. telecommunication equipment contracts),

b) Research, product development, engineering, and marketing (e.g. R&D for new products or services),

c) Capital facilities design and construction (e.g. major building construction),

d) Information systems (e.g. development and installation of an executive information system in a large firm),

e) Management projects (e.g. business process re-engineering projects), and

f) Major maintenance projects (e.g. renovation and expansion of a stadium).

2) Interdependencies. Projects often interact with other projects which may be carried out simultaneously by the organization. And there is often an interaction between the project organization (e.g. the research and development department) and other functional areas (e.g. marketing, production, finance) which have a vested interest in one way or another in the project. That is, a project may be carried out on the functional area's behalf, and/or it may consume resources which they control.

3) Uniqueness. Every project has some characteristics which are unique and require special attention in selecting it for inclusion in the development portfolio, or which requires some customization in the way it is managed if it is selected.

4) Conflict. Every project selected must compete for scarce resources and for the attention of management at every phase of its life cycle. The amount and type of resources required, and the type and intensity of management activity, including progress reviews, depends upon the phase of the project.

Among the published methodologies, there has 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 there are many complexities in making a selection, including:

1. There are multiple and often conflicting objectives (or criteria) associated with portfolio selection,

2. Even when all the objectives have been identified, there are still problems associated with determining the trade-offs among the various criteria. In this respect, the importance of guidance from pre-determined organizational policies and budget controls cannot be over-emphasized, in establishing selection guidelines. But there are still other non-tangible trade-offs; for example, are economic objectives more important than political objectives (as in the relative importance of undertaking at least one project for each department involved, as compared to an emphasis on the projects with the most overall strategic significance to the corporation). How important are these considerations, relative to overall economic considerations?

3. The evaluation of proposed individual projects is complicated by two additional factors. First, some of the criteria are qualitative, as opposed to quantitative, in nature. The comparison of qualitative (often intangible) factors, usually based on the judgement of one or more stakeholders, is normally quite different from comparing quantitative factors, for which data or analytical models may be available to assist in the judgement process. Second, each project has risk (the probability of failure) associated with its undertaking, and there may be a large amount of uncertainty associated with the both the level of this risk and the scoring of individual projects on each specific criterion. Assessing both risk and uncertainty may be difficult. There are risks associated with both the development process (technical risk) and the marketplace (commercial risk). Uncertainty in estimating project parameters tends to decline as the project moves from its early to later life cycle stages, but risk in the application of the product or service (in the marketplace or installing it in a business) can rarely be assessed until the project is complete. For example, there is normally a high risk associated with the likely technical or market success of a new product that is in an early developmental phase, and the uncertainty in the estimated risk will also be high, depending upon the organization's experience with this type of product.

4. Projects may be highly interdependent with other projects. This could be due to value contribution or resource utilization. As an example in information systems, developing and implementing an Executive Information System (EIS) might require several precursor projects

(e.g., a number of Transaction Processing Systems (TPS), and so on), each of which could have benefits in its own right.

5. In addition to the difficulties associated with project objectives, often several constraints must be considered. Major constraints which are normally very important include overall project budgets, scheduling, and program considerations. Other important constraints include the market, and limitations on the workforce and its technological capabilities.

6. The number of feasible projects, especially in big organizations, is often very large, and there may be an enormous number of possible combinations of the projects to be considered for the portfolio. For example, there are potentially 2^{100} possible portfolios if there are 100 individual candidate projects. Hence, it is important to eliminate projects from consideration independently on other grounds where it is feasible to do so before the portfolio selection process begins, in order to reduce the total number of projects to be considered.

7. Selection of, or adjustments to, a project portfolio is a process which recurs at more or less regular intervals. Projects which have previously been included in the portfolio should also be re-evaluated at appropriate "milestones" or "gates" to determine whether they continue to merit further development, in competition with projects which have not previously been included. Cancellation decisions are probably the most difficult to implement, since they often involve serious behavioural and organizational consequences.

8. Finally, portfolio selection is usually not the sole responsibility of one individual. It is frequently 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 (e.g. a proposed project may be needed to support services related to an existing product) of the different organizations represented on the project selection committee.

One underlying assumption in this discussion will be that the projects being selected are from one particular class. The overall allocation of resources to each class is assumed to be an overall strategic decision arrived at by some means such as top-down planning external to the portfolio selection process. That is, in our analysis we do not expect to compare between classes such as internal information systems projects, consumer product research and development projects, and construction projects in the same portfolio selection process unless there is a direct relationship among them, such as a support association or direct competition for resources in the same organization. Otherwise it would be impossible to develop a consistent approach that fairly judges among the competing projects in making a selection decision. (For completeness, we do include several portfolio selection methods which can be used for strategic decisions concerned with allocation among classes.) It is also probable that the methodologies most useful in developing a portfolio for one class of projects may not be the best for another class (e.g. payback period may be useful for comparing long term major capital projects, but it may be irrelevant for short term consumer product development projects; development projects carried out under contract have virtually no commercial risk, while a company carrying out development for products it intends to market must consider commercial risk).

A second important assumption is that there is unlikely to be a single best way of portfolio selection. Each organization must choose, within 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 in making selection decisions. For this reason, although it is not feasible to consider all project portfolio or selection methodologies in this paper, we will provide a relatively broad review of a sample of project selection methodologies. This is followed by a general discussion and an approach to portfolio selection will be outlined that allows an organization to design its own decision support approach by choosing among available methodologies. Tools for *decision support*, not *decision making* tools, are emphasized in this discussion, since the thought processes in decision making should be supported and not supplanted by the tools used. This support is provided through models, data, and management of the large amounts of available information so the decision maker can make logical decisions based on what are regarded as the most important facts. In this respect, the human-computer interface plays an important role in displaying the required information in the most meaningful manner, without explicitly requiring the user to consider such distractions as known constraints or complex project interactions which can be managed automatically by the decision support system.

The objectives of this paper are: a) to evaluate the current state of the art in project portfolio selection methods and relevant computer decision support systems, and b) to suggest an integrated approach to providing decision support for portfolio selection which allows decision makers to utilize a desired subset of available methodologies in a logical manner.

In this paper, the existing literature is briefly reviewed. 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 a logical approach is proposed which integrates the best aspects of these methods in a manner that allows a choice of methodologies. An integrated approach would help decision maker(s) to select a suitable balanced project portfolio based on both quantitative and qualitative objectives, subject to resource limitations and project interdependencies which could be automatically managed and displayed by a decision support system during the portfolio selection process.

2. Literature Review

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). Attempts at categorizing these techniques have been only partially successful. But it does seem possible to classify these techniques into two primary categories: *benefit measurement techniques* and *project selection/resource allocation techniques* (Baker and Freeland, 1975). Although some of the techniques we will discuss belong to both of these categories, the first category tends to deal more with the evaluation of individual projects on some basis (economic or otherwise), while the second category deals with the development of project portfolios based on known evaluations of candidate projects.

2.1 Benefit Measurement Techniques

Benefit measurement methods can be described as systematic procedures for obtaining and integrating subjective and objective benefit data. Baker and Freeland (1975) suggest the following classification of benefit measurement techniques on the basis of the thought processes that are imposed on the respondents, although it is possible for a particular benefit measurement method to belong to more than one of these classifications.

2.1.1 Comparative Approaches

This category includes approaches such as Q-Sort (Souder 1984), ranking (Martino 1995: pairwise comparison, and the Analytic Hierarchy Procedure or AHP), dollar metric, standard gamble, and successive comparison (Churchman & Ackoff 1954; Pessemier & Baker 1971). Of these techniques, Q-Sort is most adaptable to achieving consensus in a group situation. In these methods, first the alternatives are compared and then a set of project benefit measures is computed that is based on the stated preferences. In principle, 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. The AHP approach is discussed in more detail below.

Advantages: a) Most of these techniques are relatively easy to understand and use, and
b) they allow the integration of quantitative and qualitative attributes.

Disadvantages: a) the large number of comparisons involved in these techniques makes them difficult to use when there are a large number of projects to compare,
b) any time a project is added or deleted from the list, the entire process must be repeated,
c) risk is not explicitly considered, and
d) they do not answer the question "Are any of these projects really good projects?"

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a comparative approach which was developed by Thomas Saaty in the 1970s (Saaty, Rogers, & Pell 1980). Since that time, it has received much attention, has been applied in a variety of areas (Golden et al. 1989), and a voluminous body of literature on it has appeared (Zahedi 1986). Its main use is in selecting one project from a list. The use of AHP in solving a decision problem involves the following steps (Johnson 1980):

Step 1- Setting up the decision hierarchy by breaking down the decision problem into a hierarchy of interrelated decision elements.
Step 2- Collecting input data by pairwise comparisons of decision elements.
Step 3- Using the "eigenvalue" method to estimate the relative weights of decision elements.
Step 4- Aggregating the relevant weights of decision elements to arrive at a set of ratings for the

decision alternatives.

The AHP method has been discussed briefly (Harker 1989), and in detail (Saaty 1990). Example uses of AHP for project portfolio selection have also been described (Brenner 1994; Martino 1995). Commercial software (Expert Choice®), which is an implementation of AHP, is readily available. It also addresses some of the concerns with AHP to be discussed below.

Despite the logical and scientific foundations of AHP and its wide application, a number of criticisms of this approach have also appeared. However, the major advantages of AHP are:

a) The AHP structures the decision problem in levels that correspond to an understanding of the situation: goals, criteria, sub criteria, and alternatives. By breaking the problem into levels, the decision maker can focus on smaller sets of decisions (Harker 1989). The evidence from psychology suggests that humans can only compare about seven items at a time (Miller 1956),

b) In pairwise comparison only two factors are compared at each time. This helps analysts and decision makers to better focus, understand, and discuss issues,

c) People may often disagree on certain judgments, but these judgments usually have little or no impact on the final decisions (Harker 1989). AHP allows for performing sensitivity analysis, reducing the rhetoric in debates that can often arise in group settings (Harker 1989),

d) AHP is quite accessible and conducive to consensus building (Bard & Sousk 1990),

e) AHP handles qualitative as easily as quantitative factors.

The following disadvantages are associated with the use of the AHP method:

a) Relative ranking of alternatives may be altered by the addition of other alternatives. This issue, perhaps the most controversial aspect of AHP, has been discussed in a number of articles by both critics and proponents of AHP (Dyer 1990),

b) The bounded 9 point scale used in the AHP method inherently may give results that are outside accepted consistency standards. The problem is most severe with large numbers of alternatives, but it can exist when there are only three (Murphy 1993). Experimentation may be necessary to reach a consensus on the numerical values to be associated with the AHP semantic scale (Harker & Vargas 1987),

c) As the number of criteria and alternatives increases, the number of pairwise comparisons required of the decision maker quickly becomes burdensome (Lim Kai & Swenseth 1993). For example, in a hierarchy with 4 levels and 6 alternatives on each level, the decision maker must make $(4*6*5)/2 = 60$ comparisons (Harker 1989). In order to reduce this problem in large scale AHP problems, Saaty and Vargas (1981) have developed a modification of the method in which fewer comparisons are performed. If this method is used, the analyst has to strike a comparison between robustness of the estimates and speed of the procedure in order to determine how many comparisons to perform (Kamenetzky 1982).

A set of techniques are available which reduce the number of pairwise comparisons in AHP that the decision maker must make during the analysis of a large hierarchy. This allows the decision maker to reduce the effort involved in the elicitation of pairwise comparisons but also allows redundancy, an important component of AHP (Harker 1987a; Harker 1987b; Harker 1989). Lim Kai and Swenseth (1993) found a point where one alternative becomes dominant to such a degree that, regardless of the effects of the remainder of the comparisons, it can not be overtaken as the preferred choice. While this *dominance point* differs for every problem, results indicate that, in this way, an average of about 50% of the comparisons can be eliminated,

d) The AHP method implicitly assumes that evaluators are inconsistent in expressing their preferences. Once some level of consistency is achieved through consistency checks, no errors should exist in the input data (Zahedi 1986). This is not actually the case in practice, since not all random errors are likely to be eliminated by consistency checks,

e) When decision makers select a project portfolio, they must often deal with some interdependency among projects. To our knowledge, this issue is not addressed in the AHP literature, and decision makers must explicitly or implicitly assume independence, and

f) The AHP method does not address resource limitations in portfolio selection. We do not know whether the best portfolio of projects should only involve the projects ranked at the top of the list.

g) The AHP method does not address the important issues of project interdependence.

2.1.2 Scoring Models

These approaches (Martino 1995) assume that a relatively small number of decision criteria, such as cost, work force availability, probability of technical success, etc., can be defined which will be used to specify the desirability of each alternative project. The merit of each project is determined with respect to each criterion. The scores are then combined (when different weights are used for each criterion, the technique is called "Weighted Factor Scoring", probably the most commonly used scoring model) to yield an overall benefit measure for each project.

Advantages: a) Although the benefit measures are relative, projects can be added or deleted without affecting the benefit scores of other alternatives,

b) they allow the integration of quantitative and qualitative attributes, and

c) these techniques are relatively easy to understand and use.

Disadvantages: a) Risk is not explicitly considered,

b) weights are required, which are cumbersome and difficult to evaluate,

c) these techniques are not well suited for situations where selection of one project influences the desirability of another, and

d) they do not answer the question "Are any of these projects really good projects?"

2.1.3 Benefit Contribution Models

Project benefit with these methods is measured in terms of contributions to a number of project or program objectives. The resulting measure may or may not be relative depending on the specific approach. Alternatives may be added or deleted without influencing the benefit score of other alternatives. This category includes methods such as:

i) *Economic return* (Martino 1995; Remer et al 1993): 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). The latter allows a consideration of risk at various project stages, usually based on either IRR or NPV. The Capital asset pricing model (CAPM) can also be used (Sharpe 1964; Khan & Fiorino 1992). It has the advantage that it includes a provision for risk, but it does not appear to be suitable for discrete project comparisons. A 1991 industry survey of the use of the above techniques (not including CAPM) indicated recent movement towards the use of NPV, a moderate reduction in the use of IRR, and a significant reduction in the use of PBP (Remer et al 1993) when compared to a 1978 survey.

ii) *Benefit/Cost techniques* (Canada & White 1980). These techniques involve the calculation of a ratio of benefits to costs, where the inputs may in fact be derived from present value calculations of both benefits and costs, in order to transform them to the same time basis.

Advantages of i) and ii): a) comparisons are in an easily understood language, and

b) with certain techniques, the best projects are clearly identified by the calculated measure, depending upon the class of projects being considered.

Disadvantages of i) and ii): a) it is difficult to include non-tangible benefits, and

b) detailed data are needed for estimated cash flows, etc.

iii) *Risk analysis*, including decision theory/Bayesian statistical theory/trees (Canada & White 1980; Hess 1993; Martino 1995; Riggs et al 1994), and decision theory combined with influence diagram approaches (Krumm & Rolle 1992; Rzasa, Faulkner & Sousa 1990). These approaches involve a succession of choices, where the probabilities of particular outcomes must be estimated.

Advantages: a) More than one stage in a project can be considered, and

b) the expected values of outcomes at each stage can be determined.

Disadvantages: a) these approaches require estimates of probabilities of possible outcomes, which may be difficult to determine, and

b) the Bayesian approach is not universally regarded by mathematicians as valid.

2.1.4 Market Research Approaches

There are a wide variety of market research approaches which can be used to generate data for forecasting the demand for new products or services, based on concepts or prototypes that can be presented to potential customers to gauge the potential market for the product or service. Techniques used include consumer panels, focus groups, perceptual maps, and preference mapping, among many others. Wind, Mahajan, and Cardozo (1981) give a good exposition on this topic, including related techniques for data analysis.

Advantages: a) the 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,

b) projections of market demand and pricing are essential to the determination of resources that can be devoted to development projects,

Disadvantages: a) market research does not consider other factors such as development, production, and distribution costs and timing,

b) 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,

c) 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 extremely high.

2.2 Project Selection/Resource Allocation Techniques

Although they may be used in their own right in certain cases, project selection/resource allocation techniques may be used to represent a second stage in portfolio selection, with inputs which can be the outputs of first stage benefit measurement methods. A number of these approaches have been suggested in the literature, and several will be discussed briefly here.

2.2.1 Ad Hoc Approaches

i) *Profiles* (Martino 1995). This 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. The human-computer interface aspects of related approaches have been investigated by Todd & Benbasat (1993), who found that users prefer an approach which minimizes effort, and not necessarily the one which provides an optimal solution.

Advantages: a) it is very efficient, and

b) it judges all projects on the same basis, given the values of particular attributes.

Disadvantages: a) it is very arbitrary, and requires specific limits to be set on various criteria. These may be difficult to determine.

ii) *Interactive selection* (Hall & Nauda 1990). This involves an interactive process between the managers championing projects and decision maker(s) responsible for choosing the portfolio. The key feature is that selection criteria are better articulated as the process continues.

Advantages: a) Project managers have an incentive to make their projects look more attractive to the decision maker (this may be a disadvantage!),

b) it helps managers to become very familiar with all aspects of the project, and

c) the projects are more likely to fit the strategic objectives of the decision maker(s).

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

2.2.2 Strategic Planning Tools

The strategic implications of portfolio selection are complex and varied. The best sources of related material appear in Hax & Majluf (1984) and Hax & Majluf (1996), who discuss a number of techniques for developing strategies, including the use of portfolio matrices, to be discussed below. The first two of the following relate to other tools which have been discussed in the literature.

i) *Cognitive modeling or policy capturing* (Martino 1995; Schwartz & Vertinsky 1977). This is a method which examines global decisions to determine the components (actual decision processes) that went into them. There are two approaches: replication of decisions, and evaluation of decisions. The intent is to calibrate the decision process so future decisions can be consistent within the context of previous decisions.

Advantages: a) Allow the analysis of global decisions in order to understand how they were made

Disadvantages: a) Only past decisions can be examined, and it requires a relatively large number in order to get the maximum benefit, and

b) these approaches are of little use in relatively new situations.

ii) *Cluster analysis* (Mathieu & Gibson 1993). This is a method which helps in selecting projects that support the strategic positioning of the firm.

Advantages: a) Assists in maintaining the firm's strategic direction.

Disadvantages: a) Only helps in finding clusters of similar projects, but doesn't select specific projects from within the clusters.

iii) *Portfolio Matrices*

Portfolio matrix methods can be used to prioritize and allocate resources among competing projects. The use of these methods has been promoted by several noted consulting firms during the last few years (Cooper 1993). The Strategies Decision Group (SDG) and Arthur D. Little Corp. have both developed well-known and widely used portfolio matrix methods for project portfolio selection, and their implementations are described briefly in Appendix I.

Portfolio matrices are basically two-dimensionsal pictorial representations of all the projects under consideration. Figure 1 is an example of an SDG matrix model. In a portfolio matrix, usually one dimension represents the likelihood of success, and the second represents the economic value of the project. In all such matrix approaches, the position of a project within a matrix suggests the pursuit of a certain strategy. The intent is that, by using these methods, a reasonable mix of projects on the dimensions represented can be selected by decision makers.

Independent of the specific type of matrix display used, the advantages of project portfolio matrices are:

a) Portfolio matrices are well organized, disciplined methodologies that facilitate the selection of a portfolio of projects,

b) Managers often neglect to use a rational economic approach. Portfolio matrices lead managers to make decisions that are more rational than if they use unaided judgment,

c) 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 believe their use of portfolio planning methods has a positive impact (Haspelagh 1982),

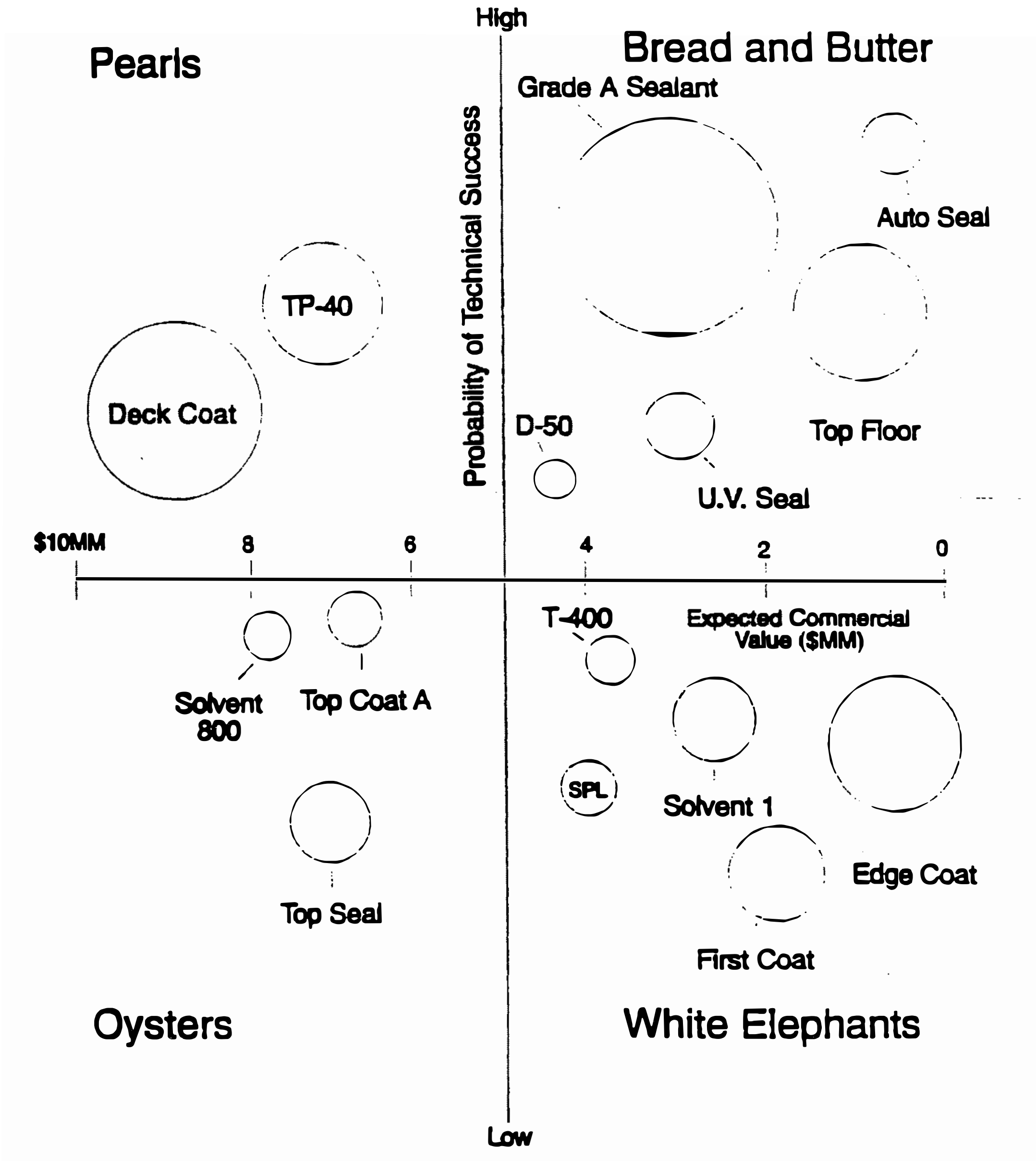
d). Portfolio matrices present information to decision makers in a "user-friendly" manner. They can also be used by groups of managers in decision-making meetings,

e) Portfolio matrices give an overall perspective of all projects underway on a single map, and

f) Portfolio matrices tend to enforce a strategic discipline in decision making. They also provide a commonly understood vocabulary to facilitate idea exchange among decision makers.

The major disadvantages associated with project portfolio matrices are:

a) The scope of portfolio matrices ignores other relevant strategic issues,



Example based on a sealants and coating firm (disguised).

Figure 1 (source - Cooper 1993)

Project Portfolio Matrix Display

b) Portfolio matrices have little theoretical or empirical support (Armstrong & Brodie 1994),

c) Use of project labels (e.g., pearl, oyster, and so on), common in this approach, are appealing and easy to use, but they may lead decision makers to overlook profit maximization (Armstrong & Brodie 1994),

d) No single empirical study has demonstrated that portfolio matrices are valuable as a decision aid (Armstrong & Brodie 1994),

e) Research showed that the BCG matrix approach interferes with profit maximizing, as may other matrix methods (Hax & Majluf 1983). As a result, some researchers have advised against using matrix methods under all circumstances, until evidence is produced that they give superior results (Armstrong & Brodie 1994),

f) Thus far, portfolio matrix techniques have seen limited success (Cooper 1993),

g) 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 & Majluf 1984), and

h) 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, Mahajan, & Swire 1983).

2.2.3 Optimization Models

The objective of an optimization model is to select from the list of candidate projects a set that provides maximum benefit (e.g. maximum net present value) to the firm. Optimization models are generally based on some form of mathematical programming, which not only supports the optimization process, but takes into account project interactions such as resource dependencies, budget constraints, technical interactions, market interactions, or program considerations (Martino 1995). These models also generally support sensitivity analysis (Canada & White 1980), an important aspect of making choices when the portfolio is being fine-tuned. Optimization models based on a variety of mathematical programming techniques or combinations of these have appeared in the literature (see Martino 1995, Chapter 5, for a partial list). However, most of these models do not seem to be used extensively in practice (Souder 1973). Probable reasons for their disuse include the need to collect massive amounts of input data, the inability of most such models to include considerations of risk, and in some cases the model complexity.

There are potential uses of mathematical programming in conjunction with other approaches. For example, 0-1 integer programming could be used to apply constraints such as resource utilization and project interactions, and goal programming allows multiple objectives to be considered simultaneously (Santhanam et al 1989), while a project matrix approach is used. Applications of 0-1 integer programming are described in more detail below.

Advantages: a) mathematical programming approaches maximize overall portfolio objectives, and

b) they allow for interdependencies and other constraints on projects.

Disadvantages: a) these approaches don't deal with tradeoffs between risk and return,

b) don't provide for evaluation of non-tangible benefits and costs,

c) may require data that aren't available,

d) normally cannot include risk considerations (an exception is stochastic programming),

e) with the exception of goal programming, these don't handle multiple criteria, and

f) there is danger that the results may give a false sense of accuracy, even if the input data are highly uncertain.

Zero-one Integer Programming

Zero-one (0-1) integer programming is an optimization approach to project portfolio selection. Such an optimal portfolio is a feasible one (i.e., satisfying all constraints input by the decision maker) which optimizes an overall objective function. This overall objective function could also be defined as a weighted function of various sub-objectives or criteria (i.e. a goal programming approach).

The 0-1 approach is chosen for elaboration here because, from the wide range of possible mathematical programming models, fractional solutions cannot be used in project portfolio selection, unlike the related financial portfolio problem. That is, projects are either selected or not selected. This rules out continuous techniques such as linear and nonlinear programming. Several cases are reported in the literature in which 0-1 integer programming has been used for project portfolio selection (Evans and Fairbairn 1989; Mukherjee 1994; Schniederjans and Santhanam 1993). A comprehensive discussion of 0-1 programming and a classification of different solution methods for 0-1 multiple criteria problems has been given by Rasmussen (1986).

In the following we will limit our discussion to advantages and disadvantages of the *0-1 integer linear programming* (0-1 ILP) model. A more detailed discussion of 0-1 ILP applications to portfolio selection is given in Appendix II.

Advantages of 0-1 ILP are:

a) Using 0-1 ILP for project portfolio selection allows implicit consideration of a multitude of different combinations of candidate projects,

b) The model structures the decision problem in a very clear and understandable manner,

c) The model allows for sensitivity analysis, creating the opportunity to analyze effects of changing the supply of one or more resources,

d) The model handles interdependence among projects, and mutually exclusive projects,

e) Mandatory and ongoing projects can be considered, and

f) The model explicitly considers resource limitations throughout the entire planning period, and also in each individual period if desired.

The disadvantages of 0-1 ILP are:

a) The model does not explicitly handle qualitative factors such as political or social issues, which are usually important and sometimes critical in portfolio selection,

b) The model does not take risk and uncertainty factors into consideration, and

c) The majority of solution methods developed for 0-1 programming problems thus far are not applicable to large problems (Rasmussen 1986).

2.3 Summary of Project Portfolio Selection Techniques

In this section we will summarize the characteristics of some of the portfolio selection techniques we have discussed. This discussion is relatively general, in that we do not consider special adaptations of the techniques mentioned, which may have been made to broaden and enhance the application of the technique mentioned. Column one of Table 1 shows some of the project selection techniques previously discussed, and column two indicates whether the technique has a rigorous theoretical grounding. For each technique an indication is given of which of the set of project or portfolio characteristics shown in columns three to eleven are taken into consideration. Columns 12 to 17 are decision support characteristics which the technique may provide to decision makers. In the best of all possible worlds, a good portfolio selection technique would consider all of the project/portfolio characteristics, and provide decision support of all the types indicated. In practice this has not been the case, as shown in the table, but we will discuss this further in the next section. The following is a brief discussion of the characteristics considered and decision support supplied, in the order of the columns in the table.

Theoretical Basis of the Portfolio Selection Method: The existence of a sound theoretical basis for a portfolio selection method greatly increases the likelihood that its application will produce a result which can be trusted by decision makers. On the other hand, even if the method is theoretically strong, if it is complex to apply or requires large amounts of highly uncertain input data, decision makers will be less likely to consider using it. For example, optimization techniques are well-grounded in theory, but they are not widely used in general because of the large amount of data required, much of which may be highly uncertain. And most of these techniques do not allow the explicit consideration of uncertainty or risk.

A Comparison of Project Selection Methods

Method	Theoretical Basis	Multiple Objectives	Project Interdependence	Mutually Exclusive	Resource Limitations	Qualitative Attributes	Number of Projects	Project Phases	Project Risk	Parameter Estimate Uncertainty	Sensitivity Analysis	Portfolio Balancing	User-Friendly Interface	Overall Perspective	Group Support	Strategic Considerations
		Project/Portfolio Characteristic									**Support Characteristic**					
Comparative																
Q-Sort					Y	Y	S-M								Y	Y
Pairwise Comparison					Y	Y	S									
Scoring		Y			Y	Y	S-L									
Analytic Hierarchy Process	Y	Y			Y	Y	S-M				Y		Y	Y	Y	
Benefit Contribution																
Economic Return	Y						S-L	Y			Y					
Risk Analysis	Y	Y					S-L	Y	Y	Y	Y					
Market Research																
Market Research		Y				Y	S									Y
Strategic Planning																
Portfolio Matrix		Y			Y	Y	S-M		Y			Y	Y	Y	Y	Y
Cognitive Modeling		Y				Y	M-L					Y		Y	Y	Y
Cluster Analysis	Y	Y				Y	M-L							Y		Y
Ad Hoc																
Profiles		Y					S-L							Y		
Optimization																
0-1 Integer LP	Y		Y	Y	Y		S-M	Y			Y					
Goal Programming	Y	Y	Y	Y	Y		S-L	Y			Y			Y		

Table 1

2.3.1 Explicitly Supported Project/Portfolio Characteristics

Multiple Objectives: In selecting projects, more than one objective may be considered simultaneously in making portfolio selection decisions. Examples of objectives include maximize net present value, maximize profitability, maximize market share, minimize cost, etc. Objectives used will depend upon the organization, but these criteria obviously must be uniform across the entire project portfolio.

Project Interdependence: In some cases, projects may not be independent of one another. For example, one project may need to be completed before another project can begin. Other examples include situations where the success of one project may change the likelihood of success of another project (e.g. enhancing or cannibalizing sales), or there may be resource overlap where work done on one project can be used in another related project.

Mutually Exclusive Projects: A good example of mutually exclusive projects arises when several alternative approaches are proposed to solve a particular problem. Then the choice must be made among the alternatives, with only one being chosen. Optimization techniques can handle this type of constraint, even when it is considered in the context of a number of other unrelated projects.

Resource Limitations: Resource limitations are ever-present, but are not explicitly considered by methods which consider only one project at a time, such as benefit contribution and market research methods. On the other hand, constraints such as these can be handled by comparison techniques, which rank projects according to some objective(s). Then resources are typically allocated to the top ranked projects in order until they are exhausted. Some methods such as AHP address the allocation of single resources in this manner, but not multiple resources.

Qualitative Attributes: Some project attributes such as resource requirements may be expressed quantitatively. But qualitative attributes may be needed to express project characteristics such as those for which there may be considerable uncertainty or which are normally expressed as “fuzzy” values (e.g. consumer attitude towards a proposed product may be described as "lukewarm" or "enthusiastic" rather than a quantitative estimate of sales volume) or political characteristics (such as "the capability and experience of a product champion").

Number of Projects: The number of projects that can be considered during portfolio development depends upon the technique used. Smaller numbers help to reduce information overload for decision makers, making it easier to use a broader selection of selection methods. For medium to large numbers of projects, decision makers need the type of support that allows them to consider the most relevant information without being buried by it. In Table 1, the number of projects typically handled by each method is shown as S (small - less than 10), M (medium - 10 to less than 30), and L (large - 30 or more). There are few methods which successfully handle large numbers of projects without using relatively arbitrary selection criteria. Hence, it is important to use screening to eliminate as many projects as possible on other logical grounds not related to overall considerations (e.g. projects which have failed to pass a go-nogo decision at a decision gate).

Project Phases: Most projects, unless they are very small, are broken down into phases, for ease of management control. Some of these phases represent points at which the project has reached some recognized state of completion and can be evaluated against measures of objectives achieved, such as resource consumption, perceived quality of the product or service under consideration, and degree of satisfaction with the project to that point. This allows decisions to be made on committing further resources to the next phase, putting the project on hold, or abandoning it. These decision points may be called “Gates” (Cooper 1993), or “Milestones” (Meredith & Mantel 1995). Each project which has reached a gate should be re-considered in relation to other projects, in the context of the entire project portfolio selection process. But it is also necessary at that time to consider the entire remaining life cycle in evaluating each project. This can only be done by explicitly considering the costs and benefits of all the remaining phases, which can be done with more certainty as each project phase is completed. Several of the benefit contribution and optimization techniques allow this to be done explicitly.

Project Risk: Risk should play a large role in making project selection decisions. This is very clear from the portfolio matrix approaches which frequently use risk as one of the dimensions displayed. The reason for its importance is that projects with potential for break-throughs often have a high payoff, but this is often associated with higher risk. We will define project "risk" as the probability that a project will fail. This can be estimated conditionally for each phase of the project and then combined into an overall project risk. A related measure is the "downside risk", which is the product of the amount at stake and the probability of failure. There are two important sub-categories of risk: "technical risk", which is the probability that a project will not successfully complete the development process, and "commercial risk" which is the probability that the products or services will not be successful in the marketplace, given that it has been successfully developed and manufactured. Technical risk is normally higher during the early phases of a project, declining as the project successfully progresses through its phases. Commercial risk can be estimated through market studies or by evaluation of similar products. The estimation of risk for the purpose of portfolio selection is a topic which requires further study and elaboration, and will be the topic of an additional paper.

Uncertainty: We will define uncertainty as the innaccuracy in the estimates of resource requirements, risk, and any other parameters associated with a project. Uncertainty in most parameters should also decline as the project moves through its phases, because decision makers have more accurate data upon which to base their predictions as the project moves closer to completion. Uncertainty will also depend upon the amount of past organizational experience with similar projects, technologies, and markets. How uncertainty in project parameter estimates can affect project outcome criteria such as risk, benefit/cost, cash flow, etc. may be calculated either through simulation techniques, or by considering extremes in the uncertainty ranges of the parameter estimates. Clearly, the overall estimate of gain or loss if a project is undertaken will be subject to both risk and uncertainty.

2.3.2 Decision Support Characteristics

Sensitivity Analysis: The value of a portfolio's objective function is an estimate of the sum of contributions from all the projects in the portfolio. Clearly, this will be dependent upon the values used for each of the independent variables or attributes of each project, such as payoffs, costs, risks, etc. Sensitivity analysis provides a means of measuring how robust the objective function is to changes in these parameters. If it is very sensitive to particular parameters, then close attention must be paid to improving the accuracy of parameter estimates. If not, then the inevitable inaccuracies in parameter estimates may not seriously impact the overall result. Sensitivity analysis also allows a determination of the impact of additional resources on the portfolio objective function. If additional resources such as financing can improve the objective significantly more than the cost of these resources, then it may be cost effective to invest more in an expanded portfolio.

Portfolio Balancing: Portfolio balance is important on certain portfolio dimensions, such as risk, size of project, and short term vs. long term projects. For example, the proportion of high risk projects should not be too high due to the fact that failures of a large number of these projects could be extremely dangerous to the future of the company. On the other hand, low risk projects may not carry the high return that is often 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 to the firm if more than one fails. And too many long term projects, no matter how promising they are, may cause cash flow problems.

User-Friendly Interface: Decision makers with the responsibility for making portfolio selection typically are managers who are not highly experienced computer users, but in recent years they have come to expect to use computers as decision support tools. For this reason, the computer interface must be very easy to use, should present information in a highly understandable manner (graphical, or easily read concise forms of data if at all possible) and should be based on graphical user interfaces for ease of use. A decision support system with an interface without these characteristics may not be used by managers if its use is optional.

Overall Perspective: Selecting a project portfolio is a strategic decision, and the relevant information must be presented so it allows decision makers to develop an overall view of the portfolio without overloading them with related information unless they specifically need it . An overall view is encouraged by simple plots or matrices on the general dimensions of interest to the decision makers, such as those seen in portfolio matrix plots.

Group Support: As mentioned earlier, a large proportion of portfolio selection decisions are made by groups of managers. This requires that all the managers involved in the decision should have ready access to relevant information, and that they be able to contribute their knowledge in the decision making process. This involvement can range from using simple tools that support rating the relative merits of the projects on various attributes, to more complex tools available through group decision support systems, often set up with multiple computer monitors and displays in "decision rooms", complete with human facilitator support. Characteristics of successful Group Decision Support Systems or GDSS have been determined through research studies (Buckley & Yen 1990).

Strategic Considerations: Certain methods such as Q-Sort lend themselves to overall considerations of the set of projects proposed for the portfolio, thus being qualified as strategic methods. These methods provide a means for high level classification of projects into strategic categories. Strategic planning approaches such as cognitive modeling and cluster analysis also take a broad strategic perspective (Souder 1978; Martin 1984). A more comprehensive study of concepts and tools which can be used in making relevant strategic decisions relevant to project choices is given in Hax and Majluf (1984). As discussed previously, we believe that portfolio approaches should only be applied to groups of projects which have been assigned to particular strategic categories, to avoid apple and orange comparisons.

3. Conclusions From The Review

The following are the conclusions we drew from our examination of existing project portfolio selection methods:

a) *Popular Use of Existing Techniques*. A review of Table 1 indicates that there are sparse areas of coverage by most of the methods examined. It also reveals why certain methods may have been proposed, because they cover project characteristics or they provide support in certain areas that other methods do not. For example, project interdependence and mutually exclusive projects are handled by optimization techniques, while project phases are explicitly handled by only some of the benefit contribution and optimization models. Parameter uncertainty is recognized as one of the more important measures in portfolio selection and management (Meredith & Mantel 1995), yet only the risk analysis technique evaluates it explicitly (see Canada & White 1980). And only risk analysis and portfolio matrix techniques explicitly consider project risk. On the other hand, a number of techniques can be applied to projects with qualitative attributes. AHP and portfolio matrices are popular among decision makers, partly because of their ability to consider a broader range of project/portfolio characteristics, and partly because they offer more decision support coverage, as can be seen in Table 1. However, AHP does not allow the consideration of multiple resource constraints. Although some of the benefit measurement techniques such as scoring, economic return, etc. are widely used 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.

b) *Information Overload.* Helping to reduce the amount of information that managers need to consider in making their decisions has been shown to be attractive to decision makers, since they tend to favour a least-effort approach (Todd and Benbasat 1993). On the other hand, it is important to ensure that decision makers do not forget or ignore important information during the selection process. For complicated problems which involve many projects or interrelated projects, implicit model support may be necessary if a method is to perform well. Any suggested approach to portfolio selection needs to address this issue and to provide support across the areas suggested in Table 1. That is, it should provide a user-friendly interface that is adaptable to group support, in a system that gives an overall strategic perspective and avoids information overload, but at the same time allows the decision maker to do sensitivity analysis and to balance portfolios. None of the techniques we have considered are close to filling these requirements, although the analytic hierarchy process (AHP) and portfolio matrix techniques could be considered to be the best. The following is a brief summary of the aspects of these more widely used techniques as they relate to the issues we have raised.

c) *Analytic Hierarchy Process.* AHP is well-grounded theoretically although it has its critics (see our previous discussion on AHP). It also has the advantage that it has been incorporated into a relatively usable and friendly software package called Expert Choice®, it offers support for a reasonable number of project/portfolio characteristics, and its decision support characteristics are good. Unfortunately it does not address the project risk issue which is normally an important dimension in adjusting portfolio balance, it does not consider multiple resource constraints, and AHP is time consuming to use when there is more than a small number of projects.

d) *Portfolio Matrix Techniques.* It is well-known that matrix techniques are popular for portfolio selection, but it is not so well-known that these techniques appear to be counter productive in terms of meeting stated objectives such as profit maximization (Armstrong & Brodie 1994). Table 1 shows one reason for the popularity of matrix methods - they consider a number of important project/portfolio dimensions and they provide decision support in a majority of the categories identified. Unfortunately, the lack of a solid theoretical grounding is a drawback which leads to a lack of confidence in this type of approach.

e) *Group Decision Support.* The more successful portfolio selection techniques have some provision for group support, which is essential if committee decisions are to be made. In AHP for example, pairwise comparisons of projects on several criteria can be made by several people and the results combined to provide a group result. With portfolio matrix techniques, graphical results may be viewed on a screen, providing an opportunity for input from all committee members.

f) *Project Data Bases.* Although it has not been discussed in detail in this report, the portfolio selection techniques which can be used are constrained by the availability of suitable data on current and previous projects. A comprehensive data base, that records the history of the organization's projects completed and in process, can support the estimation of parameters for current and new projects. Coupling this database to the portfolio selection system through appropriate data analysis packages would help to widen the base of portfolio selection techniques that could be considered by the organization, and would ease the data collection burden when portfolio selection is carried out. This in turn might make it possible to re-balance the portfolio at more frequent intervals (currently, most organizations do this on an annual basis), and thus decrease the time taken to get promising projects underway.

4. An Integrated Approach to Project Portfolio Selection

The previous discussion has covered a variety of existing portfolio selection approaches, identified a number of related problems, and given some reasons why certain techniques are more popular than others. One solution to the problems identified would be to use an integrated approach which takes advantage of the best characteristics of several existing methods. This approach would make use methods which have a good theoretical base, combined with other methods that may not be strong theoretically, but which have desirable decision support characteristics, for example. Our proposal is to use a staged approach, where the most relevant methods can be selected by the organization and used at each stage in order to build a portfolio with which decision makers could be confident. Other attempts to build decision support systems for portfolio selection have been reported (Kira et al 1990; De Maio et al 1994). However, these have been quite limited and perhaps too specific in the methods that were used, rather than providing flexible choices for the users. In the following, we consider the portfolio selection process as a three-stage process, beginning with pre-processing, and going on to processing and post-processing. This is illustrated in Figure 2. We discuss model selection and development, (the choice of techniques used in this process according to organizational needs), in part e) below. The important activities in the portfolio selection process (see Figure 2) include:

a) *Pre-Screening*: This is used to eliminate infeasible projects before the selection process begins, based on preliminary information. This helps to reduce the number which must be

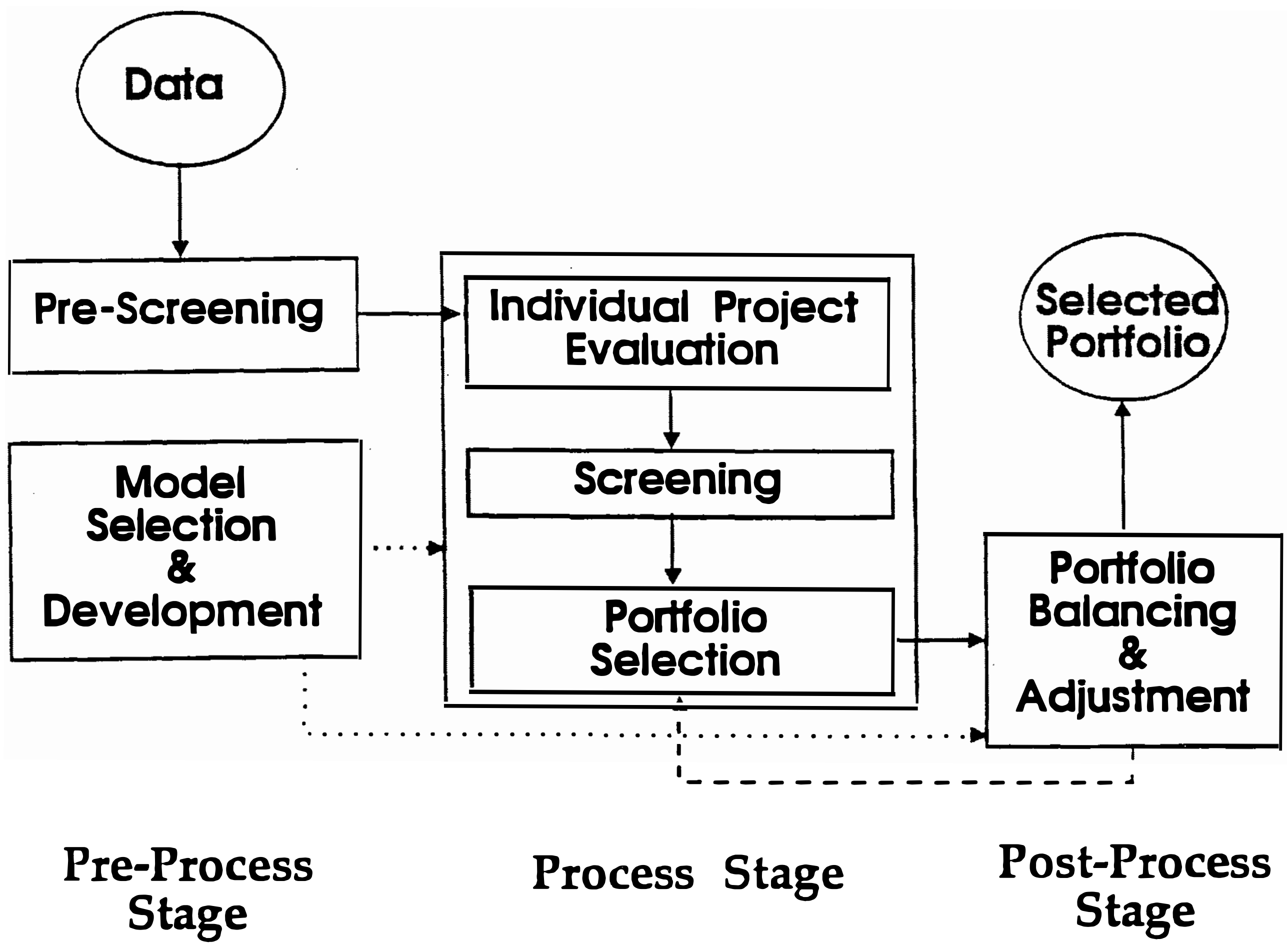


Figure 2

Proposed Project Portfolio Selection Process

considered in the selection process, thereby reducing workload and information overload problems. For example, in-process projects which are at a gate or milestone could be eliminated if they are complete, to be terminated, or put on the backburner due to unsatisfactory progress. Also, large projects which do not yet have a champion or which have not yet undergone a feasibility analysis could be screened out at this stage. However, interdependence of projects, and whether or not projects were mandatory would need to be identified first.

b) *Individual Project Evaluation:* During this process, input data from individual projects are analyzed and processed into a common form which is suitable for further analysis. For example, if the method of choice were a combination of net present value combined with risk analysis, the inputs would be estimates of costs and returns at each development phase and the commercialization phase of a product or service, and the risks at each phase, or more simply the development and commercial risks. Uncertainty could also be input in the form of likely ranges for the uncertain parameters. Other inputs could include qualitative variables such as policy or political measures. Quantitative output from this stage would be (for example) each project's expected net value, risk, and resource requirements over the time frame of the project, along with calculated uncertainties in these output results, and any input qualitative variables on a common scale.

c) *Screening:* During this activity, economic calculations from the previous stage are used to eliminate any non-mandatory projects or inter-related families of projects which do not meet pre-set economic criteria such as estimated rate of return.

d) *Portfolio Selection:* This process combines the outputs of the previous stage in a manner that selects a portfolio, based on the objectives of the organization. This could involve extensive interactions with committee members in comparing potential projects on a number of objectives, or it could involve little direct intervention if an optimization technique such as 0-1 ILP were used. The output of this stage would be a preliminary ranking of the projects, based on the objective(s) specified for the portfolio, and an initial allocation of resources up to the maximum available. This would provide only a first cut at the problem, which would then proceed to the post-processing stage where final adjustments are made by decision maker(s), and re-calculations carried out as necessary to provide support during sensitivity analysis and portfolio balancing.

e) *Portfolio Balancing and Adjustment:* At this stage decision makers apply judgment to make the final adjustments to the portfolio. The decision support display would be in the form of one or more portfolio matrices, which would display graphically the critical decision variables selected by the organization for this purpose. Any interactions among the projects, such as interdependence and mutual exclusivity, have already been taken into account in previous activities and could be displayed during this stage upon request. Portfolio balancing is a judgment problem which requires feedback to the decision maker(s) on the consequences of making deletions and/or additions at this point. Data on this would come from sensitivity calculations, using the same model applied in the portfolio selection process. Hence there could be a substantial amount of iteration between the processing and the post-processing stage during the final adjustment process.

f) *Model Selection & Development*

Before beginning the portfolio selection process, the organization needs to decide which techniques it wishes to use in each stage of the process. This would probably be a one-time process (with minor and infrequent adjustments), which would depend upon the organization's culture, experience, and the availability of information needed as input. This is complicated by the fact that there is more uncertainty about projects which are proposed but not yet underway, as compared to projects which are already underway and for which there is more data available. This may require a combination of techniques to be used, depending upon uncertainty in the estimates. For example, simple checklists of must-meet criteria could be used during the early days of the project, while more sophisticated models might be used for more advanced projects (Cooper 1993). The important point is that the data provided for later stages in portfolio selection must be in a common format so appropriate comparisons can be made among projects.

Considering the selection process shown in Figure 2, pre-screening would likely be an administrative decision based on specific guidelines. Individual project evaluation could be done by a variety of benefit contribution techniques. The screening process would again probably depend on certain guidelines which might eliminate all non-mandatory projects with an internal rate of return less than 15%, for example (if this benefit contribution technique were being used).

During portfolio selection, all remaining projects would be compared on some basis through one of the comparative techniques such as AHP or pairwise comparison, or by optimization. During portfolio balancing and adjustment all the projects, including those surviving the screening process but not selected during portfolio selection, would be displayed on certain dimensions such as those used for portfolio matrices, as chosen by the organization. Information available to the users while the final balancing process is underway should include the amount of each resource consumed and the sensitivity of the objective function to changes caused by adding or deleting projects. This might require iteration back to the previous stage to refine the portfolio calculations.

Since decision makers should be directly involved with the selection process at each of its stages, support tools will be essential to implement each technique used, and the intention should be to leave the choice of specific techniques up to the decision makers. We believe that this generic approach would allow the best parts of each technique chosen to be integrated into a system which provides far better and more acceptable project portfolios than those which can be generated by any single technique we have discussed. Further studies are being done to evaluate the potential of this flexible and integrated approach, and will be reported in the near future.

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APPENDIX

I.1 Strategic Decision Group (SDG) Project Portfolio Method

This discussion is an adaptation of material from a variety of sources (Cooper 1993; Hax & Majluf 1984; Matheson & Menke 1994). The SDG portfolio matrix consists of two dimensions. The first dimension represents the Expected Commercial Value (Net Present Value or NPV) of the project given technical success. The second dimension represents the Probability of Technical Success of the project.

The two factors mentioned above are calculated for each candidate project and then all of the candidate projects are plotted in a bubble diagram. The size of the bubbles or circles denotes the amount of financial resources devoted to each project, hence serving as a third dimension, the size of the project.

Figure 1 (see page 18) depicts a typical SDG matrix. In this figure, each quadrant has a certain name. These names might be different depending on the country or company where the matrix is being used, but the strategy that should be followed for a project falling into that quadrant is the same since projects in the same category tend to have similar characteristics. Commonly used labels for SDG quadrants are as follows:

α) *Pearl*- Highly desirable projects that have both high commercial value and high probability of technical success. Identified revolutionary commercial applications and proven technological advancement projects are typical projects in this category.

β) *Bread and Butter*- Projects with high probability of technical success but low commercial value. Evolutionary improvements in process or product, modest extensions of existing technology or applications, and minor projects are typically in this category. These projects are often necessary because they provide the cash flow that fuels operations of the firm.

γ) *Oyster*- Projects with low probability of success but high commercial value are considered oysters. Revolutionary commercial applications and innovative technological advancement projects are typical of this category. Oysters must be cultivated to yield pearls to ensure the future of the firm.

δ) *White Elephant*- These projects have neither high probability of technical success nor high commercial value. Oysters that are found to be commercially overstated, and bread and butter projects with overstated probability of success fall into this category.

The decision rule could be to seek as many pearls as possible, invest in some oysters, try to cut back on the bread and butter ones (there are usually too many of these), and delete white elephants.

The major advantages of using the SDG portfolio matrix are:

a) It considers technological risk explicitly. This is important, especially for R&D, and

b) The model reflects the project's commercial value. In most cases this is the main reason for carrying out the project.

The most important disadvantages of the SDG method are:

a) The model does not provide any assistance as to how many oysters and/or which ones should be selected or how many bread and butters and/or which ones should be cut,

b) The model assumes that all critical resource absorption can be expressed with a single index (financial). In reality there might be other critical resources such as work force and technical resources that should also be considered,

c) The SDG method does not address the important issue of interdependence among projects. For example, what should the decision maker do if a project is a pearl but another project that gives some required inputs to that project is a white elephant?

d) The issue of mutually exclusive projects is not clear in the SDG model. For example, if two mutually exclusive projects fall into the pearl quadrant which one should be selected?

e) The SDG model only considers the probability of technical success. The probability of commercial success, which is an important risk factor and is sometimes more critical, is ignored,

f) Commercialization and R&D costs are not reflected in the commercial value that is represented by NPV, so some improvements are necessary in the definition of commercial value,

g) A critical limitation arises when the model is to be used as a prescriptive methodology. This limit is implicit in the difficulty of estimating a project's probability of technical success,

h) The range of uncertainty for research more than a year or two in the future is so substantial that use of NPV as a selection factor becomes not only meaningless but possibly harmful (Roussel et al., 1991),

i) The capital and marketing investment required to exploit technological success is not explicitly considered in the model.

I.2 Arthur D. Little (ADL) Project Portfolio Matrix Method

The following description of the ADL method is adapted primarily from chapter six of Roussel, Saad, & Erickson (1991). The ADL approach first examines each individual project, then places each project within portfolio structures that accommodate strategic elements most critical to the specific company and its industry. Individual projects are evaluated in terms of four key elements:

1. Competitive technological strength
2. Technology maturity
3. Competitive impact of technology
4. R&D project attractiveness

Elements of attractiveness and their importance depend on the specific company and industry. However, the most common elements of attractiveness are presented in Figure 3. The first element- fit of the project with the business or corporate strategy- is a decisive one. The remaining criteria come into consideration only if the fit is good to excellent, otherwise the project must be rejected outright.

As different attractiveness criteria have different importance, typically each criterion is weighted, say from 1 to 5, based on the type of the firm and the industry in which it competes. A simple scoring system can then be applied to give a rough ranking of the projects under consideration.

The criteria that decide project attractiveness may be used collectively or as individual components during portfolio considerations (Figure 3). These elements typically may beconsidered and balanced duing R&D project portfolio selection.

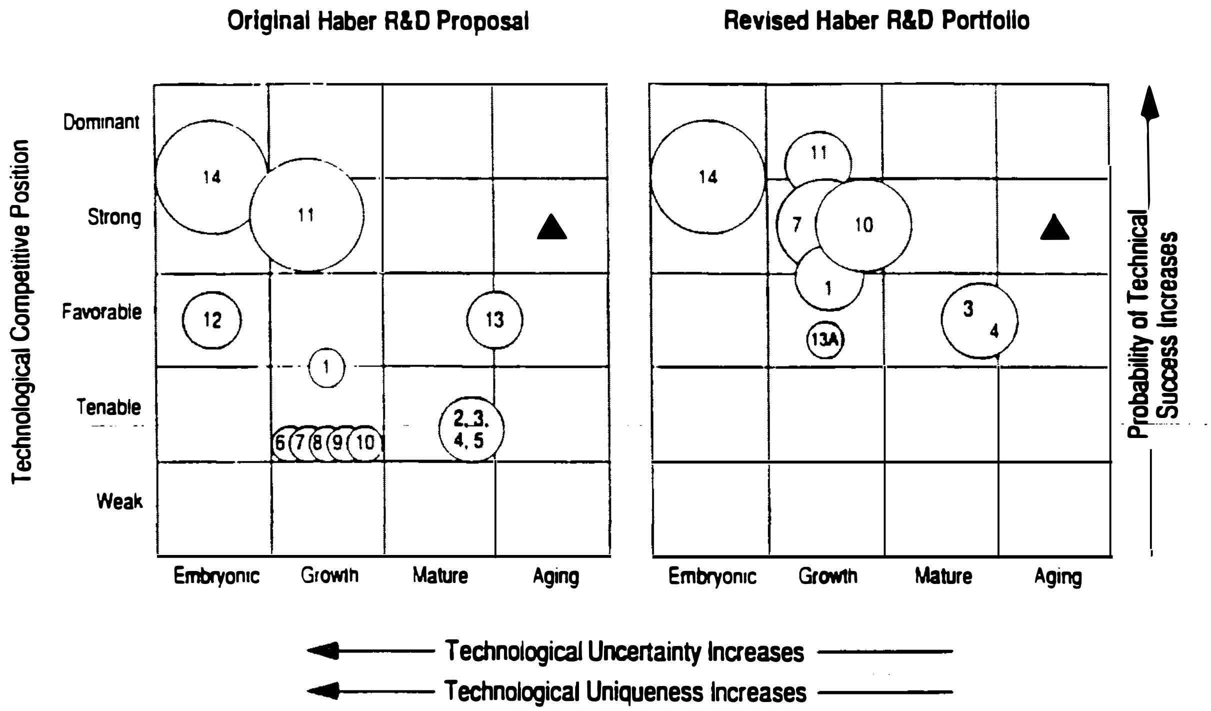
After identifying the portfolio variables that should be balanced, these variables are plotted against each other on two-dimensional grids. Then the proposed projects are examined in these different portfolio matrices. No single display can possibly convey all the complexities of the proposed portfolio but each individual matrix raises some interesting questions. For example, is it prudent to concentrate a major part of resources in high risk projects?

Figure 4 illustrates one of several different matrices that can be applied with regard to the above mentioned criteria. Each circle in the matrix depicts a project and the recommended budget is symbolized by the area within the circle. The improved portfolio is also illustrated in the Figure

Elements of R&D Project Attractiveness	Units in Which Attractiveness is Expressed
Fit with business or corporate strategy	• A judgment ranging from ***excellent to poor***
Inventive merit and strategic importance to the business	• The potential power of the sought-after result to: a) improve the competitive position of the business b) be applicable to more than one business c) provide the foundation for new businesses • A judgment from ***high to low***
Durability of the competitive advantage sought	• ***Years.*** If the R&D result can be quickly and easily initiated by competitors, the project is less attractive than one that provides a protected, long-term advantage
Reward	• Usually financial, but sometimes "necessity work" (e.g., satisfying regulatory bodies) or building a knowledge base that becomes the foundation for applied work
Competitive impact of technologies	• ***Base, key, pacing, embryonic.*** If a project is made up entirely of the application of base technologies, it is classified as "base"; if a project contains at least one key or pacing technology, the entire project is classified as "key" or "pacing"
Uncertainty	
Probability of technical success	• Probability units, ***0.1 - 0.9.*** The probability that the objective will be achieved as defined
Probability of commercial success	• Probability units, ***0.1 - 0.9.*** The probability of commercial success if the project is technically successful
Probability of overall success	• Probability units, ***0.1 - 0.9.*** The product of technical and commercial probabilities
Exposure	
R&D costs to completion or key decision point	• ***Dollars***
Time-to-completion or key decision point	• ***Time***
Capital and/or marketing investment required to exploit technical success	• ***Dollars***

Figure 3 (source - Roussel et al 1991)

Typical Elements of R&D Project Attractiveness



1 Manufacturing cost – vanillin
2 Cola extract
3 Maple extract
4 Raspberry extract
5 Blueberry extract
6 Beef natural essence
7 Shrimp natural essence
8 Salmon natural essence
9 Lobster natural essence
10 Crab natural essence
11 Enzyme Beta (noncaloric fat substitute)
12 Salt mimic
13 Cost reduction – Sweetane
13A Radical cost reduction – Sweetane
14 Fundamental (cocoa tree genetics)

▲ **Technical service to customers**

Figure 4 (source - Roussel et al 1991)

Sample ADL Project Portfolio Matrix Display

beside the elementary portfolio, in the same form. Improvements are based on discussions of different issues raised when decision makers concentrate on different matrices. Typical improvements include abandoning a project, adding the resources that are taken from the rejected projects to the retained projects, improving technological competitive position, and reducing the exposure in some projects by forming an R&D partnership to reduce the costs.

Major advantages of the ADL method are:

a) ADL considers a number of qualitative characteristics of each project that make a project attractive, instead of NPV that is not suitable for R&D projects,

b) Decision makers are forced to consider R&D costs to completion explicitly, and also the capital and marketing investment required to exploit technical success,

c) The portfolio can be balanced from different points of view, and

d) The ADL model considers the probability of technical success as well as the probability of commercial success, which is another important risk factor.

The disadvantages of the ADL method are:

1. Since several matrices are used in this approach, the method can be time consuming and boring. This also leads to information overload since users have difficulty in keeping all the information in mind at one time, thus detracting from the method,

b) The model assumes that all critical resource absorption can be expressed financially. There might also be other critical resources such as work force and technical resources that should be considered during the selection process,

c) The ADL method does not address interdependence among projects,

d) The issue of mutually exclusive projects is not clear in the ADL model, which does not provide any assistance to prevent mutually exclusive projects from being selected, and

e) A critical limitation arises if the model is to be used prescriptively. This limit is implicit in the difficulty of estimating the probability of technical and commercial success.

II. 0-1 Integer Linear Programming Optimization Method

The 0-1 ILP model includes *decision variables*, *an objective function*, and *constraints*. These components are described in detail below (adapted from Evans and Fairbairn, 1989).

Decision Variables

The decision variables are defined by

$$x_i = \begin{cases} 1 & \text{if project i is included in the portfolio} \\ 0 & \text{otherwise} \end{cases}$$

for i = 1,..., N, where N is the total number of projects being considered.

Objective function

Project portfolio selection problems are essentially multi-objective problems involving maximization of benefits in several categories as well as minimization of cost and other resources. These objectives are conflicting in nature. For example, one might select all possible projects in order to maximize the benefits, but this solution would also result in maximization of cost.

In addition, specific projects, if undertaken, may increase benefits in some categories but also will use resources that could have been used for projects that would have increased benefits in other categories. The objective of minimization of the use of resources can be treated implicitly through the use of constraints on resources. A *value function approach* (Keeney and Raiffa, 1976) can be applied to the problem of benefit maximization in the various categories to reduce the multi-attribute problem to single-attribute (Evans and Fairbairn, 1989). This overall objective function could be a weighted function of various sub-objectives or criteria. Therefore, written in an explicit form, the objective function can be given by

$$\text{Maximize } Z = \sum_{b=1}^{B} a_b \left(\sum_{i=1}^{N} q_{ib} \ x_i \right)$$

Where Z is the value function that should be maximized; B is the number of benefit categories; a_b denotes the "importance of benefit category b" to the decision maker; and q_{ib} represents "the amount of benefit" contributed by project i to category b. One could employ the AHP method to obtain estimates of a_b and q_{ib} (Evans and Fairbairn, 1989). Within the scheme of the Expert Choice® software implementation of AHP, a_b is the global priority of benefit category b, while q_{ib} is the local priority of project i with respect to category b.

Constraints

A project portfolio selection problem usually has several constraints. For example, the availability of resources which are necessary for performing the projects such as cost, facility, workforce, and so on, and also the rate of their consumption during the execution period of the projects, e.g., the cash flow of the projects, may all impose constraints.

If the total cost to completion of the selected projects (c_i) should not exceed a certain amount (C), then the following constraint should be set

$$\sum_{i=1}^{N} c_i x_i \leq C$$

If the planning period is divided into T planning periods, denoted by t = 1,...,T, and maximum allowed cost for project i during period t (c_{it}) should not exceed a certain amount in each period t (C_t), then the constraint set would be

$$\sum_{i=1}^{N} c_{it} x_i \leq C_t \quad \text{for } t = 1,\dots, T.$$

The same type of constraints could be established for each of the other limited resources such as workforce (e.g., computer staff software development time) and machine time (e.g., computer time). It should be noted that the cost and other resources that have already been spent on the projects are considered sunk, and would not be considered explicitly in the model. They are implicitly reflected in the total amount of resources that are necessary for the completion of the projects.

If there are K sets of mutually exclusive projects, and S_k is the set of k mutually exclusive projects for k = 1,..., K, then the set of constraints is given by

$$\sum_{i \in S_k} x_i \leq 1 \quad for\ k=1...K$$

Constraints of this type could be used to consider different schedules for a specific project.

Mandatory and ongoing projects which should not be eliminated may also exist in the portfolio. These projects must remain in the model and can be added to the portfolio once it is selected, because they consume resources that should be considered explicitly. The following set of constraints guarantees the inclusion of these types of projects in the selected portfolio.

$$x_{i \in S_m} = 1$$

where S_m is the set of mandatory projects, and

$$x_{i \in S_o} = 1$$

Here, S_o is the set of ongoing projects that should be continued.

Projects which must be discontinued can be eliminated by the following constraint

$$x_{i \in S_d} = 0$$

where S_d is the set of ongoing projects that should be eliminated from consideration. This constraint could also be useful in sensitivity analysis.

Interdependent projects can also be considered in the model. Let P_l be the set of precursor projects for a particular project l, where $l = 1,\ldots, L$. In other words if project l is to be selected, then all of the projects in set P_l must be selected. This is controlled by the following set of constraints.

$$\sum_{i \in P_l} x_i \geq N(P_l) * x_l \quad \textit{for } l = 1 \ldots L$$

where N (P_l) is the number of projects contained in the set P_l.

If only one project from a set of projects, R_m , must be chosen before project m can be selected, this can be managed by

$$\sum_{i \in R_m} x_i \geq x_m \qquad \text{for m} = 1,\ldots, \text{M}.$$

Many other types of constraints could be defined for this model, depending on the situation. For example, one could specify required relationships for different types of projects (e.g., the number of projects in a certain category must be at least twice the number of projects in another category). Enlarging the constraint set does facilitate obtaining an optimal solution (Evans and Fairbairn, 1989).

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