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The University of Arizona, 1991

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A MULTIPLE OBJECTIVE DECISION MODEL
FOR THE EVALUATION OF
ADVANCED MANUFACTURING SYSTEM TECHNOLOGIES

by

Johann George Demmel

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A Dissertation Submitted to the Faculty of the
SYSTEMS AND INDUSTRIAL ENGINEERING DEPARTMENT

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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As members of the Final Examination Committee, we certify that we have read
the dissertation prepared by Johann G. Demmel
entitled A MULTIPLE OBJECTIVE DECISION MODEL

FOR THE EVALUATION OF

ADVANCED MANUFACTURING SYSTEM TECHNOLOGIES

and recommend that it be accepted as fulfilling the dissertation requirement
for the Degree of Doctor of Philosophy.

Ronald G. Askin

8/6/91

Date

Paul J. Sanchez

8/6/91

Date

William J. Thompson

8/6/91

Date

Date

Date

Final approval and acceptance of this dissertation is contingent upon the
candidate's submission of the final copy of the dissertation to the Graduate
College.

I hereby certify that I have read this dissertation prepared under my
direction and recommend that it be accepted as fulfilling the dissertation
requirement.

Dissertation Director Ronald G. Askin

8/6/91

Date

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Abstract

Ordinary financial measures oversimplify the evaluation of Advanced Manufacturing System Technologies (AMST). A multiple objective decision model is developed which avoids the shortcomings of the traditional evaluation methods. The model is comprised of three objectives: Pecuniary, Strategic, and Tactical. The Pecuniary objective is based upon traditional Discounted Cash Flow techniques, with the results normalized to a $[-1, +1]$ (worst-best) scale. The Strategic and Tactical objectives are based upon the concept of qualitative flows, and a qualitative discounting method is employed to discount the qualitative costs/benefits to a present value. The three objectives are traded-off using the Composite Programming technique, resulting in a rank ordering of the alternatives which are under consideration.

The three objectives of the model are broken down into attributes which define the objective, and these attributes are “mapped” into the organization of a manufacturing environment. It is shown that the model covers the entire manufacturing organization in accounting for the costs/benefits of the proposed AMST alternatives.

The influence of the three objectives on the final score is analyzed using a mixture experiment. The mixture experiment provides insight into the effect of varying the importance of each objective and its effect on the final rankings. This provides the analyst a method to determine which attributes and/or objectives are critical for the AMST alternative being investigated.

Realizing that the evaluation of AMST hinges on events which are to occur in the future, and these events are not known for certain, the procedure is extended

to include a measure of risk. Cash flows, qualitative flows, interest rates, and project lengths are provided by the decision maker as pessimistic, most likely, and optimistic estimates. An analysis is provided where the inputs are assumed to be independent. The model is then further enhanced to allow time dependence between cash flows and qualitative flows of a single attribute. Results are provided as a mean and variance of the evaluation score, objective scores, and indices, along with frequency distributions.

A case study analysis is provided which shows the application of the techniques developed in this work.

Chapter 1

Introduction

“During the past two decades American managers have increasingly relied on principles which prize analytical detachment and methodological elegance over insight, based on experience, into the subtleties and complexities of strategic decisions.” [52]

The purpose of this research is to develop a model which can assist a decision maker in the evaluation of Advanced Manufacturing System Technologies (AMST). This chapter provides some background on the evaluation of AMST, the problem statement, research contribution, and the organization of this dissertation.

1.1 Background

Manufacturing technology has progressed a great deal in the past 30 years. Technologies such as Numerical Control (NC), Computer Aided Manufacturing (CAM), Computer Aided Design (CAD), Computer Integrated Manufacturing (CIM), Robotics, and Flexible Manufacturing Systems (FMS) were unknown then. Today these are common technologies in the manufacturing environment, and make up what is called Advanced Manufacturing System Technologies (AMST).

Investments in AMST are difficult to justify using ordinary financial measures. Canada and Sullivan [20] cite four fundamental conditions that point to the need for improved economic evaluation of AMST and Cost Management Systems (CMS):

1. Traditional financial techniques are inappropriate for technology planning.
2. Direct labor is no longer the driver for production control.

Table 1.1: Predominant Approaches to Evaluating Manufacturing Investments [130]

METHOD	MAJOR PROJECT EVALUATION	MINOR PROJECT EVALUATION
PAYBACK	88%	87%
IRR	76%	61%
ARR	63%	59%
NPV	27%	21%

3. Cost patterns have changed.

4. Cost accounting systems no longer reflect the manufacturing process.

Net Present Value (NPV), Return On Investment (ROI), Internal Rate of Return (IRR), Payback period, and Accountant Rate of Return (ARR) are the traditional techniques used to evaluate investments in manufacturing. NPV, ROI, and IRR are generally grouped into a category referred to as Discounted Cash Flow (DCF) techniques. A survey by Swindle [130] found that no single method was used in either major or minor project evaluation. A combination of technologies was used instead. This survey provided a ranking of the techniques as shown in Table 1.1. While these measures are each valid in their own right, they oversimplify the investment decision. They ignore risk and do not provide sufficient representation of the various attributes which make up AMST.

These common financial measures alone are inadequate for making decisions in investments of AMST. Kaplan [71] criticizes the DCF approach because companies tend to set arbitrarily high hurdle rates for evaluating investments into new projects. These high hurdle rates cause companies to invest in incremental, rather than revolutionary, projects. This in turn propagates several small investments

which result in the long run “to a less-than-optimal material flow and to obsolete process technology” [71]. Additionally, the costs of AMST have increased faster than the hurdle rates have changed, posing a significant problem in the justification of new technologies.

The traditional financial techniques are also inappropriate due to the use of inadequate methodology. Companies tend to underinvest in AMST because of a failure to properly evaluate all of the relative alternatives. The common error is in assuming that if no investment is made, the current market share, selling prices, and costs will remain the same. However, experience shows that business rarely continues undisturbed. Maintaining the current methods of operation should therefore assume a situation of declining cash flows, market share, and profits. This is due to the likelihood that if one company does not invest in new technologies, its competitors will.

Another shortcoming of the DCF techniques is their inability to account for intangible benefits such as greater flexibility, shorter throughput, shorter lead time, and increased knowledge in the use of new technologies. These qualitative benefits have an impact on the evaluation process, however they do not fit into the traditional financial models. Thus, these benefits are usually valued at zero in a DCF justification analysis. Analysts “who assign zero values to many intangible benefits prefer being precisely wrong to being vaguely right” [71].

As stated in the second condition, direct labor is no longer the dominant force in production that it used to be. Production is beginning to rely more on indirect functions in getting the job done. Due to this change, performance measurement no longer mirrors the production process. Since all of the current systems in manufacturing are focused on direct labor, management does not have a good

Figure 1.1: Overhead Dominating As Value Added Element [9]

grasp on the factors which impact production performance and control.

The shift from direct to indirect labor means that overhead costs are beginning to become a dominant part of the value added in a product. This is the third condition relating to the need for improved evaluation of AMST. Figure 1.1 depicts the direct to indirect labor relationship. Traditional blue-collar workers are being replaced by information workers, such as design engineers and systems analysts. This change in costs signifies that the high cost element of manufacturing is no longer labor, but rather the machinery associated with AMST.

The shift in employment structure will render traditional accounting methods that allocate overhead to direct labor hours at best irrelevant, and more likely counterproductive. Thus, as the fourth point indicated, Cost Accounting systems no longer reflect the manufacturing process. Variable costs will likely all but disappear (except for purchases of material and the energy required to operate equipment) due to the new manufacturing technology available today.

Madu and Georgantzias [84] discuss the need for a formal approach to evaluate

Table 1.2: Capital Investment and Related Productivity Increase of Western Countries, 1974-1982 [144]

	CAPITAL INVESTMENT (as % of output)	PRODUCTIVITY INCREASE
JAPAN	17.1%	79%
FRANCE	13.6%	43%
WEST GERMANY	11.2%	29%
UNITED KINGDOM	13.0%	16%
UNITED STATES	11.1%	18%

AMST, which includes intangible and non-quantifiable factors. They conclude that such a method can greatly enhance the decision making capabilities of a manufacturing enterprise. Additionally, as shown in Table 1.2, investment trends have a direct impact on productivity. Therefore, in order for the United States to maintain its competitiveness, it must find a method to be able to assist in improved evaluation of capital projects.

1.2 Problem Statement

The literature review of Chapter 2 provides several different views of the AMST problem. Some of the papers reviewed perceive the situation as strictly quantitative, using monetary criteria. Others have chosen to look at the mix of flexible and non-flexible capacity to acquire, and when the capacity should be acquired. A few have concentrated solely on the strategic issues associated with AMST evaluation. The rest have investigated methodologies which combine the qualitative issues related to AMST evaluation with a quantitative analysis. In all cases, the quantitative analysis has relied upon the traditional principles of DCF techniques.

For the reasons discussed in Section 1.1, the analysis of AMST cannot rely on quantitative measures only. The analysis must adequately incorporate qualitative issues with a quantitative analysis. The quantitative analysis shall avoid the shortcomings of the DCF procedures, specifically the misuse of the magical hurdle rate. The analysis shall not only provide a ranking of the alternatives, but also an understanding of the objectives which make up the AMST evaluation. Therefore, the methodology of the analysis is as important as the analysis itself. The methodology will be viewed from the standpoint of the company, rather than a single individual who is attempting to maximize short-term (sometimes personal) gains. The ranking of the alternatives also shall include an evaluation of the “do-nothing” alternative, or maintaining current operations. A measure of risk (uncertainty) shall be incorporated into the model in order to account for unknown future events which are part of the evaluation. Finally, the technique and methodology shall be intuitive to understand, and practical enough to be utilized by the individuals who perform such analysis in a “real world” setting.

The model used in this AMST evaluation will take the following form. Let X denote the set of alternative AMST's to be evaluated. Let $Z_P(\mathbf{x})$ be the Pecuniary (quantitative) objective, $Z_S(\mathbf{x})$ be the Strategic (qualitative) objective, and $Z_L(\mathbf{x})$ be the Tactical (qualitative) objective. The Pecuniary objective will address the monetary aspects of the evaluation using a DCF technique. The Strategic objective captures the issues which arise in the planning functions of a company, and the Tactical objective addresses the issues in the operational areas of a company. The general form of this problem is represented by:

$$\max Z_P(\mathbf{x})$$

$$\max Z_S(\mathbf{x})$$

$$\max Z_L(\mathbf{x})$$

subject to:

$$\mathbf{x} \in X$$

Further details surrounding the objectives and relating to the set X is provided in Chapter 3.

1.3 Research Contribution

The research undertaken in this dissertation constitutes a contribution to the AMST evaluation area in the following ways. This work defines a methodology to be used in the evaluation of AMST. The methodology is intuitive to the user, and at the same time logical to apply. The methodology has well defined parameters to be used in the evaluation process. The model defined by this work is generic enough to fit the uniqueness of any manufacturing related company. The model depends upon the company's strategic plan, organization, and operations, and as such captures the individuality of the company.

A categorization of the attributes which define the multiple objectives of the AMST evaluation is provided. This information delineates the attributes which make up an objective. Additionally, the importance of these criteria can be defined to capture the uniqueness of the company, so that the evaluation is specific for a particular company's needs. The evaluation of qualitative objectives is performed in a period by period basis, and discounted to a present value, which has not been performed in the existing methods. An assessment of the "do-nothing" alternative is also defined in a broader scope than the existing combination techniques.

Finally, the issue of risk is investigated. A great deal of the evaluation hinges on events which are to occur in the future. These events are unknown for certain,

and a decision made on these events contains risk. A methodology to incorporate the risk factors into the model also contributes to the current research efforts.

The incorporation of these issues into a single model that will prove useful to a practitioner in the field, along with providing avenues for continued research, will be a formidable task.

1.4 Organization of Dissertation

This chapter has provided a background of the problem, along with the motivation to perform work in this area. Chapter 2 provides a review of current research efforts in the area of evaluation of AMST. Chapter 3 presents a deterministic model formulation. Determination of risk is presented in Chapter 4. Chapter 5 provides a case-study example. Extensions to and evaluation of the developed model are provided in Chapter 6. Conclusions and a summary are presented in Chapter 7.

Chapter 2

Literature Review

“All that mankind has ever learned is nothing more than a single grain of sand on a beach that reaches to infinity.” [14]

2.1 Introduction

Various work is currently being undertaken in the area of economic justification and planning with relation to AMST. Some methods deal specifically with the justification of AMST, while others address the planning of AMST with respect to certain financial measures. The methods used represent techniques utilizing quantitative criteria only, qualitative criteria only, and a mix of quantitative and qualitative criteria. The overview provided herein is broken into five categories. They are methods which are based upon traditional engineering economics, operations research, artificial intelligence, control theory, and multiple criteria decision making. Sections are also provided which discuss the attributes commonly used in the evaluation of AMST, and the determination of risk in AMST evaluation. The Chapter concludes with a summary.

2.2 Traditional Engineering Economics

In the area of traditional engineering economics, the work has been directed around two methods: Net Present Value and Cost/Benefit Analysis.

2.2.1 Net Present Value (NPV)

One of the most used methods of economic evaluation of AMST is Net Present Value. This classic method utilizes the time value of money in order to evaluate

the merit of one or several proposed capital expenditures. The form for expressing NPV is:

$$P_0 = \sum_{t=0}^T \frac{Y_t}{\prod_{k=0}^t (1 + i_k)} \quad (2.1)$$

where:

P_0 - present value.

Y_t - net cash flow at the end of period t .

i_k - interest rate in period k , $k \in T$.

T - life of the project.

Kulatilaka [76] performs conventional capital budgeting using NPV, and shows that conventional capital budgeting techniques can be used to justify an FMS. The NPV is determined from the expected cash flows, and is calculated as an incremental NPV compared to a reference alternative. Some guidelines for a cash flow forecasting model are presented, along with methods of incorporating uncertainty into these cash flows using a risk adjusted interest rate.

The procedure is excellent in its quantitative merit, however no qualitative issues from the implementation of the FMS are considered, which may result in the exclusion of important savings from the model. The interest rate is allowed to vary between attributes, which allows for risk to be varied among the attributes. However, using a risk adjusted interest rate can be misleading. If the interest rate includes risk, the risk portion should vary over time. Hodder and Riggs [60] point out that the longer a project progresses through its development cycle, the less risky the project becomes. Thus, if a risk adjusted interest rate is used, the risk portion should be reduced as the project matures.

Canada [19] describes a method to perform a net present worth analysis aimed at evaluation of CIM opportunities. Strategic and tactical attributes, together with financial factors, are used in this method to arrive at a ranking of the alternatives. The importance of the strategic and tactical attributes are represented through a weighting scheme, as is how well each attribute is satisfied by each alternative. A traditional NPV analysis is then performed for each project. The weighted evaluation, NPV analysis, and investment for each project are then charted. A visual trade-off is performed using the highest weighted evaluation and best NPV, resulting in a rank ordering of the alternatives.

This method does not integrate the qualitative and quantitative issues well, but rather treats them as stand alone components. It is also assumed that the qualitative benefits occur at the time of implementation of the project. This is rarely the case, as these benefits take time to fully occur. No consideration of risk is employed in this model.

Bussey [16] describes the selection of projects under constraints known as the Lorie-Savage problem. Weingartner [151] developed a mathematical formulation of a constrained Lorie-Savage problem using NPV. The objective is to maximize a linear function of the net present values of the cash flows associated with individual projects.

This method is excellent in its financial analysis, however the only way to include qualitative aspects in the model would be to quantify them in cash flows. There is also no handling of risk in the analysis.

Choobineh [24] utilizes NPV with possibility distributions in order to represent uncertainty in the justification of manufacturing systems. Possibility theory is an extension of the theory of fuzzy sets. A breakdown is provided between monetary

and nonmonetary attributes used in this model. The monetary attributes are handled using NPV and the nonmonetary attributes are treated as a weighted evaluation.

This methodology arrives at a final possibility distribution for an AMST alternative. A ranking scheme is provided to rank the alternatives using the possibility distributions. This technique provides for a way to incorporate monetary and nonmonetary attributes of AMST, along with a measure of risk.

The general form of NPV shown in equation 2.1 is rarely used in practice. In most analysis, the interest rate i is chosen to be constant, which results in:

$$P_0 = \sum_{t=0}^T \frac{Y_t}{(1+i)^{-t}} \quad (2.2)$$

This constant i is the basis for the criticism by Kaplan [71] and Hayes [51]. The risk of a project tends to get incorporated into the interest rate to protect the decision maker, creating an unusually high interest rate. The use of an interest is not the objection, rather its subjective determination [71], [51], [60]. Not only does the interest rate contain the cost of capital to the firm, it is adjusted for risk and inflation. This adjustment is usually made by the decision maker on a subjective basis. When adjusting the interest rate in this way, it is easy to arrive at an arbitrarily high rate, placing any further technology justification at a compromise. Hodder and Riggs [60] point out that interest rates adjusted in this manner are done so by:

$$1 + i_a = (1 + i)(1 + i_f)(1 + i_r) \quad (2.3)$$

where:

- i_a - Adjusted interest rate.
- i - Market interest rate.

i_f - Inflation rate.

i_r - Risk premium.

Therefore, when a company has a market interest rate of 8%, inflation at 7%, and the decision maker adds in a 10% risk premium, the adjusted rate is 27.1%. This is quite a significant difference to the 15.6% rate for market interest and inflation.

The preferred method of evaluating projects containing risk is to use an interest rate that is adjusted for inflation only, and then adjust the cash flows which occur in a given year appropriately for risk [60]. By doing this, the unnecessary compounding of risk adjustments is avoided. An example of adjusting cash flows for risk is to represent the cash flows in any year as a probability distribution with appropriate parameters such as mean and variance. These cash flow distributions then represent any risk involved with the project.

2.2.2 Cost/Benefit Analysis (CBA)

Bussey [16] describes a CBA method called Benefit-Cost Ratio. This is the ratio of the NPV of the cash flows for a project to the present cost of the project. When this ratio is greater than one, the benefits outweigh the costs, and the project is deemed acceptable. Otherwise, costs outweigh the benefits, and the project is unacceptable.

The CBA ratio provides a ranking of projects based upon the net present value per dollar outlay. However, this method provides no more information than a net present value analysis, and that analysis is more straight forward. This method is strictly quantitative and does not allow for any qualitative benefits to be incorporated. Additionally, there is no provision for risk analysis except through the interest rate.

Chasen and Dow [23] provide an extremely detailed analysis for using CBA to justify CAD/CAM systems. The premise behind this CBA is that established justification using direct cost benefits is preferred. This CBA predominantly analyzes labor, and does not account for qualitative issues. Furthermore, this analysis does not account for the time value of money, which is as bad as using an arbitrarily high interest rate. Risk is not considered in this methodology, and the evaluation does not take into account the “do-nothing” alternative.

Generally, CBA techniques consider only monetary attributes. There is no methodology to incorporate qualitative issues. This technique does not differentiate between small and large investments. Since only a ratio is taken, the magnitudes of the investments become lost. Additionally, not all of the CBA techniques use an interest rate. The omission of an interest rate yields results which are not adjusted for the time value of money, and this can lead to inconsistent evaluations.

2.3 Operations Research Methods (OR)

Much of the work in evaluation of AMST has been performed in the realm of operations research. Analysis of flexible versus non-flexible automation is performed by Fine and Freund [35], [36] (two-stage convex quadratic program), Burstein [15] (mixed integer programming), and Gaimon [39], [40] (control theory). Nobel [97], Newman [94], and Randhawa and West [110] use simulation to analyze the AMST evaluation problem.

The decision of which type of manufacturing capacity to obtain in Fine and Freund [35], [36] is done prior to the actual knowledge of demand. Production decisions are then made after an observation of a demand random variable has been made. The objective of the model is to minimize costs. This model uses some sim-

plifying assumptions which are not realistic. The variable costs for dedicated and flexible capacities are assumed to be equal, which is misleading, as flexible capacities should reduce the variable costs [79]. The authors also make the statement that dedicated capacity incurs an infinite cost of production changeover, whereas flexible capacity incurs a zero change over cost. This is not realistic, as flexible capacity still has a change over cost, but it is less than the cost for dedicated capacity. A strictly decreasing demand curve is assumed, which indicates that over time the demand is decreasing. This totally ignores any new products, whose new demand curve would exhibit an increasing trend in the early stages of the product life cycle. Additionally, the time value of money is not considered, and no qualitative measures are addressed in this model.

The objective of Burstein's [15] model is to maximize the present value of the firm. The technological opportunities to invest in flexible technology are represented by an investment function. This assists in determining whether to use flexible automation, dedicated automation, or both. This model addresses the contrast between the modularity of flexible capacity and the "lumpy" or indivisible capacity for dedicated automation. Assumptions used in this model such as stationary, deterministic, and independent demand, and infinitely durable equipment are not realistic. Demand can depend on production in previous years, for if one firms' production cannot meet current demand, a competing firm can obtain the extra demand. If the first firm then obtains extra capacity to make up for the demand it could not satisfy, that firm now has to obtain that demand back from its competition. This may place the first firm in a position of having excess capacity over the current demand. Additionally, equipment is not infinitely durable. Equipment tends to fail at one point or another, and always requires

preventative maintenance. These assumptions can result in a model that may not accurately depict the environment, which in turn yields misleading information. Again, this model does not consider qualitative issues resulting from the use of flexible automation. This model also includes no measure of risk associated with implementing flexible technology.

Simulation is used to determine the future costs associated with AMST, and to provide the classic “what if” analysis. Nobel [97] uses simulation as a tool to assist in making financial decisions. Although not directly developed for analyzing AMST, the procedure can be utilized to determine future costs of existing equipment and the optimal life of new equipment for use in the analysis of AMST.

Newman’s [94] analysis focuses on a model of a particular portion of an FMS. The economic model development is a trade-off to evaluate if the increased setup costs, incurred from the use of special purpose pallets, would be offset by the savings obtained from reduced investment in pallets having a general purpose. These results can be incorporated into an economic model to determine if one method of operation is preferred to another.

Randhawa and West [110] present a three-phase approach for analyzing CIM investments, including uncertainty. Their preference for simulation is based upon the fact that CIM investment decisions are based upon many attributes that may exhibit complex dependence relationships. Simulation, in the authors’ view, can handle the many attributes and their relationships better than analytical methods. The approach of this three-phase analysis seems to incorporate all the necessary quantitative measures, along with a measure of risk.

Simulation is well suited for risk analysis, as the use of random variables can provide insight into the randomness of the evaluation. Simulation also provides

additional insight to the adverse or improved effects in other areas of an AMST, as is the case in the analysis by Newman [94]. A simulation could also be extended to include pseudo-qualitative issues, such as effects upon quality resulting in less scrap and rework. The simulation approach, although well suited to complex models, can itself become complex. This complexity in turn can become costly due to requirements for verification and validation of the simulation model.

The models of Gaimon [39], [40] are intended to capture an organization's goals, and revolve around the organization's motivations identified for acquiring automation, the purpose and use of the automation under consideration, and the manner in which the automation is acquired over time. These models provide for a very detailed analysis of the acquisition of automation, however again the qualitative issues associated with automation are not accounted for in any of the models. Some of the assumptions are also questionable, such as the continuous acquisition of automation and that demand cannot exceed production capacity. Granted automation is generally acquired modularly, however these modules are acquired at discrete points in time, generally over years. Also, it is possible for demand to exceed capacity and this occurrence should be allowed to happen in the model so that the effects of this event can be analyzed. The models do not consider risk.

The OR approaches to evaluation of AMST are all quantitative in nature and fail to include qualitative issues in their analysis. These models also require strict assumptions in order for solutions to be determined, and these assumptions can compromise the applicability of the model to a "real world" setting. Finally, these models assume that appropriate input data is available to evaluate the models. In AMST, this data is generally not available due to the newness of these systems

[110]. Thus, further assumptions about the input data are required, and these should be made in some sort of unknown (probabilistic) sense. Except for the simulation approaches, this is not generally performed in the models reviewed under this section.

2.4 Artificial Intelligence (AI)

In addressing a problem in decision analysis, it is almost impossible not to find some sort of solution in the artificial intelligence arena. Sullivan and LeClair [129] present an Expert System (ES) for use in the justification of FMS. Hengold et al. [53] use an ES to analyze venture justification of AMST. These ES's provide a "consultant service" in the evaluation of advanced manufacturing technology. Three recommended decisions are achieved from the use of these systems. They are "GO", "NOGO", or "DEFER". This results in a categorization of alternatives rather than a rank ordering. Therefore, if two alternatives yield a "GO" recommendation, nothing can be stated in terms of a preference for one alternative over another. These ES's seem to provide a good handling of qualitative issues through the use of production rules, however they are dependent upon knowledge availability in the knowledge base. The financial criteria utilize present value techniques. ES's to handle the evaluation of AMST are an excellent approach, however the primary drawback is the time required to build a substantial knowledge base in order to effectively use these systems. These ES's also have no capability to handle risk.

Padmanabhan [100] presents a tandem expert support system for use in justifying FMS's. This work takes the stand that often a wrong justification technique is used to evaluate an FMS project. The system developed uses an expert sys-

tem to assist the decision maker in selecting an evaluation technique, and then a traditional programming language is used to actually carry out the evaluation calculations. Padmanabhan [100] believes that the existing evaluation techniques can be used to quantify intangible benefits, however the effort required to do so is great and a large amount of knowledge is required in the process. Required data for the analytical model is obtained from the user through the ES.

The tandem expert support system is a good approach to assist in selecting a evaluation technique and to obtain the necessary input for that technique from the decision maker. However, there exists a serious problem in obtaining the required knowledge for the knowledge base since the decision makers are generally unable to break down into steps the way they have reached a particular decision.

AI techniques provide a way to handle qualitative issues in AMST evaluations. Their use is currently not widespread due to the time and information requirements to establish an ES. None of the AI techniques presented considered risk.

2.5 Multiple Criteria Decision Making (MCDM)

Multiple Criteria Decision Making methods have been used to analyze the AMST evaluation problem, providing the ability to include qualitative factors into the model. Several different approaches have been documented, and these approaches show the wide range of applicability in using MCDM for this problem.

2.5.1 Composite Programming

Composite Programming is an extension of the Compromise Programming technique. Composite Programming provides a two-level trade-off analysis. The first level is a trade-off among the criteria of an objective, and the second level is a

Figure 2.1: Graphical Concept of Compromise Solution and Ideal Point

trade-off among the objectives. In order to provide an understanding of Composite Programming, a brief discussion of Compromise Programming is provided.

Compromise Programming [157] is a technique which identifies a compromise solution as that point, or set of points, which minimizes the distance that a solution is from an ideal point. This concept is depicted graphically in Figure 2.1. The main objective of this technique is to reduce the set of non-dominated solutions so that the decision maker can select a “satisficing” solution based upon the decision maker’s own judgement.

Let the ideal solution be defined as a vector $Z^* = (z_1^*, z_2^*, \dots, z_N^*)$ where N represents the number of objective functions and z_n^* is the solution to:

$$\max z_n(\mathbf{x}) \quad n = 1, \dots, N \quad (2.4)$$

subject to:

$$\mathbf{x} \in X$$

It is unlikely that this ideal solution can be attained, however a measurement

can be made on how close a solution is to the ideal. A general form is the L_p -norm:

$$L_p = \left[\sum_{n=1}^N |z_n^* - z_n(\mathbf{x})|^p \right]^{1/p} \quad (2.5)$$

Since each objective n can contribute different levels to the overall result, the deviations $(z_n^* - z_n(\mathbf{x}))$ are to be weighted by a value α_n ($\alpha_n > 0$). As such, Equation 2.5 becomes:

$$L = \left[\sum_{n=1}^N \alpha_n |z_n^* - z_n(\mathbf{x})|^p \right]^{1/p} \quad (2.6)$$

Additionally, each objective n may be measured in non-commensurate units. In order to avoid this problem, the deviations $(z_n^* - z_n(\mathbf{x}))$ can be normalized by dividing the deviation by the maximum deviation found for objective n . This is done by using the normalized distance measure:

$$\frac{z_n^* - z_n(\mathbf{x})}{z_n^* - z_{n*}} \quad (2.7)$$

where z_{n*} is a component of the vector $Z_* = (z_{1*}, z_{2*}, \dots, z_{N*})$ and is the solution to:

$$\min z_n(\mathbf{x}) \quad n = 1, \dots, N \quad (2.8)$$

subject to:

$$\mathbf{x} \in X$$

Now, the distance measure is:

$$L_p = \left[\sum_{n=1}^N \alpha_n \left| \frac{z_n^* - z_n(\mathbf{x})}{z_n^* - z_{n*}} \right|^p \right]^{1/p} \quad (2.9)$$

Geometrically, $p = 1$ implies the sum of axial distances between two points. When $p = 2$, the geometric interpretation is a straight line between two points, which is the euclidean distance between two points. A p value of ∞ results in

complete domination of the largest distance over all of the other deviations. The parameter p in the L_p -norm has significance beyond its geometric interpretation. In Compromise Programming, distance is used as a proxy measure for human preference. The values for p of 1, 2, and ∞ are strategically important in interpreting the results from Compromise Programming. A p value of 1 signifies group utility in the decision making process, or simple majority rule. This most emphasizes the sum of individual utilities, and least emphasizes the individual regret of the choice. A p value of 2 signifies a move towards individual utility, or more emphasis on the individual regret of choice. When p equals ∞ , the interpretation is complete individual utility, or most emphasis on the largest individual regret of choice.

Composite Programming can be viewed as a two-level Compromise Programming technique [6]. In the first level, a Compromise Programming trade-off is performed among the criteria of an objective. The second level is then a trade-off of the objectives for each alternative. Formally, the Composite Programming distance ρ is defined by:

$$\min \rho(\mathbf{x}) = \left[\sum_{n=1}^N \beta_n \left(\sum_{m=1}^{M_n} \alpha_{nm} \left| \frac{z_{nm}^* - z_{nm}(\mathbf{x})}{z_{nm}^* - z_{nm*}} \right|^p \right)^{q/p} \right]^{1/q} \quad (2.10)$$

subject to:

$$\mathbf{x} \in X$$

where:

N - number of objectives.

M_n - number of criteria for each objective n .

z_{nm}^* - $\max_{\mathbf{x} \in X} z_{nm}(\mathbf{x})$

z_{nm*} - $\min_{\mathbf{x} \in X} z_{nm}(\mathbf{x})$

$z_{nm} \in \Re^n$

$$\alpha_{nm}, \beta_n > 0$$

$$p, q \geq 1$$

Bárdossy et al. [6] prove that ρ is a metric on $\mathcal{R}^n$, meaning that ρ as a distance measure will be zero only when the two elements being compared are identical. When the distance measure is non-zero, a difference exists between the two elements. Additionally, the authors show that the nondominated points which correspond to the minima of the composite distances are also minima for compromise distances. Although this technique has not been used to evaluate AMST, it is a good technique to apply in order to incorporate both quantitative and qualitative measures.

2.5.2 Analytical Hierarchy Process (AHP)

Troxler and Blank [141], [139], [140] present a methodology to compare and evaluate manufacturing systems based on a system value model. Their view is that value of the system to the user is the real focus of the AMST evaluation problem. A measure of system value can be obtained utilizing a methodology which includes both monetary and nonmonetary elements. In order to adequately characterize system value, the hierarchy shown in Figure 2.2 was developed. The hierarchy is not reported to be all inclusive, but rather indicative of a typical system. This hierarchy can be tailored to a specific environment (i.e. manufacturing, information systems, service, government), however the basic attributes should remain relatively constant.

The general structure of the system value model is that of a heuristic procedure providing support to decision makers. A vector measure of orders of magnitude for system value (MSV) is defined using Suitability, Capability, Performance, and

Figure 2.2: Criteria of System Value as defined by Troxler and Blank [141]

ATTRIBUTES		FACTORS
SYSTEM VALUE	Suitability	Investment
		Growth
		Technology position
		Market position
		Employee Relations
		Workforce compensation
		Organization Structure
		Operations management
	Capability	Design
		Function
		Reliability
		Availability
		CIM ability
		Flexibility
		Human factors
		Technical feasibility
	Performance	Throughput
		Quality
		Inventory
		Information
		Capacity utilization
	Productivity	Economic infrastructure
		Customer response
		Environmental influence

Productivity as attributes. Each of the four attributes are analyzed separately, and a quantitative indicator is obtained for each. Suitability, Capability, and Performance are all quantified using AHP. Uncertainty is handled by the decision maker providing most likely, optimistic, and pessimistic estimates to use for the various factors. The selection of which estimates to use in the analysis are based upon the decision makers' risk position. For example, a decision maker that does not wish to gamble on unproven technology would use the pessimistic estimate, whereas an optimistic measure may be used for proven technology. Productivity is determined by a modified NPV calculation, where the NPV for each alternative is determined, and the result is divided by the largest absolute value.

After this analysis has been performed, a vector of MSV for each alternative is available. The MSV is a quantitative indicator of the four basic characteristics of manufacturing systems. When one alternative has higher than or equal attribute values for all four measures, with at least one strictly higher, it is the preferred choice.

This method includes monetary and nonmonetary measures, and provides a means to analyze alternatives from different perspectives. However the uncertainty analysis could be more complete. The specification of pessimistic, most likely, and optimistic outcomes for the factors is a good approach, but using only one of these results in the model does not allow for a complete analysis of risk. Additionally, the analysis seems to stop short at a vector result for MSV, as each of the four attributes are not integrated together.

Wabalickis and Ghosh [146] use the AHP to analyze the tangible and intangible benefits which result from the implementation of an FMS. The problem used in the example is to find the best production system, which is the focus level of the AHP

hierarchy. The final result of this methodology is a ranking of the alternatives. Although this method includes some qualitative criteria, such as product mix response, it is not clear how the time value of money is accounted for. Costs are still an important factor in the model, and should be included. This analysis does not consider any measures of risk, also an important factor in the evaluation of AMST.

AHP is also employed by Bard [5]. He defines a methodology whereby the automation of activities for the space station are defined. A decomposition scheme is proposed where individual subsystems may be evaluated separately. The methodology obtains a representative set of alternatives, using a set of multiple objectives to account for the organizational priorities of the decision making process. The methodology allows for the selection of more than one alternative as a solution. The formulations are further set up to accommodate the potential of costs being shared by more than one alternative. This model accounts for qualitative issues, however risk is not considered. Costs are included, although no representation for the time value of money is provided.

Putrus [108] uses AHP to arrive at a nonfinancial evaluation method for CIM. CIM behavior is characterized in terms of risk, benefits, and time. Risk is perceived to be great at the beginning of a CIM project, and then reduced as expertise is gained with the new technology. Risk then increases again due to the resulting uncertain market created by the outputs of CIM. The chance for success of CIM also is viewed to increase over time, identifying CIM as a long term project. The basis of the methodology is support for the business function. Therefore, the hierarchy used for AHP is set up similar to the hierarchy of an organization. This hierarchy is depicted in Figure 2.3, which is a business plan matrix made up of

Figure 2.3: Organizational Hierarchy used for AHP CIM Justification [108]

MISSION		COMPETITIVENESS OF THE ENTERPRISE	
Objectives	Profit Level	Market Share	Sales Growth
Critical Success Factors	Reduced Lead Time	Improved Quality	Reduced Cost
Functions	Engineering	Manufacturing	Production
Selections	Short Term Risks and Benefits	Medium Term Risks and Benefits	Long Term Risks and Benefits

objectives, critical success factors, functions, and selections. The analysis revolves around tradeoffs between risks and benefits, the final result being a ratio for the three time selections of short term, medium term, and long term. This ratio is a risk to benefit relationship.

No financial terms with respect to the time value of money are considered in the methodology. Risk is strictly handled as being within one of three categories (low, medium, high), and does not seem to establish any indication of how well the project can perform. It seems as though the final results are as fuzzy as the decision which is being made.

The AHP only provides a concordance analysis. No displeasure of actions is provided by the decision maker. The results are similar to those obtained using the Project Satisfaction Index from Multicriteria Q-Analysis [103]. The methodology represents the decision makers' satisfaction toward an alternative. There are no global comparisons with other alternatives, and this technique is also not as robust

as the other techniques.

2.5.3 Goal Programming (GP)

Jose and Tabucanon [69] define an economics model using Goal Programming (GP) which identifies geographical regions to select for installation of a production system, how much to produce in a region, and what to produce in a region. The problem is decomposed into a two-phase scenario. The decision makers first identify areas for investment promotion, then select which projects should be accorded promoted status within each area.

This particular model is used for analysis of the pulp and paper industry of a country, but could be used to analyze the effect of AMST considering a plant as a region. Some qualitative issues such as employment and export are included, however the time value of money is not considered in the analysis. Additionally, no measure of risk is included. Also, since the model is subsequently solved using a modified simplex procedure, simplifying assumptions are required in order to use the technique.

Lee and Lerro [81] use GP for the traditional capital budgeting problem. The situation analyzed here is similar to the problem addressed by Weingartner [151]. The objectives are to maximize: the value of the shareholders' wealth, total resources, and owner equity over the long run. Secondary objectives include promoting planned growth, building employee loyalty, and responsible ethics. This model is more of a traditional financial approach, and considers both quantitative and some qualitative issues relevant to the financial community. The quantitative issues include capital expenditures, foreign investment, and NPV. The qualitative issues are complementary projects (pollution control requirements) and company growth rate. Unfortunately, the uniqueness of manufacturing related issues are

not incorporated in this analysis, and risk is also not accounted for in this model.

Goal Programming does not always reach a nondominated solution point. The target values to be achieved are based upon the decision makers' perception of the operation of the organization, and because the decision maker has little information concerning how much deviation the set of constraints will allow for, a dominated solution may result. This can happen when all of the deviations in a solution are zero, indicating that all target values are completely attained. Additionally, this methodology does not allow for trade-offs between the criteria or the alternatives. It simply attempts to attain the stated goals.

2.5.4 Miscellaneous (MISC)

Wymore and Duckstein [156] employ Multicriteria Q-Analysis (MCQA) to rank eleven possible automation projects for selection in a printed circuit card manufacturing area. MCQA is a multiobjective technique based upon the principles of Q-analysis and polyhedral dynamics [112]. Q-analysis provides a measure between the structure of two sets, and how they are related.

The criteria used in the analysis include IRR, investment risk, competitive edge, quality improvement, flexibility, integration, learning curve, and management commitment to a specific alternative. Preferences of the decision maker are captured with this method and incorporated to rank the alternatives based upon these preferences. IRR is included as the financial measure for the model, however IRR should not be used to compare projects [16]. The IRR does not measure the return on initial investment, rather it provides the rate of interest on the unrecovered investment balance for a project with that projects' unique cash flow stream. Additionally, the IRR has meaning only when the level of the investment is considered along with the other cash flows. Therefore, a comparison of IRRs

ignores the absolute investment levels in the projects. Finally, a measure of risk is included as a stationary measure. However risk may vary over time, and different components of the alternatives may have differing levels of risk.

A multiattribute utility model to perform multiperiod project selection is introduced by Mehrez and Sinuany-Stern [86]. The objective of this model is to maximize utility by selecting from indivisible projects under a constraint of limited resources. A scoring approach to the Keeney multiattribute utility function is used to select among projects which contain risk, are interrelated, and have utilities affected by qualitative attributes. Although the thrust of the paper is in solving the model using a branch-and-bound algorithm, the structure is quite applicable to the evaluation of AMST. Risk is well handled in this scenario by identifying a probability that a project will actually be completed. Applicable costs and the time value of money are not included, which makes this analysis strictly one of a strategic nature.

2.6 Attributes Considered in AMST Evaluation

Evaluation of AMST relies on identification of the costs and benefits of the various alternatives in order that they may be compared. Most texts on Engineering Economics provide reasonable examples of the attributes to consider when performing a cash flow analysis. These examples, however, are tied to attributes which are provided by current cost accounting systems, and these systems have been shown to be incomplete for AMST [71], [128], [9], [7], and [154]. As pointed out in Chapter 1, cost patterns in manufacturing are changing, and this is one of the reasons for the need of improved evaluation systems for AMST. This section reviews some of the attributes which should be included in the evaluation of

AMST.

Kaplan [72] identifies five nonfinancial aspects of manufacturing performance. These are quality, inventory, productivity, innovation, and workforce. Quality is defined as the conformance to specifications. Inventory is the amount of goods or material on hand, either in raw parts, subassemblies, or finished goods. Productivity is defined by parameters such as number of units produced, labor hours used, materials processed, energy consumed, and capital employed. Innovation is the introduction by a company of a "constant stream of new products," as opposed to the alternative of producing only mature products. Workforce is the people that make up the manufacturing community.

Including quality and inventory as wholesale terms is somewhat misleading in a nonmonetary perspective. If a part does not conform to specifications, that part must either be reworked to meet the specifications or the part is scrapped. In either case, this is a cost which can be accounted for in the monetary analysis. Inventory is described by the amount of goods sitting idly in a facility, and can be accounted for in the monetary analysis. Productivity is made up of criteria which carry both monetary and nonmonetary aspects. Labor hours used and number of units produced can be directly used in a monetary analysis, however the ratio of labor hours used to available hours and the ratio of the number of units produced to available capacity are good nonmonetary indicators of the productivity of a manufacturing system. These measures indicate the utilization of the workforce and the machinery. Finally, innovation and workforce are good examples of nonmonetary criteria. Innovation is related to the strategic operations of the company, and workforce deals with the greatest asset of a company, its people. Innovation can include how progressive a company is, versus maintaining a

“status-quo”, and workforce addresses issues such as morale, career enrichment, and overall well being of the employees. Therefore, innovation, workforce, and productivity are criteria that should be included in a nonmonetary analysis.

In Kaplan [71], intangible benefits of CIM are discussed. These are flexibility, throughput and lead times, and learning. Flexibility is the potential for “low-cost production of high-variety, low-volume goods”. This is further defined by the reprogramming capabilities of CIM, the ease of handling engineering change orders and product redesigns, and the potential for use after the life-cycle of the product for which it was purchased terminates. Throughput and lead times are respectively the processing time through a facility (or operation) and the time required to respond to demands. Learning is the process whereby a company (or its individuals) obtain experience with state-of-the-art technologies. Thus learning can provide unexpected competitive advantages in the future by placing the company in a leader role and getting to the market place earlier than its competition. Additionally, Kaplan [71] considers inventory and quality as part of the tangible benefits of CIM, as opposed to his earlier treatment of these criteria.

Works [155] lists CIM benefits broken down by CAD, CAPP, GT, Manufacturing Planning and Control Systems, CAM, and Robotics. These benefits are summarized in Table 2.1. The benefits which have monetary implications are identified by an asterisk. The others are considered to fall within the nonmonetary analysis framework. This list is detailed in comparison to others found in the literature, but by no means exhaustive. There is no inclusion in the list of benefits which affect the strategic position of the company, such as innovation as described earlier.

The IBM perspective of CIM lists engineering design cost, lead time, product

Table 2.1: Benefits of CIM as Identified by Works [155]

increased productivity
 improved quality *
 reduced lead time
 elimination of design prototypes *
 paperwork reduction *
 highlight in color complex designs and assemblies
 allows examination of design dynamics and kinematics on computer *
 allows myriad of design views of part
 provides valid geometric part description on computer
 reduced new part introduction cost *
 standardized part routings *
 utilizes more optimal processes *
 reduced requirement for process engineers *
 reduced new part introduction cost *
 increased machine/capacity utilization *
 reduced setup time *
 reduced scrap and rework *
 reduces the number of parts in the database *
 reduced inventory *
 increased customer service *
 reduced purchased part costs *
 reduced overtime *
 improved customer relations
 increased teamwork between company functions
 improved workforce morale
 improved planning
 reduced operator skill requirement
 increased production flexibility
 reduced floor space requirement *
 increased workforce reliability

“(*)” - attributes with monetary implications.

yields, productivity, inventory, and personnel as the criteria of CIM [67]. Inventory, engineering design, and product yields (quality) are the monetary criteria. Inventory and yields are monetary for the reasons mentioned earlier, and engineering design can be broken down into costs such as labor hours required to create or change the design, maintenance of the design, and research into the design. Lead times and productivity, as previously discussed, are part of the nonmonetary criteria. The personnel costs are a combination of monetary and nonmonetary criteria. IBM [67] cites that personnel costs are reduced through efficiencies gained from the integration of information and automation of activities, which is the monetary aspect. The nonmonetary aspect is that job satisfaction is shown to improve through integration and automation. This list again fails to delineate strategic issues, and deals more with attributes which are directly associated with the shop floor.

Tangible and intangible benefits of CIM are identified by Putrus [108]. The tangible benefits include inventory savings, reduced scrap, and reduced warranty expenses. Intangible benefits are faster introduction of new products to the market, improved quality of work life, increased job satisfaction, increased learning by employees, and improved flexibility.

Canada [19] identifies strategic and tactical attributes for CIM evaluation. These include quality, flexibility, lead times, capacity, inventory, production controls, and future capabilities.

Choobineh [24] provides examples of nonmonetary attributes used in justifying manufacturing systems. These attributes, which are strategic and tactical in nature, are listed in Table 2.2.

Noble [98] discusses the strategic benefits which should be considered when

Table 2.2: Example of Nonmonetary Attributes from Choobineh [24]

Quality Contribution to Market Share/Profitability
 New Product Introduction On Time/High Quality
 Development of Engineering/Management Expertise
 Ability to Meet Customer Due Dates
 Quality of Work Life
 Expandability to Other Products
 Ease Transition of New Product to Mature State
 Process Flexibility

evaluating CIM systems. In addition to the monetary aspects related to evaluating CIM systems, strategic aspects are defined. The strategic aspects are broken down into strategic planning, market assessment, and functional analysis. Strategic planning evaluates corporate strengths and weaknesses, defines the company mission and long-term goals, develops manufacturing performance objectives, and evaluates CIM's capability to meet the goals and objectives. Market assessment evaluates customer needs, competition, and industry trends. The functional analysis identifies areas that can be improved from the simplification and integration of operations afforded by CIM. Examples of the attributes cited by Noble [98] as strategic benefits are shown in Table 2.3. Again these attributes are not all inclusive, but rather provide a foundation upon which to build an evaluation of AMST.

2.7 Determining Risk

In the real world, the possible future outcomes of an alternative are not known with certainty. One cannot be expected to know all of the future income and expenses required in an evaluation model. The handling of risk is accomplished

Table 2.3: Attributes of the Strategic Benefits of CIM [98]

COST REDUCTION

- minimize direct labor
- minimize indirect labor
- reduce material costs
- reduce inventory costs
- minimize setup times and lead times
- maximize equipment utilization
- reduce floor space
- reduce maintenance costs
- increase throughput time
- minimize capital expenditures

PRODUCTIVITY IMPROVEMENT

- increase design productivity
- increase manufacturing productivity
- minimize forecasting lead time
- reduce paperwork
- provide real-time information
- increase employee morale
- meet increased capacity needs

COMPETITIVE

- increase market share
- increase product growth
- maximize customer satisfaction
- flexibility to meet demand
- reduced unit cost
- improve response to new market opportunities
- increase competitive advantage

in two ways [16]. The first is that the cash flows are treated as random variables (stream effect). The second is that the interest rate is treated as a random variable (rate effect).

One of the most fundamental methods to handle risk is the use of decision trees [20], [137], and [153]. The principle in this type of analysis is to maximize an expected gain or minimize an expected loss. This method is very intuitive and easy to use. However it can become complex if a large number of decision points, alternatives, and probabilities are used. This complexity is most apparent in formulating the problem. The calculations required to achieve a solution are made virtually insignificant with the advent of today's computers.

Random cash flows in NPV analysis is another method of including risk in AMST evaluation [16]. Cash flows in a given year t are represented by the random variable $\tilde{Y}_t$. The effect of risk can then be expressed through the mean and variance of the distribution $\tilde{Y}_t$. Thus, the summation of the cash flow values to obtain the NPV must result in the NPV itself being a random variable, and $E[N\tilde{P}V]$ and the $V[N\tilde{P}V]$ can be determined.

When the cash flows $\tilde{Y}_t$ are independent, the expected value and variance are determined by simple statistical procedures. However, when the cash flows are dependent, as is the case with most real world applications, the variance of the NPV changes complexity. The approach presented by Bussey [16] assumes that the cash flows form an autocorrelated time series, and that the autocorrelation coefficient matrix among the cash flows (or the autocovariance matrix) can be obtained. The variance of the $N\tilde{P}V$ is:

$$V[N\tilde{P}V] = \sum_{t=0}^T \frac{\sigma_t^2}{(1+i)^{2t}} + 2 \sum_{t_1=0}^{T-1} \sum_{\substack{t_2=t_1 \\ t_1 < t_2}}^T \frac{\rho_{t_1 t_2} \sigma_{t_1} \sigma_{t_2}}{(1+i)^{(t_1+t_2)}} \quad (2.11)$$

where:

σ_t - standard deviation of $\tilde{Y}_t$.

$\rho_{t_1 t_2}$ - correlation coefficient between $\tilde{Y}_{t_1}$ and $\tilde{Y}_{t_2}$.

If the covariance matrix is defined, $\rho_{t_1 t_2} \sigma_{t_1} \sigma_{t_2}$ can be replaced by $COV(\tilde{Y}_{t_1}, \tilde{Y}_{t_2})$. Of course, the expected value of $N\tilde{P}V$ for the dependent case is the same as for the independent case.

The difficulty in using this analysis is to determine the autocorrelation coefficients $\rho_{t_1 t_2}$ or specifying the autocovariances $COV(\tilde{Y}_{t_1}, \tilde{Y}_{t_2})$. Bussey [16] addresses two methods to use when the cash flows are correlated across time. The first is to decompose each $\tilde{Y}_t$ into its contributing elements (ie. gross sales, depreciation, operating expense, etc.) and determine the autocorrelations between these elements. This method is tedious and in many cases does not provide a satisfactory estimate of a correlation coefficient. The second approach views the cash flow stream as a time series, hypothesizes a correlative model, and tests the model for statistical goodness of fit between it and the cash flow data. This usually results in a satisfactory estimate of the correlation coefficient in a correlated time series.

Another method of handling risk is the certainty equivalent method [16] and [20]. This method analyzes a decision makers' utility function, and assumes that this utility function is applicable to future cash flows as well as present cash flows. Certainty equivalents avoid the double discounting of risk which is present in the previously described approach. The previous use of random cash flows assumed that the future riskiness is reduced by the factor $(1+i)^{-kt}$, where $k=2$, at least. According to Bussey [16], there is no rational basis for this assumption. However, the factor $(1+i)^{-kt}$ is the result of the variance calculations of the NPV of random cash flows.

Simulation is another method used to analyze risk [16], [20], and [153]. Using

simulation the analyst can obtain repeated samples from an assumed economic model of the project. Simulation generally assumes that the cash flows are completely independent, however some dependencies can be modeled into the system as reported by Bussey and Stevens [17]. This generally makes the simulation process more complex as the model takes a greater time to develop, verify, and validate. The simulation approach however does avoid the problem of assuming that the future riskiness is reduced by the factor $(1+i)^{-kt}$. This is avoided as each random cash flow is discounted by the appropriate factor $(1+i)^{-t}$. The advent of the computer has also reduced the time and cost required to run simulation models, thus making the technique more available. Randhawa and West [110], Nobel [97], Newman [94], and Kulatilaka [76] utilize simulation techniques in evaluations as pointed out in Section 2.3.

Other discussions of risk were presented earlier in this Chapter. Choobineh [24] uses possibility distributions in the evaluation of AMST. A possibility distribution of the overall measure of an AMST alternative is provided, and this is then used to analyze the alternatives. Fine and Freund [36] employ riskiness in their model by placing an uncertainty on the future demand. In this manner their model adjusts the revenues and costs based upon the realization of the unknown demand. This is fine for costs/revenues that occur outside of the organization, but does nothing to analyze the risks that arise from inside the organization such as maintenance, labor, setups, etc. Putrus [108] discuss risk in relation to the life of the project. Risk is viewed as an attribute of the model, and the decision maker(s) determine through their own judgement if the risk of a project is low, medium, or high. This assessment of risk is then used in the model to arrive at a score for each alternative. In this case risk is viewed at an aggregate level, and does not allow insight as to

the portions of a project which are risky. Wymore and Duckstein [156] include an investment risk criteria in the MCQA analysis. This risk is described as the probability that the project will not succeed, and is defined on a high, medium, or low scale. Similar to the method of Putrus [108], risk is again viewed at the aggregate level.

Risk in AMST evaluation is handled in various ways, from detailed mathematical analysis to high level assessment of overall risk. In relation to qualitative issues, risk is handled at an aggregate level. These methods are all valid in their own right and for the application in which they are employed. However, it seems that quantitative risk should be formulated at the cash flow level. Then, through analysis of the cash flows, a determination of riskiness can be established. In this manner the elements which add to the risk may be identified in order to gain a better understanding of the alternatives to be evaluated. Risk in relation to qualitative issues should be identified at a lower level than the aggregate.

2.8 Summary

The approaches taken in the evaluation of AMST are wide and varied. The traditional engineering economic techniques and operations research methods provide for a strictly quantitative analysis of the situation. The remaining techniques are capable of employing qualitative criteria, along with quantitative criteria, in their analysis. From the above review it seems that the best techniques for addressing the justification of AMST are those in the realm of Multiple Criteria Decision Making (MCDM). The MCDM cases summarized herein include a wider range of criteria than in the other techniques, and adequately cover the appropriate financial material as well. Table 2.4 provides a summary of the techniques presented

in this Chapter.

This issue of evaluation of AMST has also resulted in the development of several commercial software packages for non-traditional economic analysis. Hodge and Canada [61] provide a summary of twenty-eight such computer software packages on the market today. The summary includes cost of the package, and whether or not it contains any of the following capabilities:

1. Multi-Attribute Methods.

- Scoring/weighted evaluation.
- Analytic Hierarchy Process.
- Exclusionary screening.
- Mathematical Programming.

2. Financial/Economic Methods.

- Traditional economic analysis.
- Monte Carlo simulation.
- Decision tree analysis.

3. Goal Seeking Ability.

4. Sensitivity Analysis.

Canada [18] also provides a comprehensive bibliography on the justification of AMST, specifically CIM systems. The bibliography is divided into four sections as follows:

- Books: CIM related in general.

Table 2.4: Summary of AMST Evaluation Techniques Reviewed

METHOD	CAT	TVM	QUL	QNT	RSK	REF
Benefit-Cost Ratio	CBA	X		X		[16]
CBA for CAD/CAM	CBA			X		[23]
Conventional Capital Budgeting	NPV	X		X		[76]
Net Present Worth	NPV	X	X	X		[19]
Lorie-Savage	NPV	X		X		[16]
Possibility Distribution	NPV	X	X	X	X	[24]
Quadratic Programming	OR		X		X	[36]
Mixed Integer Programming	OR	X		X		[15]
Simulation	OR	X		X	X	[97]
Simulation	OR	X		X	X	[94]
Simulation	OR			X	X	[110]
Optimal Control	OR	X		X		[40]
Expert Systems	AI	X	X	X		[129]
Expert Systems	AI	X	X	X		[100]
System Value	AHP	X	X	X	X	[141]
FMS Evaluation	AHP		X	X		[146]
Space Station Evaluation	AHP		X	X	X	[5]
CIM Justification	AHP		X	X		[108]
Site Selection	GP		X	X		[69]
Capital Budgeting	GP	X	X	X		[81]
MCQA	MISC	X	X	X	X	[156]
MUAT	MISC		X		X	[86]
Composite Programming	MCDM					N/A

CAT - Category.

TVM - Time Value of Money.

QUL - Qualitative Analysis.

QNT - Quantitative Analysis.

RSK - Risk Analysis.

REF - Reference.

- Symposia: CIM related in general.
- Articles on justification of CIMS: Subjective overviews and guidelines.
- Articles on justification of CIMS: Quantitative techniques and analysis methodologies.

A total of 113 references are cited, along with six specific references that contain another 216 references in the following areas:

- Replacement decision in high technology industry.
- Economics of robots.
- Productivity measurement and weighted evaluation.
- Assembly automation economics.
- Software costs for manufacturing control systems.

An extensive bibliography on the “Economic Justification of Flexible Manufacturing Systems” was recently performed by Kulkarni and Parsaei [77]. This resulted in a listing of 438 articles related to economics of FMS. Therefore the area of AMST evaluation is being actively addressed, and has implications in both the academic and industrial communities.

Chapter 3

Deterministic Model Formulation

“Problems are opportunities in work clothes.” -Henry Kaiser [14]

3.1 Introduction

In order to adequately evaluate proposed AMST alternatives, a model must be able to account for not only the quantitative factors of an alternative, but also the qualitative factors associated with an alternative. The model proposed herein takes a fundamental view of the AMST evaluation problem as being composed of three objectives; Strategic, Tactical, and Pecuniary. The Pecuniary objective contains quantitative factors and will be represented by a Monetary Index. The Monetary Index will consider the cash flows created by an alternative, and use NPV to arrive at a single value which describes the Pecuniary objective. The Strategic and Tactical objectives represent qualitative factors, and they will each be represented by the attributes which describe the respective objectives. These intangible costs and benefits will be analyzed using the concept of qualitative flows, and each objective will be represented by a Nonmonetary Index array.

3.2 Objectives of the AMST Evaluation Problem

The following sections provide detailed definitions of these objectives. These definitions are provided in a hierarchical manner in order to provide a clear understanding of what each objective encompasses. The hierarchy is set up in three levels with the objective at the top level, attributes at the next level, and a description of the attributes (elements) at the lowest level. A summary is provided

relating this structure to research previously done in this area.

3.2.1 Strategic Objective

The Strategic objective relates to the planning which is performed by a company before any action takes place. The attributes which define this objective are Internal Relations, Market Position, Mission, Organization, Public Relations, and Technology. The Strategic objective is a qualitative measure. The attributes of this objective are formulated from the ideas presented in [98], [155], and [141].

Internal Relations is the factor which revolves around the people who make up the company - the employees. This attribute is described by issues such as employee morale, employee development, quality of work life, absenteeism, and use of employee skills. Employee morale deals with how the employees feel about the company, and their attitude toward the company. Do the employees feel a part of the company and are they willing to place priority on company goals as opposed to personal goals, or are they just numbers which perform assigned functions. Employee development is how the employee matures within the company. Advancement opportunities for the employee based upon training and performance is an example of employee development. Working conditions and the general environment in which the employee operates form the quality of work life. This may include issues such as locker rooms, break rooms, recreational areas, meal facilities, and general workplace comforts. Absenteeism is the frequency of absences from work. This may be caused by improper employee relations, and these absenteeisms tend to have a negative effect on the work force. This effect is usually felt in day to day operations, as either some work will not be accomplished due to the missing employee or another employee must perform additional tasks to make up for the missing employee. Finally, use of employee skills deals with how the

company utilizes its employees. Using an engineer to primarily perform clerical functions may not be the best use of the skills possessed by an engineer, and is likely not to be the function which the engineer was hired to perform.

The second strategic attribute is Market Position. Market Position refers to how the company views itself and the products it manufactures with respect to the rest of the world. Market Position is described by market share, demand, competition assessment, market penetration, vulnerability, and survivability. These issues focus on how the company stands in its market, where it wants to go, and where it can go. Market share is the percentage of the available demand of a product for which the company produces. Market penetration is the percentage of available demand for a product not already achieved by the company, which the company projects it can obtain. Demand itself is an important element. It may be possible through AMST to increase demand by offering lower price, improved quality, or more features. This increase in demand can then be captured by the company to place themselves in a better position. Competition assessment is identifying where the competition stands compared to one's own company. Issues such as price, manufacturing equipment, manufacturing advances, and profit encompass competition assessment. Vulnerability states how stable the company feels its position currently is. If the company is not secure in its current position, for example having a significantly higher variable cost or overhead on its product than its competitor, the company may be vulnerable to lost sales. Survivability is maintaining the existence of the company. Improving product mix may allow the company to make inroads in new areas to maintain their existence. The company may also be forced to expand its current market base, as is the case with defense contractors in today's market, or go bust.

Mission is the company's road map for where it is heading in the future. It is represented by the five-year plan used by most companies, and possibly even a longer range plan (10+ years). The issues under the Mission are how well the company is performing compared to the current plan (is it on course), evolution of the company, economic feasibility of the goals, and a focused factory. Comparison of the performance of the company to its plan will indicate where the company is headed. Are the deviations from the plan expected due to uncontrolled circumstances, or are they due to the company not adhering to the plan. The goals stated in the plan should be economically feasible to the company. Here is where the capital budgeting task falls. This task identifies how much money is available to the company for investments, and will vary significantly based upon the size of the company. Evolution of the company is how the company thrives in the market place. The plan and mission should be carrying the company in an anticipated direction, and if this is not the case the company needs to address modifications to the plan. A focused factory deals with a clear understanding of the goals and objectives of the factory by the manufacturing community. The goals of the manufacturing environment must be well stated, and all of the departments should understand these goals in order to operate as a harmonious unit. Thus, the Mission sets in place where the company should be headed and tracks how well the company is getting there.

Organization defines the structure of the company. This attribute describes how well the company can control its own actions, how responsive it can be to changes, and the general management of information. Issues such as duplication of functions, and barriers between departments are included in this objective. Ideally there should be no duplication of functions and the departments should

operate harmoniously together, however historically the design and manufacturing functions tend to operate as stand alone units. How well the company is structured for efficient operation is also addressed herein.

Public Relations is an attribute which transmits the operations of the company to the outside world. This attribute is described by image of the company, company prestige, and service. Image of the company is how the public perceives the company. A good image may be as simple as having a well groomed outward appearance to a facility, versus unkept surroundings and a dingy appearance, or advertisement of the company's operations such as Ford's slogan "Quality is Job 1" or Lee Iaccoca's constant presence in advertisements. Environmental factors such as hazardous wastes are also considered under image. The prestige of a company identifies the company's position in the market. Examples of this are statements such as the "Cadillac" of product identifying it as the best product, or the act of making a "Xerox" copy. All in all, how the external world perceives the company and what the company is doing is captured in this objective.

The final attribute of the Strategic objective is Technology. This attribute deals with the position the company is in relative to AMST, and where it would like to be. Issues such as scientific information yield, technological position, and availability all describe Technology. Scientific information yield is the advancement the company can obtain in pursuit of the new technology. An AMST project may not have a great financial return, however the knowledge gained may be useful to the company in another endeavor. In relation to this is the technological position. An investment in AMST may place the company in a better position for future AMST projects. A company that has never undertaken an AMST project may be less confident about the results than a company which has already implemented some

AMST projects. Availability addresses if the technology is currently available, or if the company will have to expend significant resources to develop the technology. This may be as simple as being able to buy a device from a vendor off the shelf, or having to internally design and build a device because it does not yet exist in the market. Alternatively, an electronics manufacturing company may not want to manufacture surface mount devices until other companies have proven it can be done, while another company may take a leading role and become the first to perform this task. This company thus has the potential of setting the standard for the industry, or becoming the “leader.”.

3.2.2 Tactical Objective

The Tactical objective includes those qualitative issues which arise due to the actions or operations of the company. They are the actions taken which serve the purpose laid out by the Strategic objective. The attributes which describe this objective are Design, Flexibility, Integration, Material, Personnel, and Producibility. These attributes are derived from [71], [155], [67], [98], and [141].

The Design attribute identifies those aspects of the company which are involved in the design of a product. Design is defined by issues such as efficiency, features, lead times, and standardization. Efficiency deals with how the design is performed and stored. Using an AMST for design is efficient because the designer can use a computer to analyze several options before committing the design to a final drawing. Computer design systems also allow the designer to run simulations on the design to evaluate performance. Thus the functionality of a product can be determined at an earlier stage of the development. CAD systems (an AMST) store drawings in a computer. Therefore, paper storage of drawings is not required, which is an efficiency improvement. Features are the “extras” a product

may have, usually decided by customer demand. The features available on a design characterize that design. Items such as electronic door locks and electronic windows on automobiles are examples of features. Lead times are the amount of time required to create a design and have it available for manufacture. CAD systems can significantly reduce these lead times, allowing designs to become a reality in a shorter amount of time. Standardization is where parts used by a company are the same (or as similar as possible) across all products. Having various bill of materials available to the designer through the CAD system, the designer can make use of existing parts in new designs, thus standardizing the parts required to manufacture all products.

Flexibility deals with how well the company can react to changes. This attribute is defined by issues such as versatility, response to change, batch size, lead times, and throughput. AMST are characterized by their flexibility. They are versatile in being able to handle a wide variety of products, without the need of detailed and specialized machinery. They can respond to changes quickly due to this versatility, without disrupting the flow of products in a manufacturing environment. This versatility allows batch sizes to be small, as changeovers are not a drastic disruption to the manufacturing environment. Since changeovers are not as disruptive, lead times are shortened. The product does not have to wait as long for its turn in the production process. Flexibility also affects throughput, as the more flexible a system is, the more product it can handle, and thus the more product it can produce.

Flexibility can be thought of in aggregate terms such as low, medium, or high. Low flexibility is defined as having a series of stand alone machining cells which are not interconnected. Each machining cell can only handle a specific part fam-

ily. The material handling between cells is manual, as is the storage of products. The control system is specific for the machining cells and does not account for decisions in routing of materials when problems arise. Medium flexibility carries the interconnection a step further and connects the machining cells with conveyors or tow lines. Thus, the product may now automatically move between the various cells. Rudimentary control logic is employed which optimizes part routings through the cells, however this is in a nonreal-time manner. Some of the cells take on the capability to handle more than a single part family, yet a certain amount of operator setup is required to assist in tooling changes between part families. End item storage is accommodated by an Automated Storage and Retrieval System (AS/RS), however this usually is not integrated with the conveyor system. High flexibility is the final step to virtually complete integration. Single machining cells can accommodate any part family, with automated tooling changes as required. The cells are interconnected with Automated Guided Vehicle Systems (AGVS) which allow a part to travel from one cell to any other cell in the factory. Control logic in the system monitors for machine breakdowns, overloads, and re-tooling requirements, and automatically re-routes and re-schedules parts to other machines maintaining smooth material flow and adherence to delivery schedules. The AGVS is interconnected with an AS/RS for storage, either final or intermediate, and the control system tracks location of parts and their state of assembly. Therefore, high flexibility approaches the utopia of an ideal manufacturing environment.

The attribute Integration deals with how well all of the operations and departments operate together within a company. Issues such as communication, duplication, synergism, data requirements, and data usefulness describe Integration. Communication relates to communication of information between depart-

ments and people, in addition to machinery and equipment. AMST has well documented benefits with improvements due to computer networks [148], however the ability of people to better communicate and convey information is also a plus of these systems. Duplication refers to the requirements of several departments or people to have the same data or information. The norm in this instance is that every department maintains its own data, and this data is generally used across departments. The result is conflicting information. A classic example of this duplication is the duplication of a bill of materials, one for design use and one for manufacturing use. Needless to say this results in a tremendous amount of errors in the product and its design. Ideally, only one department needs to maintain data for use by all other departments. Synergism is the ability of departments to share not only information, but knowledge. Why spend design engineering time to investigate and implement a design change when that change has already been identified by a manufacturing function? By sharing knowledge such situations can be avoided. Data requirements and data usefulness tie in to what kind of data the departments (and company) require to operate at an efficient level. What data is required to make decisions and what data is presented because the computer provides it are addressed with these issues. Often more data is presented than is really required just because the computer prints it. This can hamper the decision making process, as the saying goes "one cannot see the forest because of the trees." Additionally, poor data usefulness creates unwanted reports. Computers were intended to minimize paperwork, and yet they seem to generate more paper than companies know what to do with.

Material deals with the control and movement of product through the manufacturing environment. Issues such as control, scheduling, planning, expediting,

and handling encompass the Material attribute. Control consists of process control and shop floor control. These ensure that processes are operating within acceptable parameters, and that there is visibility of the product as it moves through the manufacturing environment. Visibility allows the product to be located within the manufacturing process. Scheduling is comprised of master production scheduling and material requirements planning. Scheduling ensures that orders are accounted for in the manufacturing process, and planning provides the appropriate parts for the product as they are required. Handling is the normal movement of parts through the manufacturing environment, and expediting is the emergency movement of parts. The goal of AMST is to eliminate expediting.

The Personnel attribute deals with the people aspect required to carry out the operations of the Tactical objective. The skill requirements and training of the people, along with the type (direct/indirect) of people required for the task are delineated. Human factors issues are included such as work place design and overall safety of the employees. Employees are the most valuable asset used in manufacturing, and even with the advances in automation people will always be required in the operations. How these people are used, and how they fit into the new manufacturing arena cannot be overlooked in evaluating manufacturing systems.

The final attribute of the Tactical objective is Producibility. This attribute deals with how the product is made, and the issues involved include consistency, compatibility, feasibility, reliability, capacity, and external interface. Consistency is how well the product can repetitively be made. Ideally a product should be manufactured the same each time, with virtually no variation. Compatibility deals with how well the product and the machine work together. For example, the

tooling should not be awkward to use with a machine and the product. Setups for instance should be quick and foolproof. Feasibility deals with the applicability of using the machine to build a product. If necessary machining speeds or tolerances are unobtainable, the use of the machine is not feasible. Reliability addresses the dependability and durability of the machine. A reliable machine will hold up in the environment in which it is placed, and it will hold up under the mix and volume of the product it is to produce. Capacity is the volume that can be passed across a machine. Exactly how many units of the required products can the machine accommodate. External interface is how well a subassembly or product purchased from outside the plant fits into the operations of the plant. The subassembly or product should meet or exceed the standards of product manufactured within the plant.

3.2.3 Pecuniary Objective

The third objective addresses the financial attributes involved in the AMST evaluation process. These are all costs associated with an AMST alternative, and so the term Pecuniary is used to describe this objective. The attributes which make up the Pecuniary objective are Operation and Maintenance, Plant and Equipment, and Product. This breakdown follows the broad categories presented in [38].

Operation and Maintenance are the costs related to the operations of the company. Included in this attribute are operating labor, maintenance labor, overtime, labor turnover, absenteeism, training, direct/indirect costs (including health care and savings incentive benefits), supervision, setup, maintenance tools and supplies, production rates, routings, shop floor control, expediting, interrupted production, insurance, and documentation. Operating labor, maintenance labor, and supervision include wages and benefits for these divisions of labor. Overtime accounts for

overtime costs of the above. Labor turnover includes recruiting and termination. Absenteeism is illness (including feigned) or injury. Other costs not associated with the aforementioned are included in either direct or indirect costs. Setup is the cost incurred in the preparation of machinery or workstations to perform a job, and routings is the movement of material through the facility. Maintenance tools and supplies are the equipment maintenance requires to perform its function, not including spare parts for factory machinery. Production rates include the volume of material processed, and consists of down-times and efficiency. Expediting is the addition of costs for the urgent or unplanned movement of material. Shop floor control includes costs for part tracking and cost tracking (value added). Documentation covers the costs of paperwork, work instructions, build drawings, etc., and insurance costs are self explanatory.

The Plant and Equipment attribute includes the costs incurred due to the physical resources of a company. The attribute is made up of the following costs: equipment, start-up, installation, tooling, hardware development (including modification of existing equipment for compatibility with AMST equipment), software development, spare parts, space, safety equipment, energy, depreciation, and taxes. Equipment, installation, and tooling are self explanatory. Hardware development includes any unique in-house machinery developed and built by the company. Start-up costs are the costs associated with getting an AMST project underway, and are one-time costs not covered by installation. Spare parts are the necessary replacement parts for the factory machinery, and safety equipment are the additional accessories required to provide a safe environment for the employees. Space is the normal floorspace consideration, including site preparation for new activities, and energy is comprised of heating, lighting, etc. Software development is any

Table 3.1: Accelerated Cost Recovery System Summary [20]

ACRS Life (years)	Examples
3	Specialized manufacturing tools, material handling equipment. (Life ≤ 4 years)
5	Research and experiment property, semiconductor manufacturing equipment. (Life > 4 and ≤ 10 years)
7	“Renewable energy property”, property not otherwise classified. (Life ≥ 10 and < 16 years)
10	Assets for manufacture of castings and other basic products of ferrous metals. (Life ≥ 16 and < 20 years)
15	Wastewater treatment plants, two-way data and voice communication equipment. (Life ≥ 20 and < 25 years)

in-house software required for machines, interfaces, and systems. The Accelerated Cost Recovery System (ACRS) from the Tax Reform Act of 1986 is generally used for depreciation, and it provides a method where a portion of an asset's initial value may be deducted each year for a specified number of years [20]. Equipment related to AMST falls into a 3, 5, 7, 10, or 15 year category. This is depicted in Table 3.1. Taxes in engineering economic analysis are considered in the money which is made by a project. This treatment of taxes is only an approximation, and is included in the analysis for completeness. Tax rates tend to vary by size of company and also by the state in which the company is located. There are also differing tax rates for capital gains and losses. A single corporate tax rate is employed in this analysis. Any capital gains and losses will be discussed on an as needed basis.

The final attribute of the Pecuniary objective is Product. These are the costs which are directly related to the product(s) which the company manufactures. Ex-

amples of costs included under the Product attribute are design changes, inventory, engineering, quality, and sales. Quality costs include internal and external failures, rework, scrap, cost due to customer receipt of a bad product, etc. Engineering costs include design, manufacturing, and support. Inventory costs include raw materials, work in process, and finished goods. Design changes are costs incurred to improve the product, either for the customer or for manufacturing. Sales are the revenues received for a product.

3.2.4 Model Completeness

Table 3.2 lists the three objectives used in this model, along with the attributes of each objective and the elements which describe each of the attributes. These objectives represent a high level breakdown of the company. There are monetary (Pecuniary) considerations, and nonmonetary considerations broken down by planning (Strategic) and implementation (Tactical).

Before presenting a proposition which provides the basis for using the objectives listed in Table 3.2, the following definition is required.

Definition 3.1 *A typical manufacturing enterprise is represented by the functions and subfunctions depicted in Figure 3.1.*

The functions are based upon organizational hierarchies presented in Gibson et al. [43], Riggs [111], and this author's own professional experience. Additional insight was provided by the idealized organizational model of Garrett [41]. Figure 3.1 is a representation of the functions found in a typical manufacturing enterprise. The structure of the functions may be allocated differently for various organizations, however these functions will be present. A brief description of each of the functions is provided in the following paragraphs.

Table 3.2: Objectives of the AMST Evaluation Problem

OBJECTIVE/ Attribute	ELEMENTS
STRATEGIC	
Internal Relations	employee morale, employee development, use of skills, quality of work life, compensation, absenteeism.
Market Position	market share, competition assessment, market penetration, survivability, vulnerability, demand.
Mission	match to plan, evolution, economic feasibility, focused factory.
Organization	control, responsiveness, information management.
Public Relations	company image, company prestige, service.
Technology	scientific information yield, technological position, and availability.
TACTICAL	
Design	efficiency, features, lead times, standardization.
Flexibility	versatility, response to change, batch size, lead times, throughput.
Integration	communications, reduced duplication, synergism, data requirements, data usefulness.
Material	process control, scheduling, part tracking, shop floor control, cost tracking, expediting, handling, planning.
Personnel	skill requirements, training, safety, direct/indirect, human factors.
Producibility	consistency, compatibility, feasibility, reliability, capacity, external interface.
PECUNIARY	
Operation & Maintenance	operating labor, maintenance labor, direct/indirect costs, absenteeism, training, supervision, insurance, overtime, labor turnover, setup, maintenance tools/supplies, production rates, documentation, routings, shop floor control.
Plant & Equipment	equipment, start-up, installation, tooling, spare parts, energy, space, safety equipment, hardware development, software development, depreciation, taxes.
Product	design changes, inventory, quality, engineering, sales.

Figure 3.1: Organizational Structure of a Manufacturing Enterprise

The Executive function represents the top level in a company. Subfunctions include strategic planning and policy decisions. It is within this function that plans for the future of the company are made, along with keeping the current operations within previously defined plans.

Human Resources deals primarily with the recruitment and training of the people required to operate the company and support the manufacturing operations. Subfunctions include personnel development, recruiting, training, health/safety, wage administration, and labor relations. Thus, all of the responsibilities of maintaining the company's most important resource are handled through Human Resources.

Determining future demands and customer relations are part of the Marketing function. Additional subfunctions include sales, advertising, and customer service. This function determines the customer's satisfaction with a product, and also has

an impact on the Design Engineering function as to what future products might be considered.

The Financial function is best described by Riggs [111] as a scorekeeper of the company, "to see how well the firm and its component departments are scoring in the business competition game." Subfunctions include budgeting, investment reviews, and the collection of cost data. Included is the traditional capital budgeting function, which determines the amount of capital available to spend for capital projects.

Procurement deals with the acquisition of material from outside sources. They operate to obtain the required materials and equipment for the company which satisfy quality, timing, and volume constraints at the best price possible. Subfunctions are acquisition of parts and supplies for the operations, acquisition of the required capital equipment, and vendor certification/relations.

Maintaining the existing equipment and plant site fall under the Facilities function. This function also has responsibility for installing newly acquired equipment. Additionally, Facilities provides for the use of energy (electricity, water, etc.) to the operations of the company and assures that these resources are efficiently used.

The Product Assurance function monitors the manufacturing operations to assure that the products produced meet the required specifications. In addition this function provides support in the determination of the dependability and durability of machinery and product (ie. reliability).

Management Information Systems deals with the handling and reporting of information required by the company. Subfunctions include traditional data processing and data management. Data processing deals primarily with establishing data requirements, and data management deals with dissemination of the data.

Additionally, this function provides a medium for effective communication between other functions and ensures that all functions use the same information.

The heart of the manufacturing enterprise is Manufacturing Operations. It is within this function that the actual product is built. The subfunctions for Manufacturing Operations include production control, material handling, inventory, tooling, production, and support engineering. The support engineering subfunction includes Industrial and Manufacturing Engineering.

The Research and Development function is where new technologies are investigated. These technologies may be related to new product designs for the company to produce. Alternatively, the technologies may be advances in the manufacturing process or enhancements to existing products.

Finally, Design Engineering deals with actually specifying the components required to build a product and how the components are to fit together. This includes totally new designs and enhancements to existing designs. The result of the design is a drawing of the product including the bill of materials.

Proposition 3.1 *The Pecuniary, Strategic, and Tactical objectives allow all of the costs and benefits associated with AMST to be evaluated.*

TEST: In order to confirm that the objectives allow all of the costs and benefits to be evaluated, the objectives will be related to the organization of a typical manufacturing enterprise. If the objectives can “cover” all of the functions in the organization, then all of the costs/benefits can be accounted for. The traditional monetary costs are captured in the Pecuniary objective. The intangible issues are accounted for in the Strategic and Tactical objectives, which address the planning and implementation aspects of the company as a whole. The test is performed by identifying an association of

the elements in Table 3.2 to the subfunctions of the manufacturing enterprise which encompasses the element. This “covering” is shown graphically in Figures 3.2 thru 3.4. The minimal aspect of the cover is shown by the fact that each element of Table 3.2 is associated to only one subfunction, representing the primary subfunction to which the element contributes costs/benefits. Some subfunctions are associated to more than one element. This multiple association of elements describe the subfunction and does not duplicate costs/benefits, as shown in the discussion which follows.

The strategic planning subfunction is comprised of the strategic elements competition assessment, match to plan, evolution, and technological position. Competition assessment provides planning parameters based upon the competition, match to plan rates how well the company is on its intended course, evolution describes how the company is thriving in the market, and technological position identifies the position of the company for future AMST endeavors. Each of these provides costs/benefits which fall under the strategic planning subfunction. The policy decisions subfunction is comprised of the strategic elements focused factory and control. The clarity of the goals and objectives provided by the focused factory and the control a company has over its own actions contribute to the costs/benefits incurred via policy decisions.

The personnel development subfunction is composed of the strategic elements employee morale and employee development, and the tactical element skill requirement. The costs/benefits associated with the attitudes of the employees toward their company and how the employee matures in the company fall into this subfunction. The recruitment subfunction is comprised of

Figure 3.2: Covering of Strategic Objective

Figure 3.3: Covering of Tactical Objective

Figure 3.4: Covering of Pecuniary Objective

the strategic element use of skills and the pecuniary element labor turnover. Use of skills deals with how well the company uses the talents of an employee, and labor turnover is the cost incurred by having to hire (or fire) employees. The training subfunction is made up of the tactical element training and the pecuniary element training. Training has a financial impact in the cost of courses, materials, etc. , however the tactical impact encompasses the value of training as to how well the employee performs as a result of training. The health and safety subfunction is comprised of the tactical element safety and the pecuniary element safety equipment. Safety is how well employees are protected on the job, and safety equipment represents the cost of attaining a certain level of protection. The wage administration subfunction is comprised of the pecuniary elements operating labor, maintenance labor, and supervision. The costs of these elements are identified by the wage administration subfunction, and the balance of each is associated with different facets in the operations. The labor relations subfunction is made up of quality of work life and absenteeism strategic elements, direct/indirect tactical element, and absenteeism pecuniary element. Quality of work life relates to labor relation in the general environment in which the employee operates, while absenteeism concentrates on the effect to labor relations due to the time the employee is away from the work place, along with associated costs. The effect of the treatment of direct/indirect employees in the operations is accounted for in the tactical element.

The sales subfunction is comprised of the strategic elements market share and vulnerability, and the pecuniary element sales. Market share identifies the current sales of the company, and vulnerability is the potential of the

market share to change in the future. Thus, these elements complement each other. Sales, of course, also equates to dollars. The future demand subfunction is made up of market penetration and demand strategic elements. Market penetration identifies the available demand which the company has yet to achieve, and demand is the increase in the available demand that the company may be able to achieve. Again, these are complementing elements. Customer relations is comprised of the strategic element company prestige and the tactical element features. Prestige is the perception of the company by the customer, and features are the "extras" on a product which the customer desires.

The investment review subfunction is made up of the pecuniary elements depreciation and taxes. This is the impact to the Financial function, and these parameters are normally provided by this function. The collection of cost data subfunction is composed of the pecuniary elements direct/indirect costs, overtime, and insurance. These are all elements established by the financial function and monitored as part of their scorekeeping responsibilities.

Quality is comprised of the tactical element process control and the pecuniary element quality. Process control is how well operations are performing with respect to established parameters, and quality is the cost incurred due to internal/external failures, rework, scrap, etc.

Data processing is made up of the tactical element data requirements and the pecuniary element software development. Data requirements deals with the usefulness of data and its availability. Software development encompasses the costs associated with developing software. The data management subfunction is composed of the strategic elements information management and

responsiveness, and the tactical elements data usefulness and reduced duplication. Information management and responsiveness are strategic elements identifying how well information is managed and how well that information is being used to respond to conditions in the operations. Data usefulness and reduced duplication are tactical elements which complement the strategic elements. These identify how useful the data is to the operations and the appropriate sharing of the same data by several functions in the organization. The communications subfunction is made up of communications and synergism tactical elements. Communications is the sharing of information between functions, and synergism is the sharing of knowledge, complementing elements assisting in the overall communications of the organization.

The support engineering subfunction is composed of the tactical elements human factors and feasibility, and the pecuniary elements start-up, documentation, and hardware development. Human factors are the responsibility of the support engineering subfunction, usually the industrial engineering responsibility. Feasibility being the applicability of using a machine to build a product falls under the manufacturing engineering responsibility, another support engineering area. The start-up of new AMST is performed by the support engineering subfunction, as any hardware development and associated documentation. The support engineering function also provides interface for software development, however the primary association for software development is Data Processing. The production control subfunction is comprised of the tactical elements lead times, throughput, scheduling, shop floor control, expediting, and planning. Also included is the pecuniary element shop floor control. Scheduling, planning, expediting, and shop floor control

are the major areas of production control. Costs/benefits from these elements directly impact the production control subfunction. The Flexibility elements lead times and throughput are critical elements complementing the major areas of production control in that they provide an important relationship to scheduling and planning. Shop floor control is also a pecuniary element identifying the actual costs (or savings) incurred to this element from changes due to AMST. These are all production control related issues. The material handling subfunction is comprised of the pecuniary elements routings and setups. Since material handling has the responsibility for moving product, or otherwise identified as non-value-added operations, routings and setup are logically part of this subfunction. The production subfunction is made up of the tactical elements versatility, response to change, batch size, consistency, compatibility, and capacity. Versatility, response to change, and batch size are Flexibility attributes which relate to production. Versatility relates the ability to handle a wide range of products, response to change addresses the ability to change production with minimal disruptions, and batch size relates the ability to handle various quantities of products. Each element clearly complements the other. Consistency, compatibility, and capacity are Producibility attributes directly affecting production. Capacity being the volume of product that can pass through a facility, compatibility being the interaction of product and machine, and consistency being how well the product can be repetitively made are again complementary elements affecting the production subfunction.

The new technology subfunction is comprised of the strategic elements scientific information yield and availability. These are all related to research

and development. Scientific information identifies the benefits to the company of a new endeavor, while availability is an associated cost for obtaining a new technology.

The product design subfunction is composed of the tactical elements efficiency and lead times. Lead times are from the Design Engineering function and address the time required to create a new design and have it available for manufacture. Efficiency deals with how well the design is performed and stored. Both elements relate to the design of the product and as such are associated with product design. □

This methodology is an improvement over several of the methodologies reviewed in Chapter 2 in that this methodology includes a quantitative and qualitative analysis. Of the methodologies reviewed which include both quantitative and qualitative measures, this method is an improvement in that it is structured along the organizational functions of a typical manufacturing enterprise. This allows the method to be tailored to fit a specific organization's structure, including those attributes/elements which are important to the organization and eliminating those attributes/elements which are not applicable. Therefore, this breakdown is considered to be a complete representation of the costs/benefits which can result from AMST in an organization.

Many of the techniques reviewed in Chapter 2 treat the qualitative issues in a single manner, whereas this method clearly divides the qualitative issues into Strategic and Tactical objectives. This breakdown forces the decision maker to take a structured view of AMST and how it relates to the operations of the entire company, from planning to implementation. Additionally, the Expert Systems techniques require that a knowledge base be built containing the required ex-

pert knowledge. The required knowledge could take years to amass, whereas this method addresses the relevant issues through interaction with the decision maker in a reasonable (order of weeks) time.

The greatest impact in designing this structure is from the work of Troxler and Blank [141]. Their research developed a System Value made up of four criteria; Suitability, Capability, Performance, and Productivity. Capability and Performance contain similar factors which were related to the day-to-day operations of the manufacturing environment. Factors such as design and throughput, flexibility and information should belong under the same objective. Therefore, the Tactical objective encompasses Troxler and Blank's [141] Capability and Performance attributes. These are all factors which are small scale actions serving a larger purpose. The Strategic objective parallels the Suitability attribute. The issues in both are of a strategic nature. The Productivity attribute is similar to the Pecuniary objective. Both of these use NPV to arrive at a numerical measure. The structure presented herein is an improvement over one presented by Troxler and Blank [141] in that it clearly divides monetary and nonmonetary issues. Furthermore, the nonmonetary issues are divided into Strategic and Tactical objectives which capture the planning and implementation actions of the organization. This is an improved representation, reflecting the organization of a manufacturing company. Lastly, completeness for the model has been documented.

3.3 Monetary Index

The Monetary Index of this model will use traditional NPV methods to set up a cash flow analysis for each alternative under consideration, including the "do-nothing" alternative. The interest rate used will be a true cost of capital

to the firm, with no magical adjustments for risk. The NPV result will then be used to determine a ratio of NPV's which will result in the Monetary Index. This Monetary Index will be used as the single value which defines the Pecuniary objective.

3.3.1 Net Present Value Analysis

The methodology of NPV analysis is the traditional form of analysis found in any reference on Engineering Economics. In order to establish notation, the after tax cash flow in any period t is denoted by:

$$Y_t = \sum_{k=1}^K C_{tk} (1 - \tau_c) + D_t \tau_c$$

where:

C_{tk} - Cash flows occurring from a project.

D_t - Non-cash items chargeable only during t (i.e. depreciation).

τ_c - Corporate tax rate.

Y_t - After tax cash flow during t .

t - Period of the project (i.e. years).

k - Monetary attribute.

K - Total number of monetary attributes.

The cash flows occurring from a project include gross income, operating expenses, and interest paid on borrowed funds. Some examples of gross income are savings realized by improvements made, sales, salvage values, and in general any cash in-flow which occurs. Operating expenses are made up of cash out-flows (excluding interest paid on debts) such as equipment costs, maintenance, labor, overhead, development, training, etc. Depreciation is of course the lessening in book value

over time of a physical asset, interest is the cost of borrowing funds, and taxes are the company's cost to Uncle Sam. These items correspond to the attributes for the Pecuniary objective.

Using the after tax cash flows Y_t , the present value is determined as described in Section 2.1.2, where the NPV of the cash flows is determined by:

$$NPV = \sum_{t=0}^T Y_t (1+i)^{-t}$$

This requires that the interest rate i be provided. This interest rate has been cause for much discussion as Kaplan [71] believes companies set an arbitrarily high hurdle rate. As discussed in Chapter 1, this interest rate can be the cause for rejecting projects which may actually be worthwhile for a company to undertake. Shinnar et al. [119] determined interest rates for several corporations. Of the 14 manufacturing firms identified in that paper, the interest rate averaged between 5% and 8%. These are the rates which will be used in this dissertation.

3.3.2 Monetary Index Formulation

An index for the monetary analysis will be required in order to scale the results into a unitless value that can be compared on a -1 (worst) to +1 (best) scale. This is required for the preference ordering proposed later in this Chapter. The Monetary Index for a particular alternative j is calculated by:

$$MI_j = \frac{NPV_j}{R_{MI}}$$

where:

$$NPV_j = \sum_{t=0}^T Y_{tj} (1+i)^{-t}$$

$$R_{MI} = \max \left(\left| \min_{j \in J} NPV_j \right|, \max_{j \in J} NPV_j \right)$$

- Y_{tj} - The after tax cash flow in the t^{th} period from the j^{th} alternative.
- i - Interest rate, adjusted for inflation only.
- j - The alternative under consideration, $j = 1, 2, \dots J$.

Theorem 3.1 *The Monetary Index $MI_j = \frac{NPV_j}{R_{MI}}$ yields a result in the range $[-1, +1]$.*

The proof of this Theorem is provided in Appendix A.

Alternatively, the decision maker can define an R_{MI} as a maximum positive desirable NPV (NPV_{DM}). In the event an $|NPV_j|$ from the analysis is greater than NPV_{DM} , the decision maker will be asked to reevaluate NPV_{DM} or select as the new limit that $|NPV_j|$ which exceeded NPV_{DM} .

A Monetary Index less than zero for a given alternative shows that the alternative will not meet the decision maker's value for the time period under study. When the Monetary Index is greater than zero for a given alternative, the alternative will meet the decision maker's value for the period under study, varying from complete attainment (1) to low attainment (around 0). A Monetary Index of zero shows that the decision maker is indifferent for the alternative. There is no gain, however there is also no loss.

As an example of the use of the Monetary Index, consider three project alternatives A, B, and C. Cash flows for these three alternatives in "then current" dollars (adjusted for inflation) are shown in Table 3.3. Assuming an 8 year project window and a market interest rate adjusted for inflation of 15%, the NPV of project A is \$136,207, \$124,716 for project B, and \$110,186 for project C. The decision maker has defined an NPV_{DM} of \$150,000. From these values, the Monetary Index for A is 0.91, B is 0.83, and C is 0.73. These results are summarized at the end of

Table 3.3: Example of the Monetary Index

YEAR	PROJECT A	PROJECT B	PROJECT C
0	(\$280,000)	(\$350,000)	(\$325,000)
1	\$85,000	\$95,000	\$85,000
2	\$90,000	\$100,000	\$120,000
3	\$90,000	\$105,000	\$110,000
4	\$95,000	\$105,000	\$105,000
5	\$95,000	\$110,000	\$100,000
6	\$100,000	\$110,000	\$100,000
7	\$100,000	\$115,000	\$90,000
8	\$100,000	\$115,000	\$90,000
NPV	\$136,207	\$124,716	\$110,186
MI	0.91	0.83	0.73

Table 3.3. As can be seen from the results, the preferred alternative based upon the Monetary Index is A.

3.4 Nonmonetary Evaluation

All of the models reviewed in Chapter 2 consider the nonmonetary (or qualitative) benefits and/or costs as an aggregate term. That is the benefits and/or costs occur instantaneously, and are rated on some scale. As an example, consider the methodology described by Canada [19]. The strategic and tactical criteria of this model are analyzed for each alternative, and an aggregate “weighted evaluation” is provided for each criteria within each alternative. Specifically, Canada [19] uses examples for tactical criteria as how well the CIMS aims are met and serviceability. These criteria are then assigned weights as to how well they are fulfilled by each alternative. The question that arises is; will these criteria be fulfilled immediately upon installation or procurement of the alternative, or will the benefits/costs occur over time? Just as the monetary benefits and costs do not arrive “all at once,”

the nonmonetary benefits do not arrive “all at once”. The nonmonetary benefits accrue at different levels during different periods of the project’s life.

Since the nonmonetary benefits and/or costs do not accrue instantaneously, it is necessary to perform a nonmonetary qualitative flow analysis just as the monetary criteria used a cash flow analysis. This qualitative flow analysis will then provide the foundation upon which the nonmonetary evaluation can be defined.

Whereas the Pecuniary objective resulted in a single attribute of the Monetary Index to describe the objective, the nonmonetary evaluation will arrive at indices for each of the attributes of the Strategic and Tactical objectives.

3.4.1 Net Present Qualitative Flow Analysis

The Net Present Qualitative Flow (NPQF) analysis is an analysis of how well a particular alternative performs, with respect to a given attribute, over a period of time. This performance is then adjusted to a present time measure and normalized into an appropriate range.

Definition 3.2 *The expected performance of alternative j for attribute k in period t , $t = 1, \dots, T$ is Q_{tkj} , with $-100 \leq Q_{tkj} \leq +100$. -100 is the worst rating, 0 is a neutral rating, and $+100$ is the best rating.*

For each alternative j , the decision maker rates the expected performance Q_{tkj} . As with cash flows, positive values indicate a positive effect toward the end result, negative values a negative effect, and zero a no change situation. This is an extension on the methodology performed by Canada [19] in two ways. First, the performance of the qualitative attributes is examined on a period by period basis. Second, the performance of the qualitative attributes is allowed to take on negative values indicating a worsening of the attribute.

Note that expected performance Q_{tkj} is specified for each attribute, and not each element of the attributes. This was done in order to clearly present the methodology. The decision maker may prefer to specify a unique Q_{tkj} for each element, because he/she may have differing views for each of the elements which describe an attribute. This provides the decision maker with some flexibility in the level of detail which is to be used in the model.

In order to account for the attainment of different levels of the nonmonetary benefits during different periods, a Net Present Qualitative Flow ($NPQF$) function is defined. This is similar to the NPV for the monetary function previously described.

Definition 3.3 *The $NPQF$ of attribute k for alternative j is:*

$$NPQF_{kj} = \sum_{t=1}^T Q_{tkj}(1+h)^{-t} \quad (3.1)$$

where:

Q_{tkj} - Qualitative flow in period t of attribute k for alternative j .

$k = 1, \dots, 12$.

T - The time window of the analysis.

h - Qualitative interest rate.

Generally, $k = 1, \dots, 6$ denote attributes from the Strategic objective and $k = 7, \dots, 12$ denote attributes from the Tactical objective. However, not all six of the attributes from each objective are required to be utilized, and as such k should be appropriately defined for the evaluation being performed.

The term $(1+h)^{-t}$ is merely a weight applied to Q_{tkj} that represents the importance of the expected performance over time. When these weights decrease in

magnitude over time $((1 + h)^{-t_1} > (1 + h)^{-t_2} > (1 + h)^{-t_3} \dots)$, the decision maker is said to exhibit impatience [37]. Impatience is where the decision maker desires preferred things to happen sooner than later. When h is between 0 and 1 (a percentage) and the t 's are ordered such that $t_3 > t_2 > t_1$, the weights will decrease over time. The decision maker may elect to set h to the same value as i , or discount the qualitative attributes at a different rate depending upon the company's level of impatience. As with i , h should not be adjusted arbitrarily for risk. Risk will be addressed in the next Chapter.

3.4.2 Nonmonetary Index Formulation

As with the monetary analysis, a Nonmonetary Index will be required in order to scale the results into a unitless value that can be compared on a -1 (worst) to $+1$ (best) scale. The $NPQF$'s for all alternatives (including the "do-nothing") and qualitative attributes will be determined. The Nonmonetary Index for attribute k of alternative j will then be determined by:

$$NI_{kj} = \frac{NPQF_{kj}}{R_{NI}}$$

where:

$$NPQF_{kj} = \sum_{t=1}^T Q_{tkj}(1 + h)^{-t}$$

$$R_{NI} = 100 \sum_{t=1}^T (1 + h)^{-t}$$

Q_{tkj} - Qualitative flow in period t of attribute k for alternative j .

h - Qualitative interest rate.

Theorem 3.2 *The Nonmonetary Index $NI_{kj} = \frac{NPQF_{kj}}{R_{NI}}$ yields a result in the range $[-1, +1]$.*

The proof of this Theorem is provided in Appendix A.

As an example of how these qualitative flows are incorporated, consider an AMST project where lead times will be improved. Let lead times be denoted by $k = 1$, and the alternative as $j = A$. In the first year of the project, lead times are expected to worsen somewhat due to the installation requirements and training of personnel, and as such $Q_{11A} = -10$. In year 2 and year 3, the lead times are expected to improve to a performance level of +30 and +60 respectively, and by year 4 the lead time performance will be +85. If operations remain as they are (“do-nothing” alternative B), the performance of lead times would be +40, +30, 0, and -20 for years 1 through 4. Table 3.4 shows these Q_{tkj} ’s and the associated $NPQF$ and NI when h is 8%.

Why is it important to analyze the qualitative attributes in this manner? If the project in the previous example lasts 4 years, it is true that the AMST alternative (A) is preferred over the current operations, but what if the project for some reason lasts only 2 years? Then only part of the benefit is realized, and the $NPQF_{1A} = 16.46$ and $NPQF_{1B} = 62.76$. This results in $NI_{1A} = 0.08$ and $NI_{1B} = 0.35$. Now, the current operations are the better selection. Current methods of analysis do

Table 3.4: Qualitative Flow for Lead times

YEAR	Q_{t1A}	Q_{t1B}
1	-10	+40
2	+30	+30
3	+60	0
4	+85	-20
NPQF	126.57	48.06
NI	0.38	0.15

not allow for this sort of breakdown, and as such errors can result when analyzing the alternatives. If the project lasts less than the four years required (in the example) to achieve the desired benefits, the entire qualitative benefits would not be realized. Furthermore, AMST projects are on the order of 8 to 12 years in duration [98] [123], and it may take this long for the entire range of benefits to be realized. Therefore, the evaluation model must be able to accommodate this, and by using the *NPQF* it can.

To summarize the steps to obtain the *NPQF*, each appropriate element suggested in Table 3.2 under the Strategic and Tactical objectives will first be rated on performance (Q_{tkj}) by the decision maker for each period t . Next, determine the *NPQF* per Equation 3.1. The interest rate i without adjustments for inflation or risk may be used as the qualitative interest rate h . This is performed separately for each attribute, or for each element. The decision maker then determines the NI_{kj} . The result is a vector of NI_{kj} for each alternative j being evaluated.

3.5 Composite Programming Solution

The structure of the proposed AMST evaluation problem lends itself nicely to a solution using Composite Programming. As presented in Chapter 2, Composite Programming is a two-level trade-off analysis. The first level is a trade-off between the attributes/elements of an objective, and the second level is a trade-off among the objectives. Not only does Composite Programming lend itself well to this situation, it is a technique which has not been applied to the AMST evaluation problem. This technique can be used to provide a ranking of the alternatives being evaluated in a very elegant manner.

3.5.1 Formulation

The formulation for evaluation of AMST using Composite Programming is:

$$\min_j \rho_j = \left[\beta_1 \left(\alpha_{11} \left| \frac{1 - MI_j}{2} \right|^p \right)^{q/p} + \sum_{n=2}^3 \beta_n \left(\sum_{k \in S_n} \alpha_{nk} \left| \frac{1 - NI_{kj}}{2} \right|^p \right)^{q/p} \right]^{1/q}$$

where:

- ρ_j - Composite evaluation of alternative j .
- β_n - Weighting factor for the importance of the objectives.
 $n = 2$: strategic, $n = 3$: tactical.
- α_{nk} - Weighting factor for the importance of the attributes/elements of an objective.
- S_n - Set of elements/attributes for objective n .
- MI_j - Monetary Index for alternative j .
- NI_{kj} - Nonmonetary Index for attribute/element k and alternative j .
- p - L-norm for the attributes/elements.
- q - L-norm for the objectives.

The resulting composite evaluation is a score for each alternative which describes the “distance” that the alternative is away from an “ideal” solution. The ranking of the composite evaluation scores is based upon the $\min_j \rho_j$ being the best alternative from the set of alternatives being evaluated. The set of alternatives is required to include the “do-nothing” alternative.

The weights α_{nk} indicate the importance of the attributes/elements (k) for objective (n) as compared to the other attributes/elements for the same objective. The weights β_n indicate the importance of the objective n to the overall result. These weights are determined by the decision maker on a scale of 0 to 100, and

normalized to 100. This is done within each objective for α_{nm} , and across the objectives for β_n . The weight allows the decision maker to define the importance of the attributes/elements in order to obtain an accurate measure of their effects upon the specific objective, and the importance of the objectives to the overall composite evaluation. Similar weighting techniques are used in [98], [19], and [24].

The terms $\left(\frac{1 - MI_j}{2}\right)$ and $\left(\frac{1 - NI_{kj}}{2}\right)$ are taken directly from the term

$$\frac{z_n^* - z_n(x)}{z_n^* - z_{n*}}$$

as presented in Chapter 2. The term z_n^* is represented by the value 1, the maximum value that the MI and NI can take on. The minimum value that the MI and NI can attain is $z_{n*} = -1$. Thus the term $(z_n^* - z_{n*})$ is 2.

3.5.2 Attribute versus Alternative Matrix

In order to efficiently use the Composite Programming technique, the values for MI_j and NI_{kj} are organized into an attribute versus alternative matrix. This matrix shows the relationship between the attributes of all of the objectives and the alternatives, and allows the decision maker to systematically perform the AMST evaluation. The matrix may be as detailed as to list all of the individual elements of the Strategic and Tactical objectives, or be as simple as delineating only the attributes as shown in Table 3.5. Having defined this matrix and the appropriate values for α_{nk} and β_n , the decision maker is ready to carry out the evaluation process.

3.5.3 Numerical Example

In order to demonstrate the use of this technique, a numerical example is provided. The intent of the example is to show how the qualitative issues can impact

Table 3.5: Attribute versus Alternative Matrix

Objective	Element	ALT 1	ALT 2	...	ALT J
Design	Monetary Index	MI_1	MI_2	...	MI_J
Strategic	Internal Relations	NI_{11}^S	NI_{12}^S	...	NI_{1J}^S
	Market Position	NI_{21}^S	NI_{22}^S	...	NI_{2J}^S
	Mission	NI_{31}^S	NI_{32}^S	...	NI_{3J}^S
	Organization	NI_{41}^S	NI_{42}^S	...	NI_{4J}^S
	Public Relations	NI_{51}^S	NI_{52}^S	...	NI_{5J}^S
	Technology	NI_{61}^S	NI_{62}^S	...	NI_{6J}^S
Tactical	Design	NI_{71}^T	NI_{72}^T	...	NI_{7J}^T
	Flexibility	NI_{81}^T	NI_{82}^T	...	NI_{8J}^T
	Integration	NI_{91}^T	NI_{92}^T	...	NI_{9J}^T
	Material	NI_{101}^T	NI_{102}^T	...	NI_{10J}^T
	Personnel	NI_{111}^T	NI_{112}^T	...	NI_{11J}^T
	Producibility	NI_{121}^T	NI_{122}^T	...	NI_{12J}^T

Table 3.6: Current Operations Cash Flows

	0	1	2	3	4	
Labor	\$0	(\$109,200)	(\$119,600)	(\$130,000)	(\$140,400)	
Maintenance	\$0	(\$2,000)	(\$2,000)	(\$2,200)	(\$2,200)	
Training	\$0	(\$1,000)	(\$1,150)	(\$1,323)	(\$1,521)	
Documentation	\$0	(\$5,000)	(\$5,000)	(\$5,000)	(\$5,000)	
Space	\$0	(\$5,000)	(\$5,000)	(\$5,000)	(\$10,000)	
Rework	\$0	(\$75,600)	(\$84,000)	(\$92,400)	(\$100,800)	
Transportation	\$0	(\$10,000)	(\$10,000)	(\$10,000)	(\$10,000)	
Cash Inflow	\$0	\$816,000	\$912,000	\$998,400	\$1,094,400	

	5	6	7	8	9	10
Labor	(\$150,800)	(\$161,200)	(\$171,600)	(\$182,000)	(\$192,400)	(\$202,800)
Maintenance	(\$2,420)	(\$2,420)	(\$2,662)	(\$2,662)	(\$2,928)	(\$2,928)
Training	(\$1,749)	(\$2,011)	(\$2,313)	(\$2,660)	(\$3,059)	(\$3,518)
Documentation	(\$5,000)	(\$5,000)	(\$5,000)	(\$5,000)	(\$5,000)	(\$5,000)
Space	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)	(\$15,000)	(\$15,000)
Rework	(\$113,400)	(\$121,800)	(\$134,400)	(\$147,000)	(\$163,800)	(\$180,600)
Transportation	(\$15,000)	(\$15,000)	(\$15,000)	(\$15,000)	(\$20,000)	(\$20,000)
Cash Inflow	\$1,228,800	\$1,315,200	\$1,459,200	\$1,593,600	\$1,776,000	\$1,958,400

the evaluation. This example deals with a hypothetical electronics manufacturing company which is evaluating two alternatives over its current operations of component insertion. The current operations are entirely manual, and are performed offshore due to the attractive labor rates. Two alternatives deal with bringing the operations back to the U.S., the other with leaving the operations offshore and simply adding people. Alternative one employs semi-automatic component insertion machines, the second uses a totally automatic component insertion machine.

The cash flows for each alternative, adjusted to include inflation, are shown in Tables 3.6 thru 3.8. A project window of ten years is used, with an interest rate of 8% and an inflation rate of 5%.

Currently the offshore operations utilize 8 people to perform component insertion. An additional person will need to be added to the operations each year in order to keep up with the expected demand. In addition a support engineer is required one quarter time to support the operations. Due to the increase of employees, space requirements increase over time. There is also a cost incurred in

Table 3.7: Semi-Automatic Alternative Cash Flows

	0	1	2	3	4	
Depr Investment	(\$120,000)					
Nondepr Investment	(\$30,000)					
Salvage value						
Labor		(\$270,400)	(\$228,800)	(\$291,200)	(\$291,200)	
Maintenance		(\$6,660)	(\$6,660)	(\$6,660)	(\$6,660)	
Training		(\$20,000)	(\$20,000)	(\$15,000)	(\$15,000)	
Documentation		(\$2,500)	(\$2,500)	(\$2,500)	(\$2,500)	
Space		(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)	
Rework		(\$75,600)	(\$75,600)	(\$73,920)	(\$70,560)	
Programming		(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)	
Cash Inflow		\$806,400	\$921,600	\$1,027,200	\$1,132,800	

	5	6	7	8	9	10
Depr Investment						
Nondepr Investment						
Salvage value						\$5,500
Labor	(\$291,200)	(\$353,600)	(\$353,600)	(\$353,600)	(\$353,600)	(\$353,600)
Maintenance	(\$6,660)	(\$6,660)	(\$6,660)	(\$6,660)	(\$6,660)	(\$6,660)
Training	(\$10,000)	(\$15,000)	(\$10,000)	(\$10,000)	(\$10,000)	(\$10,000)
Documentation	(\$2,500)	(\$2,500)	(\$2,500)	(\$2,500)	(\$2,500)	(\$2,500)
Space	(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)
Rework	(\$68,040)	(\$60,900)	(\$60,480)	(\$58,800)	(\$65,520)	(\$72,240)
Programming	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)
Cash Inflow	\$1,276,800	\$1,372,800	\$1,526,400	\$1,670,400	\$1,862,400	\$2,054,400

Table 3.8: Automatic Alternative Cash Flows

	0	1	2	3	4	
Depr Investment	(\$600,000)					
Nondepr Investment	(\$50,000)					
Salvage value						
Labor		(\$364,000)	(\$353,600)	(\$301,600)	(\$301,600)	
Maintenance		(\$16,000)	(\$16,000)	(\$16,000)	(\$16,000)	
Training		(\$40,000)	(\$40,000)	(\$30,000)	(\$20,000)	
Documentation		(\$5,000)	(\$3,000)	(\$3,000)	(\$3,000)	
Space		(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)	
Rework		(\$75,600)	(\$75,600)	(\$64,680)	(\$50,400)	
Programming		(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)	
Cash Inflow		\$777,600	\$931,200	\$1,036,800	\$1,132,800	

	5	6	7	8	9	10
Depr Investment						
Nondepr Investment						
Salvage value						\$30,000
Labor	(\$301,600)	(\$301,600)	(\$301,600)	(\$301,600)	(\$301,600)	(\$301,600)
Maintenance	(\$16,000)	(\$16,000)	(\$16,000)	(\$16,000)	(\$16,000)	(\$16,000)
Training	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)
Documentation	(\$3,000)	(\$3,000)	(\$3,000)	(\$3,000)	(\$3,000)	(\$3,000)
Space	(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)	(\$6,250)
Rework	(\$56,700)	(\$30,450)	(\$33,600)	(\$29,400)	(\$32,760)	(\$27,090)
Programming	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)
Cash Inflow	\$1,286,400	\$1,382,400	\$1,526,400	\$1,670,400	\$1,862,400	\$2,054,400

transporting the circuit boards back to the U.S. The boards require rework after they are shipped back to the U.S. and no change in this rate is anticipated over the project life. The remaining costs presented in Table 3.6 are self explanatory.

The alternative of semi-automatic insertion equipment will require the purchase of 4 semi-automatic insertion machines to replace the offshore operations. These machines will require site preparation and miscellaneous peripherals. The equipment is depreciated according to the ACRS rate for 7 year equipment. In the first year the offshore production will be maintained in full while the semi-automatic machinery is installed and placed into the manufacturing environment. In year 2 the offshore operation will begin to be phased out, and by year 3, the offshore operations will be eliminated. Additionally, operators for two of the machines will be required. A third operator will be added in year 3, and a fourth operator in year 7. The idle machines will be used for programming and training. A support engineer will also be required full time. The rework rate of boards from this operation is anticipated to decline over the life of the project. Other costs presented in Table 3.7 are self explanatory.

The fully automatic component insertion option will require one machine, with appropriate site preparation and peripherals. This equipment is also depreciated over 7 years. In the first year the offshore production will be maintained in full while the automatic equipment is installed and placed into the manufacturing environment. One operator for the machine will be required in the first year. A support engineer will also be required full time. In year 2 the offshore operation will be eliminated, and 2 people will be required to operate the automated machinery with an additional support engineer. In year 3 only $1\frac{1}{2}$ support engineers will be required, and beginning in year 5 only 1 support engineer will be needed. The

Table 3.9: Current Operations Qualitative Flows

Strategic	1	2	3	4	5	6	7	8	9	10
Internal Relations	15	0	-30	-30	-30	-30	-50	-50	-80	-80
Market Position	20	15	10	0	-25	-45	-65	-75	-80	-85
Mission	-30	-30	-35	-45	-50	-55	-60	-65	-75	-85
Organization	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50
Public Relations	20	0	-10	-20	-30	-40	-50	-60	-70	-80
Technology	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90
Tactical	1	2	3	4	5	6	7	8	9	10
Design	0	0	0	0	0	0	0	0	0	0
Flexibility	-40	-40	-40	-40	-80	-80	-80	-80	-80	-80
Integration	-15	-20	-25	-30	-35	-40	-50	-60	-70	-80
Material	25	15	0	-20	-20	-30	-30	-40	-40	-50
Personnel	35	30	30	25	15	5	-10	-15	-25	-35
Producibility	-20	-25	-30	-35	-40	-45	-50	-55	-60	-65

Table 3.10: Semi-Automatic Alternative Qualitative Flows

Strategic	1	2	3	4	5	6	7	8	9	10
Internal Relations	-35	-25	5	10	20	30	40	40	60	60
Market Position	10	-20	0	5	15	25	35	35	55	55
Mission	30	30	30	35	35	35	40	40	40	50
Organization	-35	-10	10	15	15	20	25	40	40	40
Public Relations	25	25	35	35	45	45	55	55	55	55
Technology	10	10	25	30	40	40	40	40	40	40
Tactical	1	2	3	4	5	6	7	8	9	10
Design	0	0	0	0	0	0	0	0	0	0
Flexibility	-20	-5	0	5	15	20	30	30	40	40
Integration	-15	0	5	10	15	20	25	30	35	40
Material	-10	10	15	20	25	30	40	50	50	50
Personnel	35	35	40	40	45	45	55	55	55	55
Producibility	-25	-15	5	15	25	35	45	45	55	55

rework rate of boards from this operation is anticipated to improve over the semi-automatic alternative. Other costs are shown in Table 3.8.

Next the nonmonetary attributes of the situation are examined. Performance of each of the alternatives was performed on the attributes of the Strategic and Tactical objectives. The qualitative flows are shown in Tables 3.9 thru 3.11.

These tables show in general that the current operations provide for a declining rating of the nonmonetary attributes. Internal Relations deteriorate as pressure is applied from within the company to bring work back to the U.S. This is due in

Table 3.11: Automatic Alternative Qualitative Flows

Strategic	1	2	3	4	5	6	7	8	9	10
Internal Relations	-35	-25	5	10	20	30	40	40	60	60
Market Position	10	-20	10	15	30	45	80	80	80	80
Mission	40	40	60	60	80	80	90	90	90	90
Organization	-35	-10	10	15	25	45	65	85	95	95
Public Relations	45	45	55	55	65	65	75	85	85	85
Technology	35	45	45	60	60	80	80	80	80	80
Tactical	1	2	3	4	5	6	7	8	9	10
Design	20	20	20	20	20	20	20	20	20	20
Flexibility	-20	0	10	20	30	50	80	90	90	90
Integration	-15	0	5	20	30	45	55	80	80	80
Material	-10	10	15	25	35	45	60	75	75	75
Personnel	-20	0	15	30	45	55	70	90	90	90
Producibility	-35	-25	0	40	80	80	90	90	90	90

part to the lack of control on the offshore operations from the support operations back in the U.S. Market position is expected to worsen as a result of this lack of control. The company has a current plan for modernization and automation, of which the offshore operations do not match. Organization is also not good because of poor information management between the offshore operations and the company in the U.S. Public relations are currently not a problem, but as the country is regaining its competitiveness, pressures are anticipated in returning as much of the manufacturing capability as possible back to the U.S. And the technology is, at best, antiquated. There is some impact on design, the density of components on the board has to allow for manual operations. This means that the designers have to allow space between the components for the operators to slide their fingers as they place components on the board. Flexibility is poor as the operations are not very responsive to change. Due to the offshore location, integration is almost impossible. Material is not a great problem in current operations, however it is anticipated that it will get worse unless some updated controls and communications are established between the U.S. and the offshore operations. Personnel for the

most part is adequate, but as boards become denser with components, the people will have more difficulty in inserting components. And finally, the producibility is bad because of the high rework and consistency problems reported by the offshore operations.

The semi-automatic alternative's nonmonetary performance shows that internal relations are anticipated to be poor in the first year due to the new machinery and the changes in operation. Humans are not always very adept to change. However, this will improve as the operations are brought on line. The market position should improve, as the company will be poised to better compete with greater control and improved operations. This alternative is a better match to the mission of modernization. Bringing the operations to the U.S. will initially result in some operational problems during transition, however as the offshore operations are phased out, control and information management will improve. Bringing back offshore operations will look good from a public relations view, and the technology is better than the current operations. There is no anticipated effects on design. Flexibility will be bad as the operators are first learning the new equipment, however as the machinery is placed into full service, the flexibility should improve. Similarly, integration, material, and producibility will have expected difficulties during the start up, and then improve with time. Personnel will be average during the start up, and also expected to improve.

Internal relations for the automated alternative are anticipated to be poor in the first years again due to the new machinery and the changes in operation. Due to the complexity of the machinery, this will last a year longer than in the semi-automatic alternative. The market position should improve, as the company will be poised to better compete with greater control and improved operations.

This alternative is the best match to the mission of modernization. As in the semi-automatic alternative, bringing the operations to the U.S. will initially result in some operational problems during transition, however as the offshore operations are phased out, control and information management will improve. Bringing back offshore operations will look good from a public relations view, and the use of automatic machinery should improve this over the semi-automatic equipment due to its "higher" technology. The technology of automatic insertion is also an improvement over the current and semi-automatic operations. As in the other alternatives, there is no anticipated effects on design. Flexibility will again probably be bad as the operators are first learning the new equipment, however as the machinery is placed into full service, the flexibility should improve. The flexibility is anticipated to improve rapidly due to the automation of the machinery. Integration, material, and producibility will have expected difficulties during the start up, and then improve with time. Personnel will be bad during the start up due to the complexity and frustrations associated with a new learning process, and then is expected to improve.

Having gathered the aforementioned information, the decision maker (company management) is requested to assist in determining the maximum desirable NPV to be used in the analysis. NPV_{DM} is \$5,000,000.

Using the cash flows presented in Tables 3.6 thru 3.8, the NPV of each alternative is determined. Using these NPV's, the Monetary Index is then calculated. The Monetary Index, along with the Nonmonetary Indices for the qualitative factors are then used to create the attribute versus alternative matrix shown in Table 3.12. All of the calculations in this example were performed using a software program developed for this effort entitled "AMSTEP-D: Advanced Manufactur-

Table 3.12: Attribute versus Alternative Matrix

ATTRIBUTE	MANUAL	SEMI-AUTO	AUTOMATIC
Monetary	0.6384	0.5394	0.4429
Internal Relations	-0.3049	0.1382	0.1382
Market Position	-0.2442	0.1700	0.3380
Mission	-0.4919	0.3533	0.6792
Organization	-0.5000	0.1126	0.2962
Public Relations	-0.2733	0.4052	0.6276
Technology	-0.9000	0.2916	0.6096
Design	0.0000	0.0000	0.2000
Flexibility	-0.6026	0.1132	0.3548
Integration	-0.3810	0.1298	0.3069
Material	-0.1393	0.2390	0.3421
Personnel	0.1058	0.4431	0.3829
Producibility	-0.3936	0.1812	0.3998

ing Systems Technology Evaluation Program - Deterministic." A listing of this program, written in "C", is provided in Appendix B.

Next, the decision maker is asked to assign weights to each of the attributes within an objective. Since the Pecuniary objective has only one attribute, the Monetary Index, its weight is 100 by default. The weights assigned to the attributes of the Strategic and Tactical objectives are shown in Table 3.13, along with the normalized weights. Additionally, the decision maker is requested to assign weights to the three objectives by importance. These weights, and their normalized result, are shown in Table 3.14.

Using the Composite Programming technique, the evaluation of each alternative was determined. The final results are summarized in Table 3.15. The ranking of the alternatives show that the automatic insertion machine is preferred to both the semi-automatic and current operations. The evaluation of the automatic and semi-automatic alternatives are relatively close, and the decision maker may de-

Table 3.13: Attribute Weights

ATTRIBUTE	WEIGHT	NORMALIZED
Monetary	100	100
Internal Relations	80	17
Market Position	95	20
Mission	90	19
Organization	70	15
Public Relations	60	13
Technology	85	18
Design	75	15
Flexibility	95	19
Integration	90	18
Material	75	15
Personnel	80	16
Producibility	95	19

Table 3.14: Objective Weights

OBJECTIVE	WEIGHT	NORMALIZED
Pecuniary	90	36
Strategic	80	32
Tactical	80	32

Table 3.15: Final Results and Rankings

ALTERNATIVE	EVALUATION	RANK
Manual	56	3
Semi-Automatic	35	2
Automatic	30	1

cide upon the semi-automatic operations. However, the current operations are a very poor choice compared to the alternatives.

Based entirely upon the monetary evaluation (MI), the decision would have been between the current operations and the automatic insertion machine alternative. Yet when the nonmonetary attributes of the alternatives were included into the evaluation, the current operations were no longer a contending alternative and the semi-automatic insertion machinery was in a more favorable light. Thus, having all of the nonmonetary and monetary factors in the evaluation has an effect upon the results of the evaluation of competing alternatives.

3.5.4 Effects of the Weights

An immediate question which arises from the use of the Composite Programming technique is the effect of the weights α and β on the final result. In order to analyze the effect of changing the weights, a mixture experiment was performed on the α 's and β 's independently [26]. The object of this experiment is to measure the effects of changing the proportions of the components (α and β) on the response (final score).

In accordance with mixture experiment terminology, α and β were normalized to sum to unity. This does not significantly alter the model as the desired effect remains the same, only the resulting score will differ by a constant factor. Additionally, for the mixture experiment the value of q in the Composite Programming equation was changed from 2 to 1 to create a linear equation in the objectives.

Initially, the analysis was performed on the objective weights (β_n , $n = 1, 2, 3$). The β_n 's were varied between 0 and 1, while the α_{nk} values were used as shown in Table 3.13. A simplex-centroid design for three components was used to analyze the effects of varying the proportion of β_1 , β_2 , and β_3 used in the model. This was

done for the three alternatives previously described.

The fitted third-degree model for each alternative is:

$$\begin{aligned}\hat{y}_{\text{manual}} &= 1.8\beta_1 + 7.4\beta_2 + 6.4\beta_3 + 8.8\beta_1\beta_2 + 1.6\beta_1\beta_3 + 0\beta_2\beta_3 + 1.2\beta_1\beta_2\beta_3 \\ \hat{y}_{\text{semi-auto.}} &= 2.3\beta_1 + 3.8\beta_2 + 4.1\beta_3 + 1.8\beta_1\beta_2 + 2.0\beta_1\beta_3 + 0.2\beta_2\beta_3 + 4.2\beta_1\beta_2\beta_3 \\ \hat{y}_{\text{automatic}} &= 2.8\beta_1 + 2.9\beta_2 + 3.3\beta_3 + 2.2\beta_1\beta_2 + 2.2\beta_1\beta_3 + 1.2\beta_2\beta_3 + 2.1\beta_1\beta_2\beta_3\end{aligned}$$

where $\hat{y}$ is the estimate of the Composite Programming score ρ . The derivation of these fitted models is based upon observed scores from the Composite Programming model and procedures presented in Cornell [26]. A brief background of this methodology is provided in Appendix C.

Statistically no statement can be made as to the goodness of fit of these models to the actual results since there is only one sample and as such the variance is zero. However, analysis of the coefficients indicates which parameter contributes most to the final score. Consider the large coefficients of β_2 and β_3 for the manual alternative. The inclusion of the Strategic and Tactical objectives in the model “worsens” the score and makes the manual alternative less attractive. The coefficients of the semi-automatic and automatic alternatives are more balanced, indicating a greater balance between the objectives.

The estimated shape of the surface for β_1 , β_2 , and β_3 is approximated pictorially for each alternative in Figures 3.5 thru 3.7 by a contour representation of the surface. These contour plots are based upon the fitted third-degree model for each alternative [50]. Each contour line on the plot joins the mixtures of β_1 , β_2 , and β_3 that are assumed to yield the same predicted score. The predicted scores were obtained for combinations of β_1 , β_2 , and β_3 where the specific combinations were defined as an array of points across the triangle. Predicted scores of equal magnitude are joined by the same contour line. Note that X_1 , X_2 , and X_3 on

Figure 3.6: Contour Plot of β_n for the Semi-Automatic Alternative

and β_3 are added, the score moves away from the ideal.

The contour plot of the semi-automatic alternative (Figure 3.6) is more robust as the score varies from 2.4 at $(1, 0, 0)$ to a maximum of 4.13 at $(0.12, 0.22, 0.66)$. Again, the lowest score is achieved when only the monetary objective is used, however the slope of the contour is less than the slope exhibited for the manual alternative. Whereas the peak of the manual alternative was near the point where the weight of the strategic objective dominates, the semi-automatic plot achieves its maximum closer to where the weight of the tactical objective dominates.

Figure 3.7: Contour Plot of β_n for the Automatic Alternative

Figure 3.8: Scores for the Alternatives for Various Values of β_n

Finally, the automatic alternative contour plot (Figure 3.7) is even more robust than the semi-automatic. Here the score varies by only 0.72. The slope of this contour is very gradual, and the peak is closer to the centroid of the triangle, indicating the greatest score when the the weights of the three objectives are the same. In this alternative complete dominance of either the pecuniary or the strategic objective yield similar results, indicating that the tactical objective is adding a significant “cost” to the results.

In addition to the contour plots, a comparison of the scores for the three alternatives is presented in Figure 3.8 for various combinations of β_n . The combinations of β_n used in the plot are shown in Table 3.16 and represent the following variations of β_n :

1. all the weight is in only one β_n (set # 1,2,3).
2. the weight is split evenly between only two β_n 's (set # 4,7,10).

3. the weight is split two-to-one between two β_n 's (set # 5,6,8,9,11,12).
4. the weight is split evenly between all three β_n 's (set # 13).
5. and the weight is split two-to-one where two β_n 's share the lesser weight (set # 14,15,16).
6. and the weight is split two-to-one where two β_n 's share the greater weight (set # 17,18,19).

From Figure 3.8 it can be seen that the manual alternative generally scores worse than the semi-automatic and automatic except in four areas: weight sets 3, 9, 12, and 16. These weight sets are where β_1 is at its highest values (1.00, 0.67, 0.67, and 0.50 respectively). Since the manual alternative is preferred strictly on the pecuniary objective, the strong weighting affects the final score by making the manual alternative preferable. A similar trend is noticeable with the semi-automatic alternative.

Next, the analysis was performed on the attribute weights (α_{nk} , $n = 2, 3$; $k = 1, \dots, 6$). The α_{nk} 's were varied between 0 and 1, while the β_n values were used as shown in Table 3.14. A simplex-centroid design for six components was used to analyze the effects of varying the proportion of α_{nk} used in the model. This was again performed for the three alternatives previously described.

In order to obtain the fitted sixth-degree model, additional derivations were required for the five-term and six-term components. These derivations are based upon the theory presented by Cornell [26], and are summarized in Appendix D. The fitted sixth-degree model for the strategic objective ($n = 2$) of the manual alternative is:

$$\hat{y}_{\text{manual}} = 47.9\alpha_{21} + 46.9\alpha_{22} + 50.9\alpha_{23} + 51.0\alpha_{24} + 47.4\alpha_{25} + 57.4\alpha_{26} +$$

Table 3.16: Combinations of Weights for β_n

SET	β_1	β_2	β_3	MAN	SEM	AUT
1	0.00	0.00	1.00	6.4	4.1	3.3
2	0.00	1.00	0.00	7.4	3.8	2.9
3	1.00	0.00	0.00	1.8	2.3	2.8
4	0.00	0.50	0.50	6.9	4.0	3.4
5	0.00	0.33	0.67	6.7	4.0	3.2
6	0.00	0.67	0.33	7.1	3.9	3.1
7	0.50	0.00	0.50	4.5	3.7	3.6
8	0.33	0.00	0.67	4.9	3.5	3.2
9	0.67	0.00	0.33	3.3	2.9	3.0
10	0.50	0.50	0.00	5.0	3.5	3.4
11	0.33	0.67	0.00	5.5	3.3	2.9
12	0.67	0.33	0.00	3.7	2.8	2.8
13	0.33	0.33	0.33	5.6	4.0	3.7
14	0.25	0.25	0.50	6.0	4.2	3.8
15	0.25	0.50	0.25	6.2	4.1	3.7
16	0.50	0.25	0.25	4.7	3.6	3.5
17	0.40	0.40	0.20	5.4	3.8	3.6
18	0.40	0.20	0.40	5.2	3.9	3.7
19	0.20	0.40	0.40	6.3	4.2	3.8

MAN - Manual.

SEM - Semi-Automatic.

AUT - Automatic.

$$\begin{aligned}
& 0\alpha_{21}\alpha_{22} + 0\alpha_{21}\alpha_{23} + 0.2\alpha_{21}\alpha_{24} - 0.2\alpha_{21}\alpha_{25} + 1.8\alpha_{21}\alpha_{26} + \\
& 0.4\alpha_{22}\alpha_{23} + 0.2\alpha_{22}\alpha_{24} - 0.2\alpha_{22}\alpha_{25} + 2.2\alpha_{22}\alpha_{26} - 0.2\alpha_{23}\alpha_{24} + \\
& 0.2\alpha_{23}\alpha_{25} + 0.6\alpha_{23}\alpha_{26} + 0.4\alpha_{24}\alpha_{25} + 0.8\alpha_{24}\alpha_{26} + 2.0\alpha_{25}\alpha_{26} - \\
& 6.3\alpha_{21}\alpha_{22}\alpha_{23} - 2.7\alpha_{21}\alpha_{22}\alpha_{24} + 1.2\alpha_{21}\alpha_{22}\alpha_{25} + 0.6\alpha_{21}\alpha_{22}\alpha_{26} + \\
& 1.8\alpha_{21}\alpha_{23}\alpha_{24} + 1.8\alpha_{21}\alpha_{23}\alpha_{25} + 1.8\alpha_{21}\alpha_{23}\alpha_{26} - 0.3\alpha_{21}\alpha_{24}\alpha_{25} - \\
& 0.3\alpha_{21}\alpha_{24}\alpha_{26} + 0\alpha_{21}\alpha_{25}\alpha_{26} + 1.5\alpha_{22}\alpha_{23}\alpha_{24} - 1.2\alpha_{22}\alpha_{23}\alpha_{25} + \\
& 0.3\alpha_{22}\alpha_{23}\alpha_{26} + 0.6\alpha_{22}\alpha_{24}\alpha_{25} - 0.6\alpha_{22}\alpha_{24}\alpha_{26} - 0.3\alpha_{22}\alpha_{25}\alpha_{26} - \\
& 0.3\alpha_{23}\alpha_{24}\alpha_{25} + 1.8\alpha_{23}\alpha_{24}\alpha_{26} - 0.3\alpha_{23}\alpha_{25}\alpha_{26} + 0.3\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 21.2\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24} - 2.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25} - 18.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{26} - \\
& 18.4\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25} - 11.2\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{26} + 6.8\alpha_{21}\alpha_{22}\alpha_{25}\alpha_{26} - \\
& 18.4\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25} - 20.4\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{26} - 6.8\alpha_{21}\alpha_{23}\alpha_{25}\alpha_{26} - \\
& 8.4\alpha_{21}\alpha_{24}\alpha_{25}\alpha_{26} - 2.4\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} - 12.0\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} + \\
& 12.4\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} - 3.2\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} - 9.2\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + \\
& 308.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} + 278.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} - \\
& 18.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 79.5\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + \\
& 333.5\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + 102.0\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 3160.2\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26}
\end{aligned}$$

Other fitted models are provided in Appendix D.

Again analysis of the coefficients indicates which parameter contributes most to the final score. For the strategic attributes of the manual alternative, the contribution seems to be rather uniform among the α_{2k} .

Unfortunately, the estimated shape of the surface for the α_{nk} 's cannot be depicted pictorially. Instead, a comparison of the scores for the three alternatives

Figure 3.9: Scores of Alternatives for Values of the Strategic Objective α_{2k}

is plotted in Figure 3.9 (strategic) and Figure 3.10 (tactical) for various combinations of α_{nk} . The combinations of α_{nk} used in the plots are shown in Table 3.17 and Table 3.18 and represent the following variations of α_{nk} :

1. all the weight is in only one α_n (set # 1 - 6).
2. the weight is split evenly between only two α_n 's (set # 7 - 21).
3. the weight is split evenly between only three α_n 's (set # 22 - 41).
4. the weight is split evenly between only four α_n 's (set # 42 - 56).
5. the weight is split evenly between only five α_n 's (set # 57 - 62).
6. the weight is split evenly between all six α_n 's (set # 63).

Results tend to be robust to the attribute weights. However, outcomes do highlight the strengths and weaknesses of each attribute. For the Strategic objective,

Figure 3.10: Scores of Alternatives for Values of the Tactical Objective α_{3k}

the manual alternative score is consistently higher, and the semi-automatic and automatic alternatives exhibit similar trends with respect to the weight of α_{nk} . The Tactical objective is more sensitive to the weights of α_{nk} . The lower scores of the manual alternative result from higher weights of the Design, Flexibility, and Producibility attributes. Higher weights of the Design, Flexibility, and Personnel attributes drive down the semi-automatic scores, and higher weights of Flexibility, Integration, and Personnel account for the lower scores of the automatic alternative. These shifts indicate that the Tactical objective should be given careful consideration when evaluating these AMST.

Table 3.17: Combinations of Weights for Strategic Objective α_{2k}

SET	α_{21}	α_{22}	α_{23}	α_{24}	α_{25}	α_{26}	MAN	SEM	AUT
1	1.00	0.00	0.00	0.00	0.00	0.00	47.90	35.30	34.50
2	0.00	1.00	0.00	0.00	0.00	0.00	48.90	34.80	31.30
3	0.00	0.00	1.00	0.00	0.00	0.00	50.90	31.90	25.80
4	0.00	0.00	0.00	1.00	0.00	0.00	51.00	35.70	32.00
5	0.00	0.00	0.00	0.00	1.00	0.00	47.40	31.10	26.70
6	0.00	0.00	0.00	0.00	0.00	1.00	57.40	32.90	27.00
7	0.50	0.50	0.00	0.00	0.00	0.00	47.40	35.10	33.00
8	0.50	0.00	0.50	0.00	0.00	0.00	49.40	33.70	31.10
9	0.50	0.00	0.00	0.50	0.00	0.00	49.50	35.50	33.30
10	0.50	0.00	0.00	0.00	0.50	0.00	47.60	33.40	31.30
11	0.50	0.00	0.00	0.00	0.00	0.50	53.10	34.20	31.40
12	0.00	0.50	0.50	0.00	0.00	0.00	49.00	33.40	29.00
13	0.00	0.50	0.00	0.50	0.00	0.00	49.00	35.30	31.60
14	0.00	0.50	0.00	0.00	0.50	0.00	47.10	33.10	29.30
15	0.00	0.50	0.00	0.00	0.00	0.50	52.70	33.90	29.40
16	0.00	0.00	0.50	0.50	0.00	0.00	50.90	34.00	29.50
17	0.00	0.00	0.50	0.00	0.50	0.00	49.20	31.50	26.30
18	0.00	0.00	0.50	0.00	0.00	0.50	54.30	32.40	26.40
19	0.00	0.00	0.00	0.50	0.50	0.00	49.30	33.60	29.70
20	0.00	0.00	0.00	0.50	0.00	0.50	54.40	34.40	29.80
21	0.00	0.00	0.00	0.00	0.50	0.50	52.90	32.00	26.60
22	0.33	0.33	0.33	0.00	0.00	0.00	48.60	34.10	31.20
23	0.33	0.33	0.00	0.33	0.00	0.00	48.70	35.30	32.70
24	0.33	0.33	0.00	0.00	0.33	0.00	47.40	33.90	31.30
25	0.33	0.33	0.00	0.00	0.00	0.33	51.20	34.40	31.40
26	0.33	0.00	0.33	0.33	0.00	0.00	50.00	34.40	31.40
27	0.33	0.00	0.33	0.00	0.33	0.00	48.80	32.90	29.90
28	0.33	0.00	0.33	0.00	0.00	0.33	52.40	33.50	29.90
29	0.33	0.00	0.00	0.33	0.33	0.00	48.80	34.20	31.60
30	0.33	0.00	0.00	0.33	0.00	0.33	52.40	34.70	31.80
31	0.33	0.00	0.00	0.00	0.33	0.33	51.30	33.20	30.10
32	0.00	0.33	0.33	0.33	0.00	0.00	49.70	34.30	30.10
33	0.00	0.33	0.33	0.00	0.33	0.00	48.40	32.70	28.30
34	0.00	0.33	0.33	0.00	0.00	0.33	52.10	33.30	28.40
35	0.00	0.33	0.00	0.33	0.33	0.00	48.50	34.00	30.30
36	0.00	0.33	0.00	0.33	0.00	0.33	52.10	34.50	30.30
37	0.00	0.33	0.00	0.00	0.33	0.33	51.00	33.00	28.60
38	0.00	0.00	0.33	0.33	0.33	0.00	49.80	33.10	28.60
39	0.00	0.00	0.33	0.33	0.00	0.33	53.30	33.60	28.70
40	0.00	0.00	0.33	0.00	0.33	0.33	52.20	32.00	26.50
41	0.00	0.00	0.00	0.33	0.33	0.33	52.30	33.40	28.90
42	0.25	0.25	0.25	0.25	0.00	0.00	49.20	34.50	31.40
43	0.25	0.25	0.25	0.00	0.25	0.00	48.30	33.40	30.30
44	0.25	0.25	0.25	0.00	0.00	0.25	51.10	33.80	30.30
45	0.25	0.25	0.00	0.25	0.25	0.00	48.30	34.40	31.50
46	0.25	0.25	0.00	0.25	0.00	0.25	51.10	34.70	31.50
47	0.25	0.25	0.00	0.00	0.25	0.25	50.30	33.60	30.40
48	0.25	0.00	0.25	0.25	0.25	0.00	49.30	33.70	30.40
49	0.25	0.00	0.25	0.25	0.00	0.25	52.00	34.10	30.50
50	0.25	0.00	0.25	0.00	0.25	0.25	51.20	32.90	29.20
51	0.25	0.00	0.00	0.25	0.25	0.25	51.20	33.90	30.60
52	0.00	0.25	0.25	0.25	0.25	0.00	49.10	33.50	29.40
53	0.00	0.25	0.25	0.25	0.00	0.25	51.80	33.90	29.40
54	0.00	0.25	0.25	0.00	0.25	0.25	51.00	32.70	28.00
55	0.00	0.25	0.00	0.25	0.25	0.25	51.00	33.80	29.60
56	0.00	0.00	0.25	0.25	0.25	0.25	51.00	33.00	28.30
57	0.20	0.20	0.20	0.20	0.20	0.00	48.90	33.90	30.60
58	0.20	0.20	0.20	0.20	0.00	0.20	51.10	34.20	30.70
59	0.20	0.20	0.20	0.00	0.20	0.20	50.40	33.30	29.70
60	0.20	0.20	0.00	0.20	0.20	0.20	50.40	34.10	30.80
61	0.20	0.00	0.20	0.20	0.20	0.20	51.20	33.50	29.90
62	0.00	0.20	0.20	0.20	0.20	0.20	51.00	33.40	29.00
63	0.17	0.17	0.17	0.17	0.17	0.17	50.50	33.70	30.10

MAN - Manual. SEM - Semi-Automatic. AUT - Automatic.

Table 3.18: Combinations of Weights for Tactical Objective α_{3k}

SET	α_{31}	α_{32}	α_{33}	α_{34}	α_{35}	α_{36}	MAN	SEM	AUT
1	1.00	0.00	0.00	0.00	0.00	0.00	30.30	30.20	33.60
2	0.00	1.00	0.00	0.00	0.00	0.00	32.10	30.50	36.50
3	0.00	0.00	1.00	0.00	0.00	0.00	33.60	49.90	34.70
4	0.00	0.00	0.00	1.00	0.00	0.00	42.90	38.20	31.50
5	0.00	0.00	0.00	0.00	1.00	0.00	33.00	34.80	34.80
6	0.00	0.00	0.00	0.00	0.00	1.00	30.70	46.50	33.60
7	0.50	0.50	0.00	0.00	0.00	0.00	31.30	30.30	35.10
8	0.50	0.00	0.50	0.00	0.00	0.00	32.10	42.90	34.20
9	0.50	0.00	0.00	0.50	0.00	0.00	37.80	35.00	32.60
10	0.50	0.00	0.00	0.00	0.50	0.00	31.70	32.80	34.20
11	0.50	0.00	0.00	0.00	0.00	0.50	30.50	40.60	33.60
12	0.00	0.50	0.50	0.00	0.00	0.00	32.90	42.90	35.60
13	0.00	0.50	0.00	0.50	0.00	0.00	38.40	35.00	34.20
14	0.00	0.50	0.00	0.00	0.50	0.00	32.60	32.90	35.60
15	0.00	0.50	0.00	0.00	0.00	0.50	31.40	40.60	35.10
16	0.00	0.00	0.50	0.50	0.00	0.00	38.90	44.90	33.20
17	0.00	0.00	0.50	0.00	0.50	0.00	33.30	43.80	34.70
18	0.00	0.00	0.50	0.00	0.00	0.50	32.20	48.30	34.10
19	0.00	0.00	0.00	0.50	0.50	0.00	38.60	36.60	33.20
20	0.00	0.00	0.00	0.50	0.00	0.50	37.90	42.80	32.60
21	0.00	0.00	0.00	0.00	0.50	0.50	31.90	41.70	34.20
22	0.33	0.33	0.33	0.00	0.00	0.00	32.10	39.90	35.00
23	0.33	0.33	0.00	0.33	0.00	0.00	36.10	33.70	34.00
24	0.33	0.33	0.00	0.00	0.33	0.00	31.90	32.10	35.00
25	0.33	0.33	0.00	0.00	0.00	0.33	31.10	38.00	34.60
26	0.33	0.00	0.33	0.33	0.00	0.00	36.50	41.40	33.30
27	0.33	0.00	0.33	0.00	0.33	0.00	32.40	40.60	34.40
28	0.33	0.00	0.33	0.00	0.00	0.33	31.60	44.20	34.00
29	0.33	0.00	0.00	0.33	0.33	0.00	36.40	34.90	33.40
30	0.33	0.00	0.00	0.33	0.00	0.33	35.80	39.80	32.90
31	0.33	0.00	0.00	0.00	0.33	0.33	31.40	38.90	34.00
32	0.00	0.33	0.33	0.33	0.00	0.00	36.90	41.50	34.40
33	0.00	0.33	0.33	0.00	0.33	0.00	32.90	40.60	35.30
34	0.00	0.33	0.33	0.00	0.00	0.33	32.20	44.20	34.90
35	0.00	0.33	0.00	0.33	0.33	0.00	36.80	34.90	34.40
36	0.00	0.33	0.00	0.33	0.00	0.33	36.20	39.80	34.00
37	0.00	0.33	0.00	0.00	0.33	0.33	32.00	38.90	35.00
38	0.00	0.00	0.33	0.33	0.33	0.00	37.10	42.20	33.70
39	0.00	0.00	0.33	0.33	0.00	0.33	36.60	45.40	33.30
40	0.00	0.00	0.33	0.00	0.33	0.33	32.50	44.80	34.30
41	0.00	0.00	0.00	0.33	0.33	0.33	36.40	40.60	33.30
42	0.25	0.25	0.25	0.25	0.00	0.00	35.60	39.50	34.20
43	0.25	0.25	0.25	0.00	0.25	0.00	32.30	38.80	34.90
44	0.25	0.25	0.25	0.00	0.00	0.25	31.80	41.80	34.60
45	0.25	0.25	0.00	0.25	0.25	0.00	35.40	34.00	34.20
46	0.25	0.25	0.00	0.25	0.00	0.25	35.00	38.10	33.90
47	0.25	0.25	0.00	0.00	0.25	0.25	31.60	37.30	34.70
48	0.25	0.00	0.25	0.25	0.25	0.00	35.70	40.00	33.70
49	0.25	0.00	0.25	0.25	0.00	0.25	35.30	42.80	33.40
50	0.25	0.00	0.25	0.00	0.25	0.25	32.00	42.30	34.20
51	0.25	0.00	0.00	0.25	0.25	0.25	35.20	38.70	33.40
52	0.00	0.25	0.25	0.25	0.25	0.00	36.00	40.10	34.50
53	0.00	0.25	0.25	0.25	0.00	0.25	35.60	42.90	34.20
54	0.00	0.25	0.25	0.00	0.25	0.25	32.40	42.30	34.90
55	0.00	0.25	0.00	0.25	0.25	0.25	35.50	38.70	34.20
56	0.00	0.00	0.25	0.25	0.25	0.25	35.80	43.30	33.70
57	0.20	0.20	0.20	0.20	0.20	0.00	35.10	38.60	34.30
58	0.20	0.20	0.20	0.20	0.00	0.20	34.70	41.10	34.10
59	0.20	0.20	0.20	0.00	0.20	0.20	32.00	40.60	34.70
60	0.20	0.20	0.00	0.20	0.20	0.20	34.60	37.50	34.10
61	0.20	0.00	0.20	0.20	0.20	0.20	34.90	41.50	33.70
62	0.00	0.20	0.20	0.20	0.20	0.20	35.10	41.60	34.30
63	0.17	0.17	0.17	0.17	0.17	0.17	34.40	40.20	34.20

MAN - Manual. SEM - Semi-Automatic. AUT - Automatic.

3.6 Solutions Using Other Methodologies

The AMST evaluation methodology is not tied to the Composite Programming technique, although it is an elegant solution. This section shows how Goal Programming and MCQA can be used with the AMST evaluation methodology to arrive at a ranking of alternatives.

3.6.1 Goal Programming Formulation

The goals of the AMST evaluation problem are:

- P_1 - Maximize NPV (Pecuniary)
- P_2 - Maximize Strategic Benefits
- P_3 - Maximize Tactical Benefits

The MI for the alternatives is determined as described in Section 3.3. The goal for the MI is 1, and thus an MI constraint is specified by:

$$\sum_{j=1}^J MI_j X_j + d_{13}^- - d_{13}^+ = 1$$

where:

- J - Number of alternatives.
- X_j - 0/1 Decision Variable:
0 = reject alternative j , 1 = accept alternative j .
- d_{13}^- - Underachievement of MI from goal.
- d_{13}^+ - Overachievement of MI from goal.

The NI is determined from the Strategic and Tactical objectives. Each attribute may achieve a maximum score of 100, and these are discounted to a present value using h . Therefore, an NI constraint for the Strategic goal is specified by:

$$\sum_{j=1}^J NI_{kj} X_j + d_k^- - d_k^+ = 100 \sum_{t=1}^T (1+h)^{-t} \quad \text{for } k = 1, \dots, 12$$

where:

Table 3.19: Attribute Definition for Goal Programming Implementation

k	ATTRIBUTE
1	Internal Relations
2	Market Position
3	Mission Compliance
4	Organization
5	Public Relations
6	Technology
7	Design
8	Flexibility
9	Integration
10	Material
11	Personnel
12	Producibility
13	Monetary Index

T - Life of the project.

d_k^- - Underachievement of NI from $100 \sum_{t=1}^T (1+h)^{-t}$

d_k^+ - Overachievement of NI from $100 \sum_{t=1}^T (1+h)^{-t}$

The subscript k is defined as shown in Table 3.19. Finally, only one alternative may be selected as the “best”. Thus,

$$\sum_{j=1}^J X_j = 1$$

The objective function for the model is formulated as:

$$\min Z = P_1(w_{13}d_{13}^-) + P_2\left(\sum_{k=1}^6 w_k d_k^-\right) + P_3\left(\sum_{k=7}^{12} w_k d_k^-\right)$$

where:

w_k - Weight of the attributes k .

In order to achieve a ranking of the alternatives, the Goal Programming formulation is solved $J - 1$ times. After each solution, the preferred alternative is removed from the set of alternatives J and added to the ranking of preferred alternatives. This is performed until only one alternative is remaining.

Numerical Example

The example described in Section 3.5.3 is solved using the Goal Programming formulation. The model is as follows:

$$\begin{aligned} \min Z = & 36(100d_{13}^-) + 32(17d_1^- + 20d_2^- + 19d_3^- + 15d_4^- + 13d_5^- + 18d_6^-) + \\ & 32(15d_7^- + 19d_8^- + 18d_9^- + 15d_{10}^- + 16d_{11}^- + 19d_{12}^-) \end{aligned}$$

subject to:

$$\begin{aligned} 0.6384X_1 + 0.5394X_2 + 0.4429X_3 + d_{13}^- - d_{13}^+ &= 1 \\ -0.3049X_1 + 0.1382X_2 + 0.1382X_3 + d_1^- - d_1^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ -0.2442X_1 + 0.1700X_2 + 0.3380X_3 + d_2^- - d_2^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ -0.4919X_1 + 0.3533X_2 + 0.6792X_3 + d_3^- - d_3^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ -0.5000X_1 + 0.1126X_2 + 0.2962X_3 + d_4^- - d_4^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ -0.2733X_1 + 0.4052X_2 + 0.6276X_3 + d_5^- - d_5^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ -0.9000X_1 + 0.2916X_2 + 0.6096X_3 + d_6^- - d_6^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ 0.0000X_1 + 0.0000X_2 + 0.2000X_3 + d_7^- - d_7^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\ -0.6026X_1 + 0.1132X_2 + 0.3548X_3 + d_8^- - d_8^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \end{aligned}$$

Table 3.20: Results of the Goal Programming Evaluation

ALTERNATIVE	RANK	SCORE
Automatic	1	5,983
Semi-Automatic	2	6,802
Manual	3	N/A

$$\begin{aligned}
-0.3810X_1 + 0.1298X_2 + 0.3069X_3 + d_9^- - d_9^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\
-0.1393X_1 + 0.2390X_2 + 0.3421X_3 + d_{10}^- - d_{10}^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\
0.1058X_1 + 0.4431X_2 + 0.3829X_3 + d_{11}^- - d_{11}^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\
-0.3936X_1 + 0.1812X_2 + 0.3998X_3 + d_{12}^- - d_{12}^+ &= 100 \sum_{t=1}^{10} (1.134)^{-t} \\
\sum_{j=1}^3 X_j &= 1 \\
X_j &\in [0, 1] \\
d_k^-, d_k^+ &\geq 0 \quad k = 1, \dots, 13
\end{aligned}$$

The foregoing Goal Programming problem was solved using the software package "STORM: Personal Version 2.0" for the personal computer [34]. Two iterations of the procedure were required for the three alternatives being analyzed. The first iteration yielded the automatic insertion equipment as the preferred selection. The model was then reformulated to exclude the third alternative, and only the manual and semi-automatic alternatives were evaluated. This second iteration selected the semi-automatic alternative as the preferred choice. A summary of the results is provided in Table 3.20.

The evaluation using the Goal Programming approach yielded the same rank-

ing as presented earlier. Detailed results from the solution to the Goal Programming problem are provided in Appendix E.

3.6.2 MCQA Formulation

In addition to the evaluation performed using Goal Programming, an evaluation is provided using MCQA-II. The same attribute versus alternative matrix as defined in Section 3.5.2 is used, along with appropriate weights for the attributes and objectives. Since the model is a two level analysis (objectives and attributes), each having their own set of weights, the solution methodology using MCQA-II will be decomposed to accommodate the hierarchy. Solutions are initially obtained for the Pecuniary, Strategic, and Tactical objectives. These solutions are then used to create an attribute versus alternative matrix for the objectives, which is then solved using another iteration of the MCQA-II procedure.

Numerical Example

The evaluation problem presented in Section 3.5.3 was solved using MCQA-II. The attribute versus alternative matrix used is the one presented in Table 3.12, and the normalized weights are used as shown in Table 3.13 and Table 3.14. The procedure used was as follows. MCQA-II was used to perform the evaluation on the Pecuniary objective. The attribute versus alternative matrix used was simply the MI for each alternative. The scores were then recorded, and then an evaluation was performed on the Strategic objective. In this case the attribute versus alternative matrix consisted of NI_{kj} for each alternative j , and $k = 1, \dots, 6$. These scores were recorded, and next an evaluation was performed on the Tactical objective. Similar to the Strategic objective, the attribute versus alternative matrix consisted of NI_{kj} for each alternative j , and $k = 7, \dots, 12$. The scores from these

Table 3.21: Intermediate Results from Evaluation using MCQA-II

ALTERNATIVE	PEC	PRI2	
		STR	TAC
Manual	0.000	1.659	1.555
Semi-Automatic	1.061	1.013	0.447
Automatic	1.573	0.000	0.000

Table 3.22: Results from Evaluation using MCQA-II

ALTERNATIVE	PSI	PCI	PDI	PRI1	PRI2	RANK
Automatic	189.80	2.55	0.60	0.00	0.25	1
Semi-Automatic	129.00	0.60	1.65	0.83	1.08	2
Manual	111.60	1.65	2.40	0.54	1.14	3

evaluations were then used as the attribute versus alternative matrix for input to the final evaluation. A software package was utilized which is used in SIE 565 (Multiobjective Decision Making in Engineering Systems) at the University of Arizona. The intermediate results of the evaluation of the objectives is listed in Table 3.21. Table 3.22 shows the final results from the evaluation. Again, the automatic insertion equipment alternative ranked first, followed by the semi-automated equipment, and finally the current operations. Detailed results from the solution to the MCQA-II evaluation are provided in Appendix F.

3.7 Summary

This Chapter presented a deterministic methodology and model for use in the evaluation of AMST. The objectives of the model were presented, along with

supporting documentation for the completeness of the model for a manufacturing organization. An example of using the model and methodology was presented, which showed the effect of including nonmonetary parameters in the evaluation. These parameters had the effect of altering the outcome of the evaluation. Coupled with a mixture experiment, it is possible to graphically portray the contours of each alternative as the importance of monetary, tactical, and strategic objectives vary. Additionally, a comparison of using the model with other methodologies was presented. All results were consistent.

Chapter 4

Determining Risk

“The mean is mean but the variance is meaner.” [8]

4.1 Introduction

A great deal of the evaluation of AMST hinges on events which are to occur in the future. The approach presented in Chapter 3 assumed a deterministic environment. Therefore, all of the future events were assumed to be known for certain. In a real world setting, these events are not known for certain, and as such a decision made on these events contains risk.

Loss is defined to be the deviation from the goal (ideal point) given the following parameters: cash flows, qualitative flows, monetary interest rates, and nonmonetary interest rates. Risk is defined to be the expected loss incurred by making a decision. This expectation is taken over the distributions of the parameters. The goal is to minimize the maximum loss incurred from making a decision. If the distributions of the losses from making various decisions are known, these decisions can be partially compared using the parameters which define the distributions (ie. mean and variance). Hence, the purpose of this chapter is to provide a methodology whereby the parameters which define the distribution of the Composite Programming evaluation for each alternative can be examined.

4.2 Elements of Risk

Risk in evaluation of project alternatives usually arises in four areas; cash flows, qualitative flows, project length, and interest rates. Shinnar et al. [119] have determined interest rates for various companies based upon historical financial

data for those companies. Of the manufacturing industries analyzed, interest rates have been shown to vary by as much as $6\frac{1}{2}\%$ over a ten year time period. Thus, it is important in the analysis that the interest rate be allowed to vary from year to year, and also associate an uncertainty measure with the interest rate. This interest rate will be represented by the random variable $\tilde{i}_t$ for the monetary case, and $\tilde{h}_t$ for the nonmonetary case.

Future cash flows resulting from a particular alternative are estimates based upon the past experience of a decision maker, assistance from vendors for quotes, and literature from the field. These cash flows, for attribute k of alternative j in a given year t , are represented by the random variable $\tilde{C}_{tkj}$. Similarly, qualitative flows resulting from a particular alternative are also estimates based on experience. The qualitative flows for attribute k of alternative j in any year t are represented by the random variable $\tilde{Q}_{tkj}$. The length of the project, T , is also unknown for certain. Thus the analysis will allow for the consideration of T being a random variable ($\tilde{T}$). Time is considered to be discrete in the periods of the analysis (months, quarters, years, etc.).

Each of the aforementioned random variables ($\tilde{C}_{tkj}$, $\tilde{Q}_{tkj}$, $\tilde{i}_t$, $\tilde{h}_t$, $\tilde{T}$) has an impact on the determination of NPV and $NPQF$. Since NPV is determined from $\tilde{C}_{tkj}$, $\tilde{i}_t$, and $\tilde{T}$, the NPV , is itself a random variable. Similarly, the $NPQF$ is a random variable made up of $\tilde{Q}_{tkj}$, $\tilde{h}_t$, and $\tilde{T}$. The view of the world is that an event occurs at time $\tilde{T} = t$, which is unpredictable, ends the project, and subsequently determines the final value of $N\tilde{P}V$ and $N\tilde{P}QF$.

The desired result of the risk determination is a distribution of the evaluation of the Monetary Index, Nonmonetary Indices, objectives, and final evaluation score for each alternative. The expected values of these distributions are then

determined, which is the expected deviation from the ideal (or expected loss). By having the distributional forms of the evaluations for the $\tilde{M}I$, $\tilde{N}I_k$, and the three objectives of each alternative, further insight can be gained as to which component may be causing the variation. If the alternative with the larger variability showed a large variance of the Tactical objective, this may be acceptable to the decision maker. On the other hand, a large variation in the Pecuniary objective may not be desirable. Therefore, through insight into the distributions of the evaluations, the performance of the alternatives can be analyzed with respect to risk [16], [137], [56].

Two scenarios are examined when analyzing risk. The first is that the cash flows, qualitative flows, interest rates, and time period are all mutually independent. The other is that these variables contain dependencies. If independent, the cash flows $\tilde{C}_{tkj}$ (or qualitative flows $\tilde{Q}_{tkj}$) and interest rates can be determined individually and solely from the events which occur within period t , and these events have no bearing on the events in other periods. In a real world setting this is rarely the case [16].

For completeness, a determination of risk will be presented for the case when the variables are independent. However, the main result of this chapter is based upon a dependence of the cash flows, qualitative flows, and interest rates, with respect to time.

4.3 Risk Under Independence

When the cash flows, qualitative flows, interest rates, and time period are all independent, the analysis is relatively straight forward. The simplest parameters to identify are the mean and variance of the three objectives.

The term $\frac{1}{R_{MI}}$ of the Monetary Index is essentially a constant, and will be represented by M_1 . Let $\tilde{A}_t = \left[\sum_{k=1}^K \tilde{C}_{tk}(1 - \tau_c) + D_t \tau_c \right] \prod_{n=0}^t (1 + \tilde{i}_n)^{-1}$. The subscript j representing a particular alternative has been removed for clarity of presentation, and does not affect the outcome. Therefore, the Monetary Index can be written as:

$$\tilde{M}I = M_1 \sum_{t=0}^{\tilde{T}} \tilde{A}_t$$

Suppose for the purpose of modeling, it is assumed that $\tilde{A}_t$ are independent of $\tilde{T}$. Furthermore, suppose that the moment generating function for $\tilde{A}_t$ exists, is known, and is represented by $\phi_{\tilde{A}_t}(r)$. Therefore, using the relationship $\phi(r) = \sum_{n=0}^{\infty} \prod_{i=0}^n \phi_i(r) p(n)$ [152], where:

- $\phi(r)$ - The moment generating function of a sum of independent random variables.
- $\phi_i(r)$ - The moment generating function of the random variable i .
- $p(n)$ - The probability of n random variables in the sum.

the moment generating function of the Monetary Index is:

$$\phi_{\tilde{M}I}(r) = \sum_{t=0}^{\infty} \left[\prod_{n=0}^t \phi_{\tilde{A}_n}(M_1 r) \right] p\{\tilde{T} = t\}$$

where $p\{\tilde{T} = t\}$ denotes the probability that the project life is t .

Now, the expected Monetary Index is:

$$\begin{aligned} E[\tilde{M}I] &= \phi'_{\tilde{M}I}(r) \\ &= \left. \frac{d}{dr} \phi_{\tilde{M}I}(r) \right|_{r=0} \\ &= \left. \frac{d}{dr} \left[\sum_{t=0}^{\infty} \left[\prod_{n=0}^t \phi_{\tilde{A}_n}(M_1 r) \right] p\{\tilde{T} = t\} \right] \right|_{r=0} \\ &= M_1 \sum_{t=0}^{\infty} \left[\phi'_{\tilde{A}_t}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m \phi_{\tilde{A}_n}(0) \right) p\{\tilde{T} = m\} \right] \right] \end{aligned}$$

The derivation of this result is provided in Appendix G.

The variance is:

$$\begin{aligned}
 V[\tilde{M}I] &= \phi''_{\tilde{M}I}(r) - [\phi'_{\tilde{M}I}(r)]^2 \\
 &= \left. \frac{d^2}{dr^2} \phi_{\tilde{M}I}(r) \right|_{r=0} - \left[\left. \frac{d}{dr} \phi_{\tilde{M}I}(r) \right|_{r=0} \right]^2 \\
 &= M_1^2 \sum_{t=0}^{\infty} \left[\phi''_{\tilde{A}_t}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m \phi_{\tilde{A}_n}(0) \right) p\{\tilde{T} = m\} \right] \right] + \\
 &\quad 2M_1^2 \sum_{t=1}^{\infty} \left[\sum_{\substack{v,w=0 \\ v \neq w}}^t \phi'_{\tilde{A}_v}(0) \phi'_{\tilde{A}_w}(0) \prod_{s \neq v,w} \phi_{\tilde{A}_s}(0) \right] p\{\tilde{T} = t\} - E[\tilde{M}I]^2
 \end{aligned}$$

The derivation of this result is also provided in Appendix G.

Similarly, for the Nonmonetary Index, let $M_2 = \frac{1}{R_{NI}}$, and $\tilde{B}_{tk} = \tilde{Q}_{tk} \prod_{n=1}^t (1 + \tilde{h}_n)^{-1}$. Thus, the Nonmonetary Index can be written as:

$$\tilde{N}I_k = C_2 \sum_{t=1}^{\tilde{T}} \tilde{B}_{tk}$$

Again, assume that the $\tilde{B}_{tk}$ are independent of $\tilde{T}$. Furthermore, suppose that the moment generating function for $\tilde{B}_{tk}$ exists, is known, and is represented by $\phi_{\tilde{B}_{tk}}(r)$.

Therefore, the moment generating function of the Nonmonetary Index is:

$$\phi_{\tilde{N}I_k}(r) = \sum_{t=1}^{\infty} \left[\prod_{n=1}^t \phi_{\tilde{B}_{nk}}(M_2 r) \right] p\{\tilde{T} = t\}$$

The expected Nonmonetary Index can be written as:

$$\begin{aligned}
 E[\tilde{N}I_k] &= \phi'_{\tilde{N}I_k}(r) \\
 &= \left. \frac{d}{dr} \phi_{\tilde{N}I_k}(r) \right|_{r=0} \\
 &= \frac{d}{dr} \left[\sum_{t=1}^{\infty} \left[\prod_{n=1}^t \phi_{\tilde{B}_{nk}}(M_2 r) \right] p\{\tilde{T} = t\} \right]_{r=0} \\
 &= M_2 \sum_{t=1}^{\infty} \left[\phi'_{\tilde{B}_{tk}}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=1 \\ n \neq t}}^m \phi_{\tilde{B}_{nk}}(0) \right) p\{\tilde{T} = m\} \right] \right]
 \end{aligned}$$

The derivation of this result follows the same methodology as the derivation of $E[\tilde{M}I]$.

The variance is:

$$\begin{aligned}
 V[\tilde{N}I_k] &= \phi''_{\tilde{N}I_k}(r) - [\phi'_{\tilde{N}I_k}(r)]^2 \\
 &= \left. \frac{d^2}{dr^2} \phi_{\tilde{N}I_k}(r) \right|_{r=0} - \left[\left. \frac{d}{dr} \phi_{\tilde{N}I_k}(r) \right|_{r=0} \right]^2 \\
 &= M_2^2 \sum_{t=1}^{\infty} \left[\phi''_{\tilde{B}_{tk}}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=1 \\ n \neq t}}^m \phi_{\tilde{B}_{nk}}(0) \right) p\{\tilde{T} = m\} \right] \right] + \\
 &\quad 2M_2^2 \sum_{t=2}^{\infty} \left[\sum_{\substack{v,w=0 \\ v \neq w}}^t \phi'_{\tilde{B}_{vk}}(0) \phi'_{\tilde{B}_{wk}}(0) \prod_{s \neq v,w} \phi_{\tilde{B}_{sk}}(0) \right] p\{\tilde{T} = t\} - E[\tilde{M}I]^2
 \end{aligned}$$

The derivation of this result follows the same methodology as the derivation of $V[\tilde{M}I]$.

Determining the distributional form of the objectives and the overall ranking is a bit more challenging. The moment generating functions of the Monetary Index and Nonmonetary Index have been defined, however the actual form of $\tilde{A}_t$ and $\tilde{B}_{tk}$ are not known. Therefore, the distributional forms cannot readily be determined.

For illustrative purposes, suppose that the form of $\tilde{A}_t$ is known, and is Poisson. Now, the $E[\tilde{M}I]$ and $V[\tilde{M}I]$ can be determined. The moment generating function of the Poisson with rate λ_t is $e^{\lambda_t(e^r-1)}$. Additionally, $\tilde{T}$ is Poisson with rate λ . Thus:

$$\begin{aligned}
 \phi_{\tilde{A}_t}(r) &= e^{\lambda_t(e^r-1)} \\
 \phi'_{\tilde{A}_t}(r) &= \lambda_t e^{\lambda_t(e^r-1)+r} \\
 \phi''_{\tilde{A}_t}(r) &= (\lambda_t^2 e^{2r} + \lambda_t e^r) e^{\lambda_t(e^r-1)}
 \end{aligned}$$

Therefore, the $E[\tilde{M}I]$ is:

$$\begin{aligned} E[\tilde{M}I] &= M_1 \sum_{t=0}^{\infty} \left[\lambda_t e^{\lambda_t(e^0-1)+0} \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m e^{\lambda_n(e^0-1)} \right) p\{\tilde{T} = m\} \right] \right] \\ &= M_1 \sum_{t=0}^{\infty} \left[\lambda_t \sum_{m=t}^{\infty} e^{-\lambda} \frac{\lambda^m}{m!} \right] \end{aligned}$$

The variance is:

$$\begin{aligned} V[\tilde{M}I] &= M_1^2 \sum_{t=0}^{\infty} \left[\phi''_{\tilde{A}_t}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m e^{\lambda_n(e^0-1)} \right) p\{T = m\} \right] \right] + \\ &\quad 2M_1^2 \sum_{t=1}^{\infty} \left[\sum_{\substack{v,w=0 \\ v \neq w}}^t \lambda_v e^{\lambda_v(e^0-1)+r} \lambda_w e^{\lambda_w(e^0-1)+r} \prod_{s \neq v,w} e^{\lambda_s(e^0-1)} \right] p\{T = t\} - \\ &\quad E[\tilde{M}I]^2 \\ &= M_1^2 \sum_{t=0}^{\infty} \left[(\lambda_t^2 + \lambda_t) \left[\sum_{m=t}^{\infty} e^{-\lambda} \frac{\lambda^m}{m!} \right] \right] + 2M_1^2 \sum_{t=1}^{\infty} \left[\sum_{\substack{v,w=0 \\ v \neq w}}^t \lambda_v \lambda_w \right] e^{-\lambda} \frac{\lambda^t}{t!} - \\ &\quad \left[M_1 \sum_{t=0}^{\infty} \left[\lambda_t \sum_{m=t}^{\infty} e^{-\lambda} \frac{\lambda^m}{m!} \right] \right]^2 \\ &= M_1^2 \sum_{t=0}^{\infty} \left[(\lambda_t^2 + \lambda_t) \left[\sum_{m=t}^{\infty} e^{-\lambda} \frac{\lambda^m}{m!} \right] \right] + 2M_1^2 \sum_{t=1}^{\infty} \left[e^{-\lambda} \frac{\lambda^t}{t!} \sum_{\substack{v,w=0 \\ v \neq w}}^t \lambda_v \lambda_w \right] - \\ &\quad M_1^2 \left[\sum_{t=0}^{\infty} \left[\lambda_t \sum_{m=t}^{\infty} e^{-\lambda} \frac{\lambda^m}{m!} \right] \right]^2 \end{aligned}$$

If the form of $\tilde{B}_{tk}$ were also known, a similar result can be determined for the $\tilde{N}I$.

In order to determine a mean and variance of the final composite score, these results would have to be incorporated into the Composite Programming algorithm. Again, not knowing the distributional forms of the $\tilde{M}I$ or $\tilde{N}I_k$ makes this a formidable task.

When the form of $\tilde{A}_t$ and $\tilde{B}_{tk}$ are not known or simple theoretical distributions

models do not suffice, an alternative approach is required. Note that the $\tilde{M}I$, for example, is a function of $\tilde{C}_{tk}$, $\tilde{i}_t$, and $\tilde{T}$. This can be written as:

$$\tilde{M}I = g_{MI}(\tilde{C}_{tk}, \tilde{i}_t, \tilde{T})$$

In order to determine the distribution of the $\tilde{M}I$, the following is needed:

$$p\{\tilde{M}I \leq m\} = p\{g_{MI}(\tilde{C}_{tk}, \tilde{i}_t, \tilde{T}) \leq m\}$$

which requires knowledge of the range of $g_{MI}(\tilde{C}_{tk}, \tilde{i}_t, \tilde{T})$, and the joint distribution for which $g(\tilde{C}_{tk}, \tilde{i}_t, \tilde{T}) \leq m$. Similarly, the $\tilde{N}I_k$ is a function of $\tilde{Q}_{tk}$, $\tilde{h}_t$, and $\tilde{T}$, which can be written as:

$$\tilde{N}I_k = g_{NI_k}(\tilde{Q}_{tk}, \tilde{h}_t, \tilde{T})$$

and in order to determine the distribution of $\tilde{N}I_k$

$$p\{\tilde{N}I_k \leq m\} = p\{g_{NI_k}(\tilde{Q}_{tk}, \tilde{h}_t, \tilde{T}) \leq m\}$$

is needed. Again, knowledge of the range of $g_{NI_k}(\tilde{Q}_{tk}, \tilde{h}_t, \tilde{T})$, and the joint distribution for which $g(\tilde{Q}_{tk}, \tilde{h}_t, \tilde{T}) \leq m$. In addition, the final composite score is a function of the $\tilde{M}I$ and $\tilde{N}I_k$:

$$\tilde{\rho} = g_{\rho}(\tilde{M}I, \tilde{N}I_k)$$

and in order to determine the distribution of $\tilde{\rho}$, the following is needed:

$$p\{\tilde{\rho} \leq m\} = p\{g_{\rho}(\tilde{M}I, \tilde{N}I_k) \leq m\}$$

This requires knowledge of the range of $g_{\rho}(\tilde{M}I, \tilde{N}I_k)$, and the joint distribution for which $g_{\rho}(\tilde{M}I, \tilde{N}I_k) \leq m$. There does not appear to be a simple analytical method for determining these ranges.

The approach taken in this research is to perform a partial enumeration in order to determine the distributional form of the objectives and ranking score. From this, a mean and variance can be computed for the Composite Programming score. The enumeration is performed using a discrete $\tilde{M}I$ and $\tilde{N}I_k$. The decision maker is asked to provide values for $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, $\tilde{h}_t$, and $\tilde{T}$ in the form of a distribution. $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$ are considered continuous and $\tilde{T}$ discrete in periods (i. e. years). If the distributional form is unknown to the decision maker, a triangular distribution approximation will be used. In the absence of data, Law et al. [78] suggest using the triangular distribution. This practice is used by many simulation practitioners when data does not exist to determine a distribution [4]. The values for $\tilde{T}$ used will be in integer increments from a specified lower bound to a specified upper bound.

The enumeration determines values of $\tilde{M}I$ for combinations of samples taken from $\tilde{C}_{tk}$, $\tilde{i}_t$, and $\tilde{T}$. The samples for $\tilde{C}_{tk}$, $\tilde{i}_t$, and $\tilde{T}$ are taken randomly using a triangular distribution. One thousand (1,000) samples for the $\tilde{M}I$ are generated in the evaluation. These observations are divided into ten class intervals (bins) creating the $\tilde{M}I$ distribution. The number of samples and bins can be varied by the user. A greater number of samples and bins may be selected, which may yield a greater resolution of the distribution. However, the tradeoff is that a greater sample size and number of bins results in a longer running time and a larger amount of data to be processed and stored. Similarly, random samples for $\tilde{Q}_{tk}$, $\tilde{h}_t$, and $\tilde{T}$ are generated using a triangular distribution, and 1000 samples of each $\tilde{N}I_k$ are computed. These observations are again divided into ten class intervals (bins) creating the $\tilde{N}I_k$ distributions.

Using the generated values of the $\tilde{M}I$, a distribution of the Pecuniary ob-

jective is determined by calculating $\beta_1 \left(\alpha_{11} \left| \frac{1 - \tilde{M}I}{2} \right|^p \right)^{q/p}$ for each value of the $\tilde{M}I$. Bins are set up for the Pecuniary distribution, and for each sample which falls into a bin, the sample count within that bin is incremented by one. These sample counts are then divided by the sample size to determine the probabilities of the bins. Using the generated distribution of the $\tilde{N}I_k$, a distribution of the Strategic and Tactical objective is determined. This is done using a complete enumeration of the bin values for the $\tilde{N}I_k$, where the Strategic objective is determined by $\beta_2 \left(\sum_{k \in S_2} \alpha_{2k} \left| \frac{1 - \tilde{N}I_k}{2} \right|^p \right)^{q/p}$ and the Tactical objective by $\beta_3 \left(\sum_{k \in S_3} \alpha_{3k} \left| \frac{1 - \tilde{N}I_k}{2} \right|^p \right)^{q/p}$. The probabilities are determined by summing the appropriate joint probabilities. Upon completion of the determination of the distributions, means and variances are computed.

For example, suppose the Strategic objective was comprised of two elements ($k = 1, 2$). Further suppose that the distribution of each $\tilde{N}I_k$ was made up of five bins ($\tilde{N}I_{ki}$, $i = 1, 2, 3, 4, 5$). These distributions are shown in Figure 4.1. The probabilities of the bin values for $\tilde{N}I_{1i}$ are p_{1i} , $i = 1, 2, 3, 4, 5$. The probabilities of the bin values for $\tilde{N}I_{2j}$ are p_{2j} , $j = 1, 2, 3, 4, 5$. The minimum and maximum values for the Strategic objective are then computed based upon the minimum and maximum values of the observed $\tilde{N}I_k$. The break points of the bins are then determined by dividing the range of maximum and minimum values of the Strategic objective by the desired number of bins. Next, for each bin value of the $\tilde{N}I_k$, the Strategic objective is computed as $\beta_2 \left(\sum_{k=1}^2 \alpha_{2k} \left| \frac{1 - \tilde{N}I_k}{2} \right|^p \right)^{q/p}$. The value computed is then placed into the appropriate bin for the Strategic objective, and the probability associated with that bin is incremented by the joint probability $p_{1i} * p_{2j}$. In this manner, the distribution for the Strategic objective is computed.

Figure 4.1: Example Distributions for Calculation of Strategic Objective.

Next, the resulting Pecuniary (PEC), Strategic (STR), and Tactical (TAC) objective distributions are used to determine a distribution of the final composite programming score. A complete enumeration of the bin values for the Pecuniary, Strategic, and Tactical distributions is used. Similar to the procedure described previously for the Strategic objective, a minimum and maximum score are initially determined. The scores are determined by $(PEC + STR + TAC)^{1/q}$. The break points of the bins are then determined by dividing the range of maximum and minimum values by the number of bins desired. The bin location of each calculated composite programming score is determined, and the calculated joint probability is added to the previous probability of that bin. Upon completion, a mean and variance for the scores is computed.

The following algorithm is employed:

```

get analysis parameters;
normalize weights;
for  $m = 1$  to sample size
    determine random sample of project length ( $T_m$ ) from a
        Triangular distribution;
    save  $T_m$  for later use;

```

```

for  $j = 1$  to number of alternatives
  read input data for alternative  $j$ ;
  open output file for  $NPV_j$ ;
  for  $m = 1$  to sample size
    recall  $T_m$ ;
    determine a random vector of  $i_t, t = 1, \dots, T_m$  from a Triangular
      distribution;
    initialize  $Y_{tj}$  to zero;
    for  $k = 1$  to number of Pecuniary elements
      determine a random vector of  $C_{tkj}, t = 1, \dots, T_m$  from a
        Triangular distribution;
       $Y_{tj} = Y_{tj} + C_{tkj}(1 - \tau_c) + D_t\tau_c$ ;
       $NPV_j = \sum_{t=0}^{T_m} \frac{Y_{tj}}{\prod_{k=0}^t (1 + i_k)}$ ;
    if ( $m = 1$ )
       $NPV_{jMAX} = NPV_j$ ;
       $NPV_{jMIN} = NPV_j$ ;
    if ( $NPV_j > NPV_{jMAX}$ )  $NPV_{jMAX} = NPV_j$ ;
    if ( $NPV_j < NPV_{jMIN}$ )  $NPV_{jMIN} = NPV_j$ ;
    write  $NPV_j$  to output file;
  close output file for  $NPV_j$ ;
for  $n = 2$  (Strategic) to 3 (Tactical objectives);
  open output file for  $NI_{jn}$ ;
  for  $m = 1$  to sample size
    recall  $T_m$ ;
    determine a random vector of  $h_t, t = 1, \dots, T_m$  from a
      Triangular distribution;
     $R_{NI} = \sum_{t=1}^{T_m} \frac{1}{\prod_{k=0}^t (1 + h_t)}$ ;
    for  $k = \text{all of elements in } n$ 
      determine a random vector of  $Q_{tkj}, t = 1, \dots, T_m$ 
        from a Triangular distribution;

```

$$NPQF_{kj} = \sum_{t=1}^{T_m} \frac{Q_{tkj}}{(1 + h_t)};$$

$$NI_{kj} = \frac{NPQF_{kj}}{R_{NI}};$$
 write $NPQF_{kj}$ and NI_{kj} to output file;
 if ($m = 1$)

$$NI_{kjMAX} = NI_{kj};$$

$$NI_{kjMIN} = NI_{kj};$$
 if ($NI_{kj} > NI_{kjMAX}$) $NI_{kjMAX} = NI_{kj};$
 if ($NI_{kj} < NI_{kjMIN}$) $NI_{kjMIN} = NI_{kj};$
 close output file for $NI_{jn};$
 determine the maximum NPV over all alternatives (NPV_{MAX});
 determine the minimum NPV over all alternatives (NPV_{MIN});
 $R_{MI} = \max(|NPV_{MAX}|, |NPV_{MIN}|);$
 for $j = 1$ to *number of alternatives*

$$\text{delta} = \left| \frac{NPV_{jMAX}}{R_{MI}} - \frac{NPV_{jMIN}}{R_{MI}} \right| \div \text{Bins};$$
 for $i = 1$ to *Bins*

$$\text{Distribution}_{MI}[i] = \frac{NPV_{jMIN}}{R_{MI}} + (i * \text{delta});$$

$$PEC_{MAX} = \beta_1 \left(\alpha_{11} \left| \frac{1 - \frac{NPV_{jMIN}}{R_{MI}}}{2} \right|^p \right)^{q/p};$$

$$PEC_{MIN} = \beta_1 \left(\alpha_{11} \left| \frac{1 - \frac{NPV_{jMAX}}{R_{MI}}}{2} \right|^p \right)^{q/p};$$

$$\text{delta} = |PEC_{MAX} - PEC_{MIN}| \div \text{Bins};$$
 for $i = 1$ to *Bins*

$$\text{Distribution}_{PEC}[i] = PEC_{MIN} + (i * \text{delta});$$
 open input file for NPV_j ;
 initialize *Count*[] array to zero;
 initialize *Count2*[] array to zero;
 for $m = 1$ to *sample size*
 read NPV from NPV_j file;

$$MI = \frac{NPV}{R_{MI}};$$


```

for  $i = 1$  to  $Bins$ ;
    if ( $MI \leq Distribution_{MI}[i]$ )
         $Count[i] = Count[i] + 1$ ;
        break;
 $PEC = \beta_1 \left( \alpha_{11} \left| \frac{1-MI}{2} \right|^p \right)^{q/p}$ ;
for  $i = 1$  to  $Bins$ ;
    if ( $PEC \leq Distribution_{PEC}[i]$ )
         $Count2[i] = Count2[i] + 1$ ;
        break;
close input file for  $NPV_j$ ;
divide all bin counts ( $COUNT[]$ ,  $COUNT2[]$ ) by sample size to
    determine the cell probabilities  $p_i$ ;
adjust bin limits of  $Distribution_{mi}$  to the center of the bin;
 $mean = \sum_{i=1}^{Bins} p_i * Distribution_{MI}[i]$ ;
 $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{MI}[i]^2) - mean^2$ ;
open output file for  $MI_j$ ;
for  $i = 1$  to  $Bins$ 
    write  $Distribution_{MI}[i]$  and cell probabilities  $p_i$  to file;
write  $mean$  and  $variance$  to file;
close output file for  $MI_j$ ;
adjust bin limits of  $Distribution_{PEC}$  to the center of the bin;
 $mean = \sum_{i=1}^{Bins} p_i * Distribution_{PEC}[i]$ ;
 $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{PEC}[i]^2) - mean^2$ ;
open output file for  $PEC_j$ ;
for  $i = 1$  to  $Bins$ 
    write  $Distribution_{PEC}[i]$  and cell probabilities  $p_i$  to file;
    write  $mean$  and  $variance$  to file;
close output file for  $PEC_j$ ;
for  $n = 2$  (Strategic) to 3 (Tactical objectives);
    open  $NI_{jn}$  file;
    for  $k = all\ of\ the\ elements\ in\ n$ 

```

```

     $\delta = |NI_{kj\_MAX} - NI_{kj\_MIN}| \div Bins;$ 
    for  $i = 1$  to  $Bins$ 
         $Distribution_{NI_{kj}}[i] = NI_{kj\_MIN} + (i * \delta);$ 
    initialize  $Count_{kj}[]$  array to zero;
    for  $m = 1$  to  $sample\ size$ 
        read  $NI_{kj}$  from  $NI_{jn}$  file;
        for  $i = 1$  to  $Bins$ ;
            if ( $NI_{kj} \leq Distribution_{NI_{kj}}[i]$ )
                 $Count_{kj}[i] = Count_{kj}[i] + 1;$ 
            break;
    close  $NI_{jn}$  file;
    divide all bin counts ( $COUNT_{kj}[]$ ) by sample size to determine
        the cell probabilities  $p_i, i = 1, \dots, Bins$ ;
    adjust bin limits of  $Distribution_{NI_{kj}}$  to the center of the bin;
     $mean = \sum_{i=1}^{Bins} p_i * Distribution_{NI_{kj}}[i];$ 
     $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{NI_{kj}}[i]^2) - mean^2;$ 
    determine lower limit of objective  $n$  ( $Obj_{jn\_MIN}$ );
    determine upper limit of objective  $n$  ( $Obj_{jn\_MAX}$ );
     $\delta = |Obj_{jn\_MAX} - Obj_{jn\_MIN}| \div Bins;$ 
    initialize  $Count_n[]$  array to zero;
    for  $i = 1$  to  $Bins$ 
         $Distribution_{Obj_{jn}}[i] = Obj_{jn\_MIN} + (i * \delta);$ 
    for all combinations of  $NI_{jn}$  over the number of elements;
         $Obj_{jn} = \beta_n \left( \sum_{k \in S_2} \alpha_{2k} \left| \frac{1 - Distribution_{NI_{kj}}}{2} \right|^p \right)^{q/p};$ 
        compute the joint probability  $p_i$  for the above  $Obj_{jn}$ ;
        for  $i = 1$  to  $Bins$ ;
            if ( $Obj_{jn} \leq Distribution_{Obj_{jn}}[i]$ )
                 $Count_n[i] = Count_n[i] + 1;$ 
            accumulate the joint probabilities in bin  $i$ ;
            break;

```

```

open output file for  $NI_{kj}$  distribution;
open output file for  $Obj_{jn}$ ;
write  $Distribution_{NI_{kj}}$  to output file;
write  $Distribution_{Obj_{jn}}$  to output file;
close output file for  $NI_{kj}$  distribution;
close output file for  $Obj_{jn}$ ;
open input file for Pecuniary distribution ( $PEC_j$ );
open input file for Strategic distribution ( $Obj_{j2}$ );
open input file for Tactical distribution ( $Obj_{j3}$ );
read Pecuniary distribution ( $P_f$ );
read Strategic distribution ( $S_g$ );
read Tactical distribution ( $T_h$ );
determine lower limit of final score  $\rho_{jMIN}$ ;
determine upper limit of final score  $\rho_{jMAX}$ ;
 $\delta = |\rho_{jMAX} - \rho_{jMIN}| \div Bins$ ;
for  $i = 1$  to  $Bins$ 
     $Distribution_{\rho_j}[i] = \rho_{jMIN} + (i * \delta)$ ;
initialize  $p_i$ ,  $i = 1, \dots, Bins$  to zero;
for  $f = 1$  to  $Bins$ 
    for  $g = 1$  to  $Bins$ 
        for  $h = 1$  to  $Bins$ 
             $\rho = (P_f + S_g + T_h)^{1/q}$ ;
            compute joint probability for  $\rho_j$   $p = (p_{P_f} * p_{S_g} * p_{T_h})$ ;
            for  $i = 1$  to  $Bins$ 
                if ( $\rho_j < Distribution_{\rho_j}[i]$ )
                     $p_i = p_i + p$ ;
 $mean = \sum_{i=1}^{Bins} (p_i * Distribution_{\rho_j}[i])$ ;
 $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{\rho_j}[i]^2) - mean^2$ ;
write results to output file;

```

This yields a mean and variance for the evaluation scores, which indicates a stability of the rankings to the decision maker. This, in association with the

mean and variance of the objectives and the Monetary Index and Nonmonetary Indices, provide the decision maker with the information necessary to evaluate the alternatives.

All in all, even using the simplifying assumption of independence, the mean, variance, and distributional forms of the objective values are difficult to determine analytically. The final Composite Programming scores cannot be easily determined analytically, and thus are enumerated. Additionally, due to the independence assumption, the results may not be accurate or realistic as cash flows and qualitative flows tend to be dependent with respect to time.

4.4 Example of Risk Determination Under Independence

Suppose that the cash flows and qualitative flows from the numerical example presented in Chapter 3 are actually the most likely values. The problem is then augmented to include pessimistic and optimistic values in order to determine results of risk under independence. The deviations from the most likely values for the pessimistic and optimistic values are summarized in Table 4.1. Additionally, the project length and interest rates have pessimistic, most likely, and optimistic values. These are provided, along with the remaining detailed input data used in this analysis, in Appendix H.

The algorithm presented in the previous section has been developed into a computer program entitled "AMSTEP-R: Advanced Manufacturing System Technologies Evaluation Program - Risk." A listing of this program, written in "C", is provided in Appendix I. Input to the program is provided via files created using "LOTUS 1-2-3", and contain the necessary cash flow and qualitative flow data,

Table 4.1: Deviations from Most Likely Values for Independent Risk

ATTRIBUTE	MAN (%)	SEM (%)	AUT (%)
Investment	NA	± 20	± 20
Salvage Value	NA	± 15	± 15
Labor	± 5	± 10	± 10
Maintenance	± 5	± 15	± 15
Training	± 50	± 50	± 50
Documentation	± 10	± 20	± 20
Space	± 7	± 7	± 7
Rework	± 15	± 15	± 15
Transportation	± 7	NA	NA
Programming	NA	± 50	± 50
Cash Inflow	± 20	± 20	± 20
Internal Relations	± 5	± 5	± 5
Market Position	± 20	± 20	± 20
Mission	± 10	± 10	± 10
Organization	± 5	± 5	± 5
Public Relations	± 7	± 7	± 7
Technology	± 10	± 10	± 10
Design	± 5	± 5	± 5
Flexibility	± 15	± 15	± 15
Integration	± 12	± 12	± 12
Material	± 6	± 6	± 6
Personnel	± 8	± 8	± 8
Producibility	± 11	± 11	± 11
MAN - Manual.	SEM - Semi-Automatic.		
AUT - Automatic.	NA - Not Applicable.		

along with control data such as weights, project length, interest rates, sample size, and number of bins.

The decision maker will specify pessimistic, most likely, and optimistic values for the project length ($\tilde{T}$). Next, for each of the three project lengths, a pessimistic, most-likely, and optimistic value for $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$ will be provided. This allows the cash flows, qualitative flows, and interest rates to include data for appropriate years in the project. For example, when the project length is eight years, there are no values defined for years greater than eight. The input data will be represented by a minimum of one point, or a maximum of five points. In this manner the decision maker may specify a constant value, or a declining, rising, and declining curve representing typical trends which occur over the life of a project. The format of the structure of the input for a particular element is given in Table 4.2. The pessimistic project project length is shortest, followed by the most-likely project length and the optimistic project length. To further clarify this scheme, refer to Figure 4.2. The figure shows a curve which represents the cash flow for a particular element over the life of the project. The project length may be between T_1 and T_3 , and if the project length happens to be T_2 , the cash flows beyond T_2 will not occur. Additionally, the form for this input facilitates the dependent case, which will be presented later.

The output from the program are a set of ASCII data files which provide the following data for each alternative being investigated:

1. The NPV for all computed cases.
2. The $NPQF_k$ and NI_k for all computed cases of the Strategic and Tactical objectives.
3. A frequency histogram of the $\tilde{MI}$, with mean and variance.

Table 4.2: Input Format for Cash Flows, Qualitative Flows, and Interest Rates

	YEAR BREAK 1	YEAR BREAK 2	YEAR BREAK 3	YEAR BREAK 4	YEAR BREAK 5
Pessimistic	PM value	PM value	PM value		
Project	ML value	ML value	ML value		
Length	OP value	OP value	OP value		
Most-Likely	PM value	PM value	PM value	PM value	
Project	ML value	ML value	ML value	ML value	
Length	OP value	OP value	OP value	OP value	
Optimistic	PM value	PM value	PM value	PM value	PM value
Project	ML value	ML value	ML value	ML value	ML value
Length	OP value	OP value	OP value	OP value	OP value

PM - Pessimistic ML - Most Likely OP - Optimistic

Figure 4.2: Cash Flows as Pessimistic, Most Likely, and Optimistic for Varying Project Lengths

4. A frequency histogram of each $\tilde{N}I_k$, with mean and variance.
5. A frequency histogram of each objective: Pecuniary, Strategic, and Tactical, with mean and variance.
6. The Composite Programming score for all computed cases.
7. A frequency histogram of the Composite Programming score, with mean and variance.

One thousand samples of the $\tilde{M}I$ and $\tilde{N}I_k$ were determined. Ten bins were used to determine the distributions. An analysis of using a larger sample size is presented later in this section.

The results for the mean and variance of the Composite Programming scores $\tilde{\rho}$ are shown in Table 4.3. The values of the objectives are provided in Table 4.4. The mean and variance of the values in the attribute versus alternative matrix are shown in Table 4.5. A frequency plot of the distributions of $\tilde{\rho}$ for each alternative are provided in Figures 4.3 through 4.5. Frequency plots of the objectives for each alternative are provided in Appendix J.

In order to determine if a larger sample size would provide different results, the example was analyzed using a sample size of 2,000. Since the final score $\tilde{\rho}$ is determined from the distribution of the Pecuniary, Strategic, and Tactical objectives using the joint probabilities, the analysis will be performed using the results from the attribute versus alternative matrix. These are presented in Table 4.6. The following tests were performed to determine if the means of the attribute versus alternative matrix of the two sizes of n are different:

Table 4.3: Mean and Variance for Final Scores $\tilde{\rho}$

ALTERNATIVE	MEAN	VARIANCE
Manual	54.73	1.68
Semi-Automatic	33.55	0.81
Automatic	28.98	0.99

Table 4.4: Mean and Variance for the Objectives

ALTERNATIVE	PECUNIARY		STRATEGIC		TACTICAL	
	MEAN	VAR	MEAN	VAR	MEAN	VAR
Manual	20.20	176.77	1,653.73	1,400.49	1,322.93	805.78
Semi-Automatic	93.79	775.98	464.13	334.73	569.46	243.26
Automatic	178.95	1,577.74	275.31	174.60	386.12	221.03

Table 4.5: Mean and Variance for Attribute vs. Alternative Matrix

INDEX	MANUAL		SEMI-AUTO.		AUTOMATIC	
	Mean	Var	Mean	Var	Mean	Var
MI	0.8572	0.0024	0.6806	0.0023	0.5564	0.0025
NI_1	-0.2680	0.0002	0.1516	0.0008	0.1290	0.0007
NI_2	-0.2158	0.0017	0.1496	0.0012	0.3774	0.0013
NI_3	-0.3450	0.0008	0.3584	0.0003	0.6612	0.0003
NI_4	-0.4998	0.0000	0.1287	0.0003	0.2860	0.0014
NI_5	-0.2668	0.0010	0.4196	0.0001	0.6243	0.0002
NI_6	-0.8992	0.0002	0.3004	0.0003	0.6109	0.0003
NI_7	-0.0004	0.0000	-0.0004	0.0000	0.1996	0.0000
NI_8	-0.5985	0.0005	0.0818	0.0007	0.3381	0.0013
NI_9	-0.4026	0.0007	0.1194	0.0005	0.2874	0.0011
NI_{10}	-0.1503	0.0004	0.2445	0.0005	0.3358	0.0006
NI_{11}	0.0931	0.0007	0.4096	0.0001	0.2747	0.0007
NI_{12}	-0.3896	0.0004	0.1603	0.0007	0.3909	0.0010

Figure 4.3: Frequency Distribution of $\tilde{\rho}$ - Manual Alternative

Figure 4.4: Frequency Distribution of $\tilde{\rho}$ - Semi-Automatic Alternative

Figure 4.5: Frequency Distribution of $\tilde{\rho}$ - Automatic Alternative

$$H_0 : \overline{MI}_{(n=1000)} = \overline{MI}_{(n=2000)}$$

$$H_1 : \overline{MI}_{(n=1000)} \neq \overline{MI}_{(n=2000)}$$

and

$$H_0 : \overline{NI}_{k(n=1000)} = \overline{NI}_{k(n=2000)}$$

$$H_1 : \overline{NI}_{k(n=1000)} \neq \overline{NI}_{k(n=2000)}$$

Since the distributions of the $\tilde{MI}$ and $\tilde{NI}_k$ are not known, the Mann-Whitney-Wilcoxon Rank Sum Test is used. The test statistic is determined using the assumption that the sum of the rank numbers is normally distributed. The procedure used is that presented in Pearson and Hartley [102]. Two experimental groups of size l and m ($l \leq m$, $l + m = N$) are combined and ranked in ascending order of magnitude. Each item is assigned a number in order from $1, 2, \dots, N$, where ties are assigned an average of the rank numbers associated with the tied values. Let W be the sum of the rank numbers in the smaller group of size l . When l and/or m are greater than 25, an adequate approximation is obtained by taking W as normally distributed with:

$$\begin{aligned} E[W] &= \frac{1}{2}l(N+1) \\ V[W] &= \frac{1}{12}lm(N+1) \end{aligned}$$

Using a correction for continuity, we have:

$$\Phi^{-1}(z) = \frac{W + 0.5 - E[W]}{\sqrt{V[W]}}$$

where $\Phi(z)$ is the standard normal distribution. The rank sums (W) for the final scores are shown in Table 4.7, along with the corresponding values for $\Phi^{-1}(z)$.

Table 4.6: Mean and Variance for Attribute vs. Alternative Matrix, $n = 2000$

INDEX	MANUAL		SEMI-AUTO.		AUTOMATIC	
	Mean	Var	Mean	Var	Mean	Var
MI	0.8555	0.0025	0.6792	0.0024	0.5559	0.0025
NI_1	-0.2769	0.0002	0.1524	0.0008	0.1298	0.0008
NI_2	-0.2160	0.0018	0.1495	0.0012	0.3773	0.0013
NI_3	-0.3445	0.0009	0.3587	0.0003	0.6615	0.0004
NI_4	-0.5000	0.0000	0.1297	0.0003	0.2860	0.0015
NI_5	-0.2675	0.0010	0.4198	0.0001	0.6245	0.0002
NI_6	-0.8995	0.0002	0.3007	0.0003	0.6107	0.0003
NI_7	-0.0002	0.0000	-0.0002	0.0000	0.1998	0.0000
NI_8	-0.5991	0.0004	0.0819	0.0007	0.3381	0.0014
NI_9	-0.4029	0.0007	0.1199	0.0005	0.2880	0.0011
NI_{10}	-0.1509	0.0005	0.2449	0.0006	0.3359	0.0006
NI_{11}	0.0926	0.0008	0.4067	0.0001	0.2751	0.0007
NI_{12}	-0.3902	0.0004	0.1602	0.0008	0.3913	0.0010

The value of $E[W]$ is 1,500,500.0 and $V[W] = 500,166,666.7$. At a 0.05 level of significance ($-1.96 \leq z \leq +1.96$), the null hypotheses are accepted that the means are the same. Therefore, there is no benefit for using a larger size of n .

A review of the results of the independent case shows that the score for the automatic alternative is lowest. The manual alternative has the highest score, and also the highest variance. It is clear that the semi-automatic and automatic alternatives are preferred to the manual alternative, but is there a difference between the semi-automatic and automatic alternatives? From an observation of the data it seems that there is a difference. In order to verify that the means are different, a statistical test is performed. The test is as follows:

$$H_0 : \bar{\rho}_{semi-automatic} = \bar{\rho}_{automatic}$$

$$H_1 : \bar{\rho}_{semi-automatic} \neq \bar{\rho}_{automatic}$$

Table 4.7: Rank Sums for the Attribute vs. Alternative Matrix

INDEX	Rank Sum (W)			Standard Normal (z)		
	MAN	SEMI	AUTO	MAN	SEMI	AUTO
MI	1,485,260.0	1,481,910.0	1,480,671.0	-0.6814	-0.8312	-0.8866
NI_1	1,500,492.5	1,478,613.5	1,478,524.0	-0.0003	-0.9786	-0.9826
NI_2	1,518,772.0	1,508,945.0	1,508,415.0	0.8170	0.3776	0.3539
NI_3	1,514,167.0	1,486,533.5	1,488,084.0	0.6111	-0.6244	-0.5551
NI_4	1,515,664.0	1,494,394.0	1,492,772.5	0.6780	-0.2730	-0.3455
NI_5	1,515,606.0	1,494,529.0	1,491,103.0	0.6754	-0.2669	-0.4201
NI_6	1,513,083.5	1,495,060.5	1,503,144.0	0.5626	-0.2432	0.1182
NI_7	1,472,065.5	1,472,065.5	1,472,091.5	-1.2714	-1.2714	-1.2702
NI_8	1,517,899.5	1,502,945.5	1,500,742.0	0.7780	0.1093	0.0108
NI_9	1,513,387.0	1,487,217.5	1,486,744.0	0.5762	-0.5938	-0.6150
NI_{10}	1,518,823.0	1,493,430.0	1,493,221.0	0.8193	-0.3161	-0.3254
NI_{11}	1,515,098.0	1,502,157.5	1,489,610.5	0.6527	0.0741	-0.4868
NI_{12}	1,520,621.0	1,496,239.0	1,495,546.5	0.8997	-0.1905	-0.2214

Using the Mann-Whitney-Wilcoxon Rank Sum test, $E[W] = 1,000,500.0$ and $V[W] = 166,750,000.0$. At a 0.05 level of significance ($-1.96 \leq z \leq +1.96$), the null hypothesis is rejected. The rank sum of the semi-automatic alternative is 1,496,715.5 and for the automatic alternative the rank sum is 504,284.5. $\Phi^{-1}(z) = \pm 38.43$ and clearly it is concluded that the average score ($\bar{p}$) of the semi-automatic and automatic alternatives are different.

The mean of the $\tilde{MI}$ for each alternative supports earlier comments that on a financial basis only, the manual alternative is preferred. The variances of the $\tilde{MI}$ between the alternatives is similar. The $\tilde{NI}_k$ show some trends between the attributes which may suggest that certain attributes be given more attention in the analysis. The highest variances for all alternatives occurs for $\tilde{NI}_2$ (Market Position). Therefore, particular attention should be paid to this attributes in any further analysis. Additionally, $\tilde{NI}_3$ and $\tilde{NI}_5$ (Mission, Public Relations) show high

variability for the manual alternative, $\tilde{N}I_1$, $\tilde{N}I_8$, and $\tilde{N}I_{12}$ (Internal Relations, Flexibility, Producibility) show high variability for the semi-automatic alternative, and $\tilde{N}I_4$, $\tilde{N}I_8$, $\tilde{N}I_9$, and $\tilde{N}I_{12}$ (Organization, Flexibility, Integration, Producibility) show high variability for the automatic alternative. This also indicates that these areas within each alternative may require further analysis or should be studied carefully before any final decisions are made.

4.5 Risk Under Dependence

An example of handling a situation of dependent cash flows was presented in Section 2.8. However, the example assumed that the interest rate and duration of the project were deterministic. This model considers the interest rate and duration of project to be random variables. Hillier [56] nicely summarized handling dependence with the following, "... the dependent case is very much more difficult than the independent case, so that it will not be possible to state a single result which completely solves this problem." The problem Hillier [56] refers to is the determination of the distribution of NPV for a project with dependent cash flows, deterministic (and constant) interest rate, and deterministic project duration.

Since a single result for the distribution of the Monetary and Nonmonetary Indices, along with the rankings, cannot be stated to completely solve the AMST evaluation problem, another approach must be chosen. The approach taken in this research is to determine the distributions for the rankings and the objectives through an enumeration of samples from the distributions of the cash flows, qualitative flows, interest rates, and project duration. The calculations for this enumeration will be carried out on a personal computer. Time dependence will be allowed between cash flows and qualitative flows of a single attribute. However,

independence between the attributes is still assumed.

The steps delineating this enumeration are similar to those presented in the previous section, except that cash flows, qualitative flows, and interest rates will be dependent along time. The dependence will be modeled using a multivariate normal distribution, where the number of variants is dependent upon the length of the project.

As in the independent case, the decision maker will specify a pessimistic, most likely, and optimistic length for the project life ($\tilde{T}$). Next, for each of the three project lengths, a pessimistic, most-likely, and optimistic value for $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$ will be provided. This allows the cash flows, qualitative flows, and interest rates to vary according to the length of the project. The data will be represented by a minimum of one point, or a maximum of five points, as previously shown in Table 4.2. In this manner the decision maker may specify a constant value, or a declining, rising, and declining curve representing typical trends which occur over the life of a project.

To clarify this scheme for the dependent case, refer to Figure 4.6. The figure shows three curves which represent varying cash flows for three different project lengths in a typical product life cycle [111]. Each curve is a most likely estimate, and as such each curve has associated with it a curve representing the pessimistic and optimistic estimates. An example of this representation is provided in Figure 4.7.

The pessimistic, most likely, and optimistic values provided by the decision maker reflect a triangular distribution. As discussed in Section 4.3, the triangular distribution is commonly used to estimate data [78], [4]. The pessimistic and optimistic values provide worst and best case bounds on the estimation, and the most

Figure 4.6: Potential Cash Flows for Varying Project Lives

Figure 4.7: Potential Cash Flows estimated as Pessimistic, Most Likely, and Optimistic

likely value is the decision maker's estimate, based on research and knowledge, of the most likely value which may occur. The decision maker may specify the pessimistic and optimistic values in equal distances from the most-likely value, thus yielding a symmetrical triangular shape. This symmetrical shape will be assumed to be normal such that dependence can be modeled using a multivariate normal distribution. The number of variates will be dependent on the length of the project.

In making the assumption that the symmetrical triangular distribution will estimate a normal distribution, it is important to note the effect of the tail probability introduced from this assumption. The mean and variance of the triangular distribution are:

$$\begin{aligned}\mu_{tri} &= \frac{a + b + c}{3} \\ \sigma_{tri}^2 &= \frac{a^2 + b^2 + c^2 - ab - ac - bc}{18}\end{aligned}$$

where a is the pessimistic estimate, b the optimistic estimate, and c the most likely estimate. Since the triangular distribution will be symmetrical, the length of the interval $[a, c]$ will equal the length of the interval $[c, b]$. Therefore, $c - a = b - c$ and the mean and variance are simplified to:

$$\mu_{tri} = \frac{a + b}{2} \tag{4.1}$$

$$\sigma_{tri}^2 = \frac{(a - b)^2}{24} \tag{4.2}$$

Since a and b are the tails of the triangular distribution, the triangular distribution can be related to the normal distribution using the standard normal distribution. Refer to Figure 4.8. At the left tail:

$$\frac{a - \mu_{norm}}{\sigma_{norm}} = -\Phi^{-1}(z)$$

Figure 4.8: Tail Probabilities of the Triangular Approximation to the Normal and at the right tail:

$$\frac{b - \mu_{norm}}{\sigma_{norm}} = \Phi^{-1}(z)$$

Solving for a and b , and replacing the results into Equations 4.1 and 4.2 yields:

$$\begin{aligned} \mu_{tri} &= \mu_{norm} \\ \sigma_{tri}^2 &= \frac{[\Phi^{-1}(z)]^2 \sigma_{norm}^2}{6} \end{aligned}$$

Therefore, in order for the variances to be equal, $[\Phi^{-1}(z)]^2 = 6$ and $z = \pm 2.45$. Analyzing the left end of the triangular distribution, the straight line forming the left bound has an equation of:

$$f(x) = 0.16666x + 0.40816$$

This line intersects the normal curve at three points: $z = -2.27, -1.01$, and -0.06 . Of interest here is the area in the tails of the distributions. The decision maker

has provided pessimistic and optimistic limits which are the tails of the triangular distribution. By using the assumption of a normal distribution, values beyond the pessimistic and optimistic limits may occur. The probability that a value will exceed the pessimistic limit is given by:

$$\int_{-\infty}^{-2.45} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2} dx$$

which is 0.0071. Thus using the normal distribution, 1.42% of the time values will arise which exceed the pessimistic and optimistic limits. Since the limits are estimates provided by the decision maker, it is feasible that these limits may be exceeded. This is exceedance deemed acceptable for the evaluation being performed.

Using these mean and variance estimates for the normal distribution, a covariance matrix ($\hat{V}$) and mean vector ($\hat{x}$) is constructed which is used to generate samples from a multivariate normal. The $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$ are assumed to follow a linear first-order Markovian model of the form: [16]

$$\tilde{C}_{tk} = \theta \tilde{C}_{(t-1)k} + \delta + \epsilon_t$$

where:

- θ - the one-period lag coefficient, $|\theta| \leq 1$.
- δ - trend constant.
- ϵ_t - random variable with mean zero and variance σ_ϵ^2 .

Therefore, with the assumption of a Markovian process, the autocorrelation coefficients are computed as: [16]

$$\rho_{t_1 t_2} = \theta^{|t_2 - t_1|}$$

Using this autocorrelation coefficient, the covariance matrix ($\hat{V}$) is determined as shown in Table 4.8. When the decision maker specifies $\theta = 1$, the model exhibits

Table 4.8: Determination of the Covariance Matrix

t_1	$t_2 =$	1	2	3	...	T
1		$\sigma_{C_{1k}}^2$	$\theta\sigma_{C_{1k}}\sigma_{C_{2k}}$	$\theta^2\sigma_{C_{1k}}\sigma_{C_{3k}}$	...	$\theta^{T-1}\sigma_{C_{1k}}\sigma_{C_{Tk}}$
2		$\theta\sigma_{C_{2k}}\sigma_{C_{1k}}$	$\sigma_{C_{2k}}^2$	$\theta\sigma_{C_{2k}}\sigma_{C_{3k}}$	...	$\theta^{T-1}\sigma_{C_{2k}}\sigma_{C_{Tk}}$
3		$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
$\vdots$		$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
T		$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\sigma_{C_{Tk}}^2$

perfect correlation. Mathematically $-1 \leq \theta \leq 1$, however a positive correlation for the flows is assumed with $0 < \theta < 1$.

Based upon the mean vector ($\hat{\mathbf{x}}$) and covariance matrix ($\hat{\mathbf{V}}$), random samples for cash flows, qualitative flows, and interest rates are generated based upon the multivariate dependent normal distribution. The dependence of these cash flows, qualitative flows, and interest rates is with respect to time. As such, the number of variates is determined by the length of the project. An algorithm for generating these samples is presented in Bratley et al. [11]. Given $\bar{\mathbf{x}}$ and $\mathbf{V}$, a lower triangular matrix $\mathbf{C}$ is determined such that $\mathbf{V} = \mathbf{C}\mathbf{C}'$. The matrix $\mathbf{C}$ is determined using Cholesky factorization. Next, a vector $\mathbf{z}$ of T independent standard normal variates is determined, and $\mathbf{x}$ is calculated using:

$$\mathbf{x} = \bar{\mathbf{x}} + \mathbf{C}\mathbf{z} \quad (4.3)$$

The procedure used in the enumeration of the dependent case parallels that of the independent case. The exception is in the determination of $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$. Since the means of the triangular distribution are known, the mean vector $\bar{\mathbf{x}}$ for each $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$ is determined by calculating the means of each

associated triangular distribution. The covariance matrix ($\hat{V}$) is determined by computing the variances of the triangular distributions, and constructing the matrix as previously described. Using the mean vector and covariance matrix, a vector of dependent values is generated using Equation 4.3. This is done for all $\tilde{C}_{tk}$, $\tilde{Q}_{tk}$, $\tilde{i}_t$, and $\tilde{h}_t$. Using these values, the $\tilde{M}I$, $\tilde{N}I_k$, and $\tilde{p}$ are computed.

The following algorithm is employed for the dependent analysis:

```

get analysis parameters;
normalize weights;
for  $m = 1$  to sample size
    determine random sample of project length ( $T_m$ ) from a
        Triangular distribution;
    save  $T_m$  for later use;
for  $j = 1$  to number of alternatives
    read input data for alternative  $j$ ;
    open output file for  $NPV_j$ ;
    determine a random dependent vector of  $i_t$ ,  $t = 1, \dots, T_m$  from a
        multivariate Normal distribution;
    initialize  $Y_{tj}$  to zero;
    for  $k = 1$  to number of Pecuniary elements
        determine a random dependent vector of  $C_{tkj}$ ,  $t = 1, \dots, T_m$ 
            from a multivariate Normal distribution;
         $Y_{tj} = Y_{tj} + C_{tkj}(1 - \tau_c) + D_t\tau_c$ ;
     $NPV_j = \sum_{t=0}^{T_m} \frac{Y_{tj}}{\prod_{k=0}^t (1 + i_k)}$ ;
    if ( $m = 1$ )
         $NPV_{jMAX} = NPV_j$ ;
         $NPV_{jMIN} = NPV_j$ ;
    if ( $NPV_j > NPV_{jMAX}$ )  $NPV_{jMAX} = NPV_j$ ;
    if ( $NPV_j < NPV_{jMIN}$ )  $NPV_{jMIN} = NPV_j$ ;
    write  $NPV_j$  to output file;
close output file for  $NPV_j$ ;
for  $n = 2$  (Strategic) to 3 (Tactical objectives);

```

open output file for NI_{jn} ;
 for $m = 1$ to *sample size*
 recall T_m ;
 determine a dependent random vector of $h_t, t = 1, \dots, T_m$
 from a multivariate Normal distribution;
 $R_{NI} = \sum_{t=1}^{T_m} \frac{1}{\prod_{k=0}^t (1 + h_t)}$;
 for $k = \text{all of elements in } n$
 determine a dependent random vector of $Q_{tkj}, t = 1, \dots, T_m$
 from a multivariate Normal distribution;
 $NPQF_{kj} = \sum_{t=1}^{T_m} \frac{Q_{tkj}}{(1 + h_t)}$;
 $NI_{kj} = \frac{NPQF_{kj}}{R_{NI}}$;
 write $NPQF_{kj}$ and NI_{kj} to output file;
 if ($m = 1$)
 $NI_{kjMAX} = NI_{kj}$;
 $NI_{kjMIN} = NI_{kj}$;
 if ($NI_{kj} > NI_{kjMAX}$) $NI_{kjMAX} = NI_{kj}$;
 if ($NI_{kj} < NI_{kjMIN}$) $NI_{kjMIN} = NI_{kj}$;
 close output file for NI_{jn} ;
 determine the maximum NPV over all alternatives (NPV_{MAX});
 determine the minimum NPV over all alternatives (NPV_{MIN});
 $R_{MI} = \max(|NPV_{MAX}|, |NPV_{MIN}|)$;
 for $j = 1$ to *number of alternatives*
 $delta = \left| \frac{NPV_{jMAX}}{R_{MI}} - \frac{NPV_{jMIN}}{R_{MI}} \right| \div Bins$;
 for $i = 1$ to *Bins*
 $Distribution_{MI}[i] = \frac{NPV_{jMIN}}{R_{MI}} + (i * delta)$;
 $PEC_{MAX} = \beta_1 \left(\alpha_{11} \left| \frac{1 - \frac{NPV_{jMIN}}{R_{MI}}}{2} \right|^p \right)^{q/p}$;
 $PEC_{MIN} = \beta_1 \left(\alpha_{11} \left| \frac{1 - \frac{NPV_{jMAX}}{R_{MI}}}{2} \right|^p \right)^{q/p}$;
 $delta = |PEC_{MAX} - PEC_{MIN}| \div Bins$;
 for $i = 1$ to *Bins*
 $Distribution_{PEC}[i] = PEC_{MIN} + (i * delta)$;

```

open input file for  $NPV_j$ ;
initialize  $Count[]$  array to zero;
initialize  $Count2[]$  array to zero;
for  $m = 1$  to sample size
    read  $NPV$  from  $NPV_j$  file;
     $MI = \frac{NPV}{R_{MI}}$ ;
    for  $i = 1$  to  $Bins$ ;
        if ( $MI \leq Distribution_{MI}[i]$ )
             $Count[i] = Count[i] + 1$ ;
            break;
     $PEC = \beta_1 \left( \alpha_{11} \left| \frac{1-MI}{2} \right|^p \right)^{q/p}$ ;
    for  $i = 1$  to  $Bins$ ;
        if ( $PEC \leq Distribution_{PEC}[i]$ )
             $Count2[i] = Count2[i] + 1$ ;
            break;
close input file for  $NPV_j$ ;
divide all bin counts ( $COUNT[], COUNT2[]$ ) by sample size to
    determine the cell probabilities  $p_i$ ;
adjust bin limits of  $Distribution_{MI}$  to the center of the bin;
 $mean = \sum_{i=1}^{Bins} p_i * Distribution_{MI}[i]$ ;
 $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{MI}[i]^2) - mean^2$ ;
open output file for  $MI_j$ ;
for  $i = 1$  to  $Bins$ 
    write  $Distribution_{MI}[i]$  and cell probabilities  $p_i$  to file;
write  $mean$  and  $variance$  to file;
close output file for  $MI_j$ ;
adjust bin limits of  $Distribution_{PEC}$  to the center of the bin;
 $mean = \sum_{i=1}^{Bins} p_i * Distribution_{PEC}[i]$ ;
 $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{PEC}[i]^2) - mean^2$ ;

```



```

open output file for  $PEC_j$ ;
for  $i = 1$  to  $Bins$ 
    write  $Distribution_{PEC}[i]$  and cell probabilities  $p_i$  to file;
write mean and variance to output file;
close output file for  $PEC_j$ ;
for  $n = 2$  (Strategic) to 3 (Tactical objectives);
    open  $NI_{jn}$  file;
    for  $k = \text{all of elements in } n$ 
         $\delta = |NI_{kj_{MAX}} - NI_{kj_{MIN}}| \div Bins$ ;
        for  $i = 1$  to  $Bins$ 
             $Distribution_{NI_{kj}}[i] = NI_{kj_{MIN}} + (i * \delta)$ ;
        initialize  $Count_{kj}[]$  array to zero;
        for  $m = 1$  to sample size
            read  $NI_{kj}$  from  $NI_{jn}$  file;
            for  $i = 1$  to  $Bins$ ;
                if ( $NI_{kj} \leq Distribution_{NI_{kj}}[i]$ )
                     $Count_{kj}[i] = Count_{kj}[i] + 1$ ;
                break;
        close  $NI_{jn}$  file;
    divide all bin counts ( $COUNT_{kj}[]$ ) by sample size to determine
        the cell probabilities  $p_i$ ,  $i = 1, \dots, Bins$ ;
    adjust bin limits of  $Distribution_{NI_{kj}}$  to the center of the bin;
     $mean = \sum_{i=1}^{Bins} p_i * Distribution_{NI_{kj}}[i]$ ;
     $variance = \sum_{i=1}^{Bins} (p_i * Distribution_{NI_{kj}}[i]^2) - mean^2$ ;
    determine lower limit of objective  $n$  ( $Obj_{jn_{MIN}}$ );
    determine upper limit of objective  $n$  ( $Obj_{jn_{MAX}}$ );
     $\delta = |Obj_{jn_{MAX}} - Obj_{jn_{MIN}}| \div Bins$ ;
    initialize  $Count_n[]$  array to zero;
    for  $i = 1$  to  $Bins$ 
         $Distribution_{Obj_{jn}}[i] = Obj_{jn_{MIN}} + (i * \delta)$ ;
    for all combinations of  $NI_{jn}$  over the number of elements;

```

$$Obj_{jn} = \beta_n \left(\sum_{k \in S_2} \alpha_{2k} \left| \frac{1 - Distribution_{NI_{kj}}}{2} \right|^p \right)^{q/p};$$
 compute the joint probability p_i for the above Obj_{jn} ;

```

    for  $i = 1$  to  $Bins$ ;
      if ( $Obj_{jn} \leq Distribution_{Obj_{jn}}[i]$ )
         $Count_n[i] = Count_n[i] + 1$ ;
        accumulate the joint probabilities for bin  $i$ ;
        break;
    open output file for  $NI_{kj}$  distribution;
    open output file for  $Obj_{jn}$ ;
    write  $Distribution_{NI_{kj}}$  to output file;
    write  $Distribution_{Obj_{jn}}$  to output file;
    close output file for  $NI_{kj}$  distribution;
    close output file for  $Obj_{jn}$ ;
  open input file for Pecuniary distribution ( $PEC_j$ );
  open input file for Strategic distribution ( $Obj_{j2}$ );
  open input file for Tactical distribution ( $Obj_{j3}$ );
  read Pecuniary distribution ( $P_f$ );
  read Strategic distribution ( $S_g$ );
  read Tactical distribution ( $T_h$ );
  determine lower limit of final score  $\rho_{jMIN}$ ;
  determine upper limit of final score  $\rho_{jMAX}$ ;
   $delta = |\rho_{jMAX} - \rho_{jMIN}| \div Bins$ ;
  for  $i = 1$  to  $Bins$ 
     $Distribution_{\rho_j}[i] = \rho_{jMIN} + (i * delta)$ ;
  initialize  $p_i, i = 1, \dots, Bins$  to zero;
  for  $f = 1$  to  $Bins$ 
    for  $g = 1$  to  $Bins$ 
      for  $h = 1$  to  $Bins$ 
         $\rho = (P_f + S_g + T_h)^{1/q}$ ;
        compute joint probability for  $\rho_j$   $p = (p_{P_f} * p_{S_g} * p_{T_h})$ ;
        for  $i = 1$  to  $Bins$ 

```

```

        if ( $\rho_j < Distribution_{\rho_j}[i]$ )
             $p_j = p_j + p$ ;
    mean =  $\sum_{i=1}^{Bins} (p_i * Distribution_{\rho_j}[i])$ ;
    variance =  $\sum_{i=1}^{Bins} (p_i * Distribution_{\rho_j}[i]^2) - mean^2$ ;
    write results to output file;

```

This yields a mean and variance for the evaluation scores, which indicates a stability of the rankings to the decision maker. This, in association with the mean and variance of the objectives, and the Monetary Index and Nonmonetary Indices, provide the decision maker with the necessary information to evaluate all of the alternatives.

4.6 Example of Risk Determination Under Dependence

The cash flows and qualitative flows from the numerical example presented in Section 4.4 have been modified for analysis of risk under dependence. The deviations from the most likely values for the pessimistic and optimistic values are the same as those used in Section 4.4, however the flows for each project length have been tailored to show dependence of the cash flows to the project length as shown in Figure 4.6. Detailed input data used in this analysis is provided in Appendix K. The algorithm presented in the previous section is part of the “AMSTEP-R: Advanced Manufacturing System Technologies Evaluation Program - Risk.” The output from the program are the same as described in Section 4.4.

A sample size of 1,000 was used, and each distribution was constructed using ten bins. The execution time increased from 8 hours for the independent case to 18 hours for the dependent case, due to the added overhead of the dependence

Table 4.9: Mean and Variance for Final Scores $\tilde{\rho}$, $\theta = 1.0$

ALTERNATIVE	MEAN	VARIANCE
Manual	55.96	2.34
Semi-Automatic	34.74	2.19
Automatic	29.81	3.24

determinations.

The results for the mean and variance of the evaluation scores ρ under perfect correlation ($\theta = 1.0$) are shown in Table 4.9. The values of the objectives are provided in Table 4.10. The mean and variance of the values in the attribute versus alternative matrix are shown in Table 4.11. A frequency plot of the distributions of $\tilde{\rho}$ for each alternative are provided in Figures 4.9 through 4.11. Frequency plots of the objectives for each alternative are provided in Appendix L.

The results are consistent with the independent case in that the automatic alternative is preferred, followed by the semi-automatic and manual alternatives. However, the variances of the scores for the dependent case are greater than for the independent case as would be expected. For example, the variance of the score for the automatic alternative is three times greater than the variance in the independent case. This yields a more accurate result on the riskiness of the automatic alternative, measuring the potential expected deviation (loss) from the ideal point. The attribute versus alternative matrix is also consistent with the independent case, except that again the variances are seen to be greater. Note that the objective scores differ somewhat compared to the independent case. This is a result of the dependence of the cash flows and qualitative flows on the length of the project, as discussed in Section 4.5.

Table 4.10: Mean and Variance for the Objectives, $\theta = 1.0$

ALTERNATIVE	PECUNIARY		STRATEGIC		TACTICAL	
	MEAN	VAR	MEAN	VAR	MEAN	VAR
Manual	93.42	2,694.40	1,705.24	3,701.80	1,336.80	2,714.93
Semi-Automatic	171.88	5,598.62	460.45	902.15	573.97	854.68
Automatic	237.58	7,902.44	271.79	520.80	382.87	633.37

Table 4.11: Mean and Variance for Attribute vs. Alternative Matrix, $\theta = 1.0$

INDEX	MANUAL		SEMI-AUTO.		AUTOMATIC	
	Mean	Var	Mean	Var	Mean	Var
MI	0.6921	0.0087	0.5742	0.0097	0.4969	0.0096
NI_1	-0.3144	0.0012	0.1515	0.0012	0.1518	0.0012
NI_2	-0.2210	0.0081	0.1680	0.0074	0.3767	0.0074
NI_3	-0.4224	0.0038	0.3608	0.0021	0.6616	0.0020
NI_4	-0.4997	0.0004	0.1289	0.0007	0.2865	0.0018
NI_5	-0.2613	0.0013	0.4210	0.0009	0.6255	0.0010
NI_6	-0.9008	0.0017	0.2993	0.0018	0.6094	0.0018
NI_7	-0.0008	0.0004	-0.0008	0.0004	0.1992	0.0004
NI_8	-0.6000	0.0041	0.0770	0.0035	0.3359	0.0044
NI_9	-0.4192	0.0031	0.1226	0.0029	0.2877	0.0035
NI_{10}	-0.1477	0.0008	0.2446	0.0011	0.3361	0.0011
NI_{11}	0.0684	0.0019	0.4047	0.0010	0.3038	0.0020
NI_{12}	-0.3898	0.0024	0.1509	0.0024	0.3896	0.0027

Figure 4.9: Frequency Distribution of $\tilde{\rho}$ - Manual Alternative, $\theta = 1.0$

Figure 4.10: Frequency Distribution of $\tilde{\rho}$ - Semi-Automatic Alternative, $\theta = 1.0$

Figure 4.11: Frequency Distribution of $\tilde{\rho}$ - Automatic Alternative, $\theta = 1.0$

Table 4.12: Mean and Variance for Final Scores $\tilde{\rho}$, $\theta = 0.5$

ALTERNATIVE	MEAN	VARIANCE
Manual	55.68	1.87
Semi-Automatic	34.19	1.31
Automatic	29.21	1.75

In order to show the effect of changing the correlation coefficient, the AMSTEP-R program was run again with the same data, except that θ was changed from 1.0 to 0.5. The results are shown in Table 4.12 through 4.14. A frequency plot of the distributions of $\tilde{\rho}$ for each alternative are provided in Figures 4.12 through 4.14. Frequency plots of the objectives for each alternative are provided in Appendix L.

Table 4.13: Mean and Variance for the Objectives, $\theta = 0.5$

ALTERNATIVE	PECUNIARY		STRATEGIC		TACTICAL	
	MEAN	VAR	MEAN	VAR	MEAN	VAR
Manual	63.92	1,089.44	1,702.92	2,168.41	1,334.18	1,169.67
Semi-Automatic	140.08	2,567.21	458.71	355.17	572.30	329.74
Automatic	203.74	3,809.43	270.10	228.71	381.37	311.55

Table 4.14: Mean and Variance for Attribute vs. Alternative Matrix, $\theta = 0.5$

INDEX	MANUAL		SEMI-AUTO.		AUTOMATIC	
	Mean	Var	Mean	Var	Mean	Var
MI	0.7448	0.0054	0.6133	0.0055	0.5307	0.0055
NI_1	-0.3137	0.0009	0.1523	0.0008	0.1526	0.0009
NI_2	-0.2186	0.0029	0.1691	0.0023	0.3773	0.0022
NI_3	-0.4219	0.0027	0.3605	0.0007	0.6614	0.0007
NI_4	-0.4998	0.0027	0.1288	0.0003	0.2867	0.0014
NI_5	-0.2629	0.0007	0.4197	0.0003	0.6243	0.0004
NI_6	-0.9000	0.0005	0.3002	0.0006	0.6102	0.0006
NI_7	0.0000	0.0001	0.0000	0.0001	0.2001	0.0001
NI_8	-0.5982	0.0011	0.0785	0.0010	0.3380	0.0018
NI_9	-0.4191	0.0013	0.1226	0.0009	0.2877	0.0016
NI_{10}	-0.1477	0.0004	0.2448	0.0006	0.3364	0.0007
NI_{11}	0.0671	0.0011	0.4032	0.0003	0.3023	0.0014
NI_{12}	-0.3878	0.0007	0.1517	0.0010	0.3903	0.0013

Figure 4.12: Frequency Distribution of $\tilde{\rho}$ - Manual Alternative, $\theta = 0.5$

Figure 4.13: Frequency Distribution of $\tilde{\rho}$ - Semi-Automatic Alternative, $\theta = 0.5$

Figure 4.14: Frequency Distribution of $\tilde{\rho}$ - Automatic Alternative, $\theta = 0.5$

As expected, the variances in this case are smaller than when $\theta = 1.0$. The mean scores of the three alternatives are similar to the case when $\theta = 1.0$, as are the values of the Strategic and Tactical objectives, and the $\tilde{N}I_k$. The means for the Pecuniary objective (and subsequently the $\tilde{M}I$) are different than for the case of $\theta = 1.0$. This is attributed to the formula used to determine the $\tilde{M}I$. Recall from Chapter 3 that $MI_j = \frac{NPV_j}{R_{MI}}$, where $R_{MI} = \max\left(|\min_{j \in J} NPV_j|, |\max_{j \in J} NPV_j|\right)$. Determining the $\tilde{NPV}$ with a different covariance matrix yields different values of the $\tilde{NPV}$. Therefore, $|\min_{j \in J} NPV_j|$ and $|\max_{j \in J} NPV_j|$ will differ, causing the $\tilde{M}I$ and subsequently the Pecuniary objective to differ. In order to verify this, the $\tilde{NPV}$'s for each alternative when $\theta = 1.0$ and $\theta = 0.5$ were recorded. The means of these $\tilde{NPV}$'s are shown in Table 4.15.

Upon observation, the means of the $\tilde{NPV}$'s seem to be similar. Using the Mann-Whitney-Wilcoxon Rank Sum Test, the following tests are performed for

Table 4.15: Means of the $N\tilde{P}V$'s for $\theta = 1.0$ and $\theta = 0.5$

	$\theta = 1.0$	$\theta = 0.5$
$\overline{NPV}_{manual}$	\$3,010,139.	\$3,020,937
$\overline{NPV}_{semi-automatic}$	\$2,494,960.	\$2,486,406
$\overline{NPV}_{automatic}$	\$2,158,250.	\$2,149,915

Table 4.16: Rank Sums for the $N\tilde{P}V$'s when $\theta = 1.0$

MAN	Rank Sum (W)		Standard Normal (z)		
	SEMI	AUTO	MAN	SEMI	AUTO
991,371.0	1,008,900.0	1,009,339.0	-0.7069	+0.6505	+0.6845

each alternative j :

$$H_0 : \overline{NPV}_{(\theta=1.0)} = \overline{NPV}_{(\theta=0.5)}$$

$$H_1 : \overline{NPV}_{(\theta=1.0)} \neq \overline{NPV}_{(\theta=0.5)}$$

The rank sums for the $N\tilde{P}V$'s when $\theta = 1.0$, along with the corresponding values for $\Phi^{-1}(z)$ are provided in Table 4.16. The value of $E[W] = 1,000,500.0$ and $V[W] = 166,750,000.0$. At a 0.05 level of significance ($-1.96 \leq z \leq +1.96$), the null hypothesis is accepted, and it is concluded that $N\tilde{P}V$'s calculated when $\theta = 1.0$ and $\theta = 0.5$ are the same.

4.7 Summary

This Chapter presented two risk based methodologies for use in the probabilistic evaluation of AMST. One methodology assumed independence of the cash flows, qualitative flows, and interest rates along time, the second assumed the more realistic case of dependence along time. Both analyses yielded similar results, ex-

cept that the dependent case exhibited larger variances. These larger variances impact the range of potential scores of the alternatives, which could have an affect on the final results if the distribution of the two alternatives overlap in a significant manner.

The distributions of the Monetary and Nonmonetary Indices provide insight into those indices which may require further analysis by the decision maker. The indices with larger variances indicate a greater riskiness of those elements, which could drive the final score further away from the ideal point. Therefore, having a distribution of the scores and indices allows the decision maker to fully analyze the alternatives and select that alternative which matches the objectives of the company.

Both methodologies were developed into a software program for PC-AT type compatible computers. Interfaces to "LOTUS 1-2-3" allow for ease of data input to the program, and availability of the software allows an efficient means for a practitioner in the manufacturing environment to utilize this technique.

Chapter 5

Case Study

“We do not see things as they are. We see things as we are.” [14]

This chapter presents an analysis using the proposed methodology with a “real world” example. The example originated from a study performed at the Hughes Aircraft Company in Tucson, Arizona [64] [65]. Although the example is real, the data are outdated. No representation of accuracy of the data is intended, and the data are provided solely for illustrative purposes. The data do not reflect current Hughes Aircraft Company systems, nor do they reflect current vendor systems.

5.1 Background

In the past several years Hughes Aircraft Company Missile Systems Group (MSG) has investigated issues which are aimed at improving the ability of MSG to meet current and anticipated customer requirements. These issues include:

- Product Quality
- Management Systems and Procedures
- Modern Quality Philosophies
- Worker Support to Enhance Quality
- Work Instructions (accuracy and compliance)
- Product Design

The investigations showed certain limitations to implementing the “Quality First” policy presented by Hughes Aircraft Company management. Certain of

these limitations are related to quality information systems, along with the tools and techniques necessary to monitor and analyze product and work cell performance.

While existing quality information systems have served well in the past, the current emphasis on higher quality and productivity is demanding greater application of statistical quality assurance techniques and improved communications of product status and production problems. Of particular concern is the test/inspection information system, whose limitations include:

- High rates of data errors due to manual data entry.
- Incomplete data capture.
- Non real-time and batch oriented systems.
- Systems oriented for data collection versus data analysis.
- High occurrence of down times and limited terminal access.
- Inadequate systems integration, or ability to integrate.

In order to overcome the limitations of the existing test/inspection information system, a new hardware/software system to support the implementation of a modern test/inspection information system has been proposed. Specific areas of improvement which the new system will provide include:

- Real-time data collection and documentation.
- Collection of data reflecting workmanship/process related defect trends.
- Failure history supporting troubleshooting prioritization and repeat problem identification.

- Corrective action documentation and feedback of test-discovered workmanship defects to assembly and inspection personnel and to project operations management.
- Inspection data feedback system.
- Consistency of the determination of problem cause.
- Effectiveness of audit and feedback of corrective action.

The improvements address not only the manual systems and procedures, but also the existing hardware and software tools used to support the quality activities.

Knowing the limitations of the current systems, the tasks for improvement include:

- Establish a modern, effective product and failure/defect tracking system.
- Establish an on-line system for identifying, categorizing, and communicating production problems and causes.
- Provide timely, accurate, and efficient data collection techniques.
- Provide real-time test/inspection statistical analysis tools to production personnel and management.
- Provide integrated access to production-related plant site information systems.
- Provide controlled on-line test and inspection instructions.
- Provide technical administrative support capabilities.

5.2 Alternatives

Three alternatives are proposed for the test/inspection information system. The first is do-nothing, or maintain the current operations. The second is to acquire a development system, and the third is to acquire an entirely new test/inspection information system.

The current system requires manual data entry which totals \$1,350,000 per year. This is the only monetary cost associated with the current system. It is anticipated that Internal Relations will decline with the current system as pressures to improve productivity are placed on the work force, yet the limitations of the current system provide for little improvement opportunities. Market Position is expected to decline as the ineffectiveness of the existing systems may make it difficult to obtain future contracts. The current systems do not coincide with managements' "Quality First" plan. Organization is anticipated to decline due to the decreased ability for effective information management with the current system. There is no anticipated effect to Public Relations, and Technology is expected to decline as the current system is continued into the future because no advance can be made toward the company's technological position.

Flexibility is anticipated to remain constant with the current system, while Integration is projected to decline due to the poor communications and data usefulness provided. Material is expected to decline slightly due to poor control, and Personnel is expected to decline due to the use of employees for the monotonous task of data entry. Specific cash flows and qualitative flows for the current operations are provided in Table 5.1 and 5.2.

The first alternative is to acquire a computer development system appropriate to support the design, development, and implementation of application software,

Table 5.1: Cash Flows for the Current Operations

	1	2	3	4	5
Labor	(\$1,350,000)	(\$1,350,000)	(\$1,350,000)	(\$1,350,000)	(\$1,350,000)

Table 5.2: Qualitative Flows for the Current Operations

STRATEGIC	1	2	3	4	5
Internal Relations	0	-2	-4	-6	-8
Market Position	0	0	-5	-5	-10
Mission	0	-5	-10	-15	-20
Organization	0	-6	-9	-12	-15
Public Relations	0	0	0	0	0
Technology	-10	-10	-12	-14	-16
TACTICAL	1	2	3	4	5
Flexibility	10	10	10	10	10
Integration	15	12	9	9	9
Material	15	15	10	10	10
Personnel	15	10	10	10	5

work station interfaces, and communication links for a Product Test/Inspection Information System (PTIIS). The resulting software and interfaces will subsequently be transported to target, project dedicated area processors, which ultimately will make up the distributed host systems for PTIIS.

The PTIIS development system will be a resource to allow advanced effort for the design and development of application software and interfaces for the future PTIIS. Three major efforts are identified: software development, hardware development, and software maintenance/system upgrades.

Software activities supported by the proposed development system include coding, editing, compiling, testing, and debugging of custom software applications. Also included will be evaluations, benchmarking, and integration of applicable commercial software. The functional software systems to be implemented are:

- Product and failure/defect tracking system.

- Data collection system for test/inspection work stations.
- Analytical system.
- Personal computer support system.
- Controlled document access system for test/inspection instructions.
- Electronic problem notebooks.
- Communication system.
- Data Base Management System/security system.
- Computer-Aided troubleshoot interface for “expert” product failure diagnosis system.

Hardware activities will be related to interfaces, techniques, and equipment to support real-time data collection from production test and inspection work stations, and to support communication with other related computing systems. Specific tasks include:

- Real-time data collection interfaces to automatic test and inspection equipment.
- High-performance data entry and instruction display for manual test and inspection stations.
- Evaluation and interfacing of voice recognition, touch screen, and other data collection/display equipment.

Upon completion of the development system, results will be transported to PTIIS area processors for full scale implementation. The development system will

Table 5.3: Cash Flows for the Development System

	0	1	2	3	4	5
Labor		(\$1,080,000)	(\$675,000)	(\$270,000)	(\$270,000)	(\$270,000)
Depr Invest	(\$700,000)	(\$1,120,000)				
Maintenance		(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)	(\$20,000)
Operating Cost		(\$250)	(\$250)	(\$250)	(\$250)	(\$250)
Software	(\$140,000)	(\$70,000)				
Labor/Setup		(\$320,000)	(\$320,000)	(\$320,000)	(\$50,000)	

then be utilized for continuing software configuration control activities as well as system upgrades and modifications.

The development system is anticipated to reduce the manual data entry activity by 20% the first year, 50% in year two, and 80% thereafter, which marks the estimated completion of the development system. Equipment costs, maintenance, purchased software, and labor are as shown in Table 5.3. The labor required to setup the system includes programming, installation, etc.

It is anticipated that Internal Relations will be low initially due to the establishment of a new system and related employee concern over job security and retraining. As the development system is established and comes on-line, Internal Relations will improve as employees understand the system. Market Position is expected to improve as the system is developed due to the improved capabilities which the system provides. The development system coincides with management "Quality First" plan, and as such improves the Mission as the project is completed. Organization is anticipated to start low, and as the system is implemented will improve as the ability for effective information management improves. Public Relations is expected to improve as the word gets around about the advances and modernization of the information system. Technology is expected to improve as knowledge is gained with the development system, and enhanced as the engineers learn from the development.

Table 5.4: Qualitative Flows for the Development System

STRATEGIC	1	2	3	4	5
Internal Relations	-4	-2	5	12	18
Market Position	5	10	10	10	15
Mission	5	8	15	25	40
Organization	-5	0	10	20	30
Public Relations	10	10	15	15	20
Technology	15	18	30	35	45
TACTICAL	1	2	3	4	5
Flexibility	10	15	30	30	30
Integration	10	12	25	35	40
Material	15	20	40	45	50
Personnel	10	10	15	20	25

Flexibility is anticipated to improve as the system comes on-line and the information benefits are realized. Integration is projected to improve due to enhanced communications and data usefulness. Material is expected to improve due to better control, and Personnel will improve due to the reduction of the employees' requirement to perform monotonous data entry tasks. Specific qualitative flows for the development system are provided in Table 5.4.

The second alternative is to implement PTIIS without a development system. This would result in a reduction of manual data entry of 40% the first year and 80% thereafter. Equipment, software, and labor costs are the same as for the development system. Maintenance is anticipated to be \$200,000 per year due to inefficiencies of operation and resulting system crashes resulting from the large scale implementation. The cash flows for this alternative are given in Table 5.5.

Internal Relations will be lower than for development system due to the expected frequent crashes, which will make it more difficult to gain acceptance of the new system. Market Position will also lag due to the problems encountered during start-up with the full system. Mission will be improved as the full system better meets the "Quality First" plan. Organization will be lower because of the

Table 5.5: Cash Flows for the Full System

	0	1	2	3	4	5
Labor		(\$810,000)	(\$270,000)	(\$270,000)	(\$270,000)	(\$270,000)
Depr Invest	(\$700,000)	(\$1,120,000)				
Maintenance		(\$200,000)	(\$200,000)	(\$200,000)	(\$200,000)	(\$200,000)
Operating Cost		(\$250)	(\$250)	(\$250)	(\$250)	(\$250)
Software	(\$140,000)	(\$70,000)				
Labor/Setup		(\$320,000)	(\$320,000)	(\$320,000)	(\$50,000)	

inefficiency of operations. Public Relations will be higher than for the development system due to the announcement of intentions to implement a full system, but then decline as difficulties are encountered. Technology is anticipated to be the same as for the development system.

Flexibility will be lower as a result of the inefficiencies. Integration will fall behind that of the development system due to the frequency of crashes, and then improves as the bugs are worked out. Material will be affected by data problems, causing an impact on process control. Personnel will initially be higher than the development system due to the existence of a complete system, and then will fall as problems arise. As the problems are resolved, Personnel will improve as the system becomes accepted. Specific qualitative flows for the full system are provided in Table 5.6.

The weights used in the deterministic analysis are listed in Tables 5.7 and 5.8. The monetary interest rate used is that reported in Shinnar et al. [119] for General Motors, which is 6.1% (since Hughes Aircraft Company is part of General Motors). The nonmonetary interest rate will be the same as the monetary rate (6.1%), and the tax rate is 34.0%. The ACRS rate is 7 years, and a value of 2 is used for p and q . The length of the analysis period is 5 years, and the range for the minimum and maximum NPV will be determined by the algorithm.

Table 5.6: Qualitative Flows for the Full System

STRATEGIC	1	2	3	4	5
Internal Relations	-12	-8	0	5	10
Market Position	15	13	10	7	5
Mission	10	15	25	40	40
Organization	-14	-7	0	10	20
Public Relations	20	20	15	10	10
Technology	15	18	30	35	45
TACTICAL	1	2	3	4	5
Flexibility	5	10	15	30	30
Integration	5	8	18	30	40
Material	10	15	30	40	50
Personnel	15	10	10	15	20

Table 5.7: Attribute Weights

ATTRIBUTE	WEIGHT	NORMALIZED
Monetary	100	100
Internal Relations	80	16
Market Position	95	19
Mission	85	17
Organization	75	15
Public Relations	80	16
Technology	95	19
Flexibility	90	26
Integration	90	26
Material	80	23
Personnel	85	25

Table 5.8: Objective Weights

OBJECTIVE	WEIGHT	NORMALIZED
Pecuniary	100	38.5
Strategic	80	30.8
Tactical	80	30.8

5.3 Deterministic Analysis

The case study was initially analyzed deterministically using the AMSTEP-D software package. The final results are summarized in Table 5.9. The preferred alternative is that of the development system, followed by the full system, and finally the current operations. The attribute versus alternative matrix is shown in Table 5.10. From Table 5.10 it can be seen that based solely upon a monetary measure, the development system alternative would be preferred as it minimizes the cash expenditure. However, note that the interest rate of 6.1% would most likely not be used in a monetary analysis. An interest rate with adjustments for risk would be used instead. The rate used at Hughes was 15%. When the risk adjusted interest rate is used in the monetary analysis, the net present values for the three alternatives are as shown in Table 5.11. Under this analysis, the preferred alternative is the current operations, as this alternative minimizes the cash expenditure. Thus, by removing risk from the interest rate, the preferred alternative on a monetary basis using a deterministic approach becomes the development system. Handling of risk will be addressed in the next section.

The sensitivity of the weights in this analysis is analyzed using a mixture experiment as described in Chapter 3. In accordance with mixture experiment terminology, α (strategic/tactical weights) and β (objective weights) were normalized to sum to unity. This does not significantly alter the model as the desired effect remains the same, only the resulting score will differ by a constant. Additionally, for the mixture experiment the value of q in the Composite Programming equation was changed from 2 to 1 to create a linear equation in the objectives.

Initially, the analysis is performed on the objective weights (β_n , $n = 1, 2, 3$). The β_n 's were varied between 0 and 1, while the α_{nk} values were used as shown

Table 5.9: Results and Rankings

ALTERNATIVE	EVALUATION	RANK
Development System	67	1
Full System	68	2
Current Operations	73	3

Table 5.10: Attribute versus Alternative Matrix

Attribute	CURRENT	DEVELOPMENT	FULL
Monetary	-1.0000	-0.9069	-0.9320
Internal Relations	-0.0376	0.0512	-0.0167
Market Position	-0.0017	0.0976	0.1031
Mission	-0.0941	0.1758	0.2499
Organization	-0.0797	0.0994	0.0080
Public Relations	0.0000	0.1371	0.1535
Technology	-0.1221	0.2769	0.2769
Flexibility	0.1000	0.2234	0.1717
Integration	0.1098	0.2342	0.1912
Material	0.1218	0.3287	0.2776
Personnel	0.1024	0.1553	0.1383

Table 5.11: NPV Results Using Risk Adjusted Interest Rate

ALTERNATIVE	NPV
Current Operations	(\$ 2,986,770)
Development System	(\$ 3,074,626)
Full System	(\$ 3,115,778)

in Table 5.7. A simplex-centroid design for three components was used to analyze the effects of varying the proportion of β_1 , β_2 , and β_3 used in the model. This was done for the three alternatives previously described.

The fitted third-degree model for each alternative is:

$$\hat{y}_{\text{doing nothing}} = 10.00\beta_1 + 5.29\beta_2 + 4.46\beta_3 - 0.02\beta_1\beta_2 + 0.00\beta_1\beta_3 - 0.02\beta_2\beta_3 + 0.03\beta_1\beta_2\beta_3$$

$$\hat{y}_{\text{development}} = 9.53\beta_1 + 4.30\beta_2 + 3.84\beta_3 + 0.02\beta_1\beta_2 + 0.02\beta_1\beta_3 + 0.00\beta_2\beta_3 - 0.12\beta_1\beta_2\beta_3$$

$$\hat{y}_{\text{full}} = 9.66\beta_1 + 4.36\beta_2 + 4.04\beta_3 + 0.00\beta_1\beta_2 + 0.00\beta_1\beta_3 + 0.00\beta_2\beta_3 + 0.00\beta_1\beta_2\beta_3$$

where $\hat{y}$ is the estimate of the Composite Programming score ρ .

Analysis of the coefficients indicates that the strategic and tactical objectives (β_1 , β_2) tend to reduce the overall score. Thus, the nonmonetary objectives have the effect of moving the alternatives closer to the ideal. This is not surprising since the monetary analysis results in negative values which are far away from the ideal. The pecuniary objective coefficients (β_1) are similar for the three alternatives. Note that there is very little interaction between the objectives, indicating that the score is determined primarily from the proportion of pure components (weight) of the model.

The estimated shape of the response surface score for β_1 , β_2 , and β_3 is approximated pictorially for each alternative in Figures 5.1 thru 5.3. Each contour line on the plot joins the mixtures of β_1 , β_2 , and β_3 that are assumed to yield the same predicted score. The predicted scores were obtained for combinations of β_1 , β_2 , and β_3 where the specific combinations were defined as an array of points

Figure 5.1: Contour Plot of β_n for the Current Operations

across the triangle. Predicted scores of equal magnitude are joined by the same contour line. Note that X_1 , X_2 , and X_3 on the plots correspond to β_1 , β_2 , and β_3 respectively.

The contour plot of the current operations (Figure 5.1) shows that the best score occurs when $(\beta_1, \beta_2, \beta_3) = (0, 0, 1)$. As β_1 and β_2 are increased in value, the score moves further from the ideal reaching a maximum at $(\beta_1, \beta_2, \beta_3) = (1, 0, 0)$. The slope of the contour rises from a score of 4.46 at $(0, 0, 1)$ to the maximum of 10.0. Without β_1 and β_2 (pecuniary and strategic objectives) the score approaches

Figure 5.2: Contour Plot of β_n for the Development System

the ideal, however as β_1 and β_2 are added, the score moves away from the ideal.

The contour plot of the development system (Figure 5.2) is similar to the current operations. The score varies from 3.84 at $(0, 0, 1)$ to a maximum of 9.53 at $(1, 0, 0)$. Again, the lowest score is achieved when only the tactical objective is used, and the slope of the contour is similar to the slope exhibited for the current operations.

Finally, the full system contour plot (Figure 5.3) is similar to the first two alternatives. The minimum score is achieved at $(0, 0, 1)$ and the maximum score at

Figure 5.3: Contour Plot of β_n for the Full System

Figure 5.4: Scores for the Alternatives for Various Values of β_n

(1, 0, 0), and the slope of the contour closely follows that of the other alternatives. This again shows the effect of adding the qualitative factors, which moves the score toward the ideal. Since the pecuniary indicies are all negative, it is expected that any positive addition will move the score closer to the ideal.

The contour plots show in general that the full system score tends to change uniformly with β_2 and β_3 , as the contours are almost parallel to the β_2 - β_3 axis. The development system shows that β_2 has a more pronounced effect on the result due to the shift in orientation of the contour lines. For the current operations, β_2 has even more of an impact. Therefore, the Strategic objective plays an important role in the difference in scores between alternatives. This indicates that the Strategic elements have an important impact, and should be analyzed carefully.

In addition to the contour plots, a comparison of the scores for the three alternatives is presented in Figure 5.4 for various combinations of β_n . The combinations

of β_n used in the plot are shown in Table 5.12 and represent the following variations of β_n :

1. all the weight is in only one β_n (set # 1,2,3).
2. the weight is split evenly between only two β_n 's (set # 4,7,10).
3. the weight is split two-to-one between two β_n 's (set # 5,6,8,9,11,12).
4. the weight is split evenly between all three β_n 's (set # 13).
5. and the weight is split two-to-one where two β_n 's share the lesser weight (set # 14,15,16).
6. and the weight is split two-to-one where two β_n 's share the greater weight (set # 17,18,19).

From Figure 5.4 it can be seen that the development system scores consistently better than the other alternatives. The full system scores very close to the development system, but never better.

Next, the analysis was performed on the attribute weights (α_{nk} , $n = 2$; $k = 1, \dots, 6$ and $n = 3$; $k = 1, \dots, 4$). The α_{nk} 's were varied between 0 and 1, while the β_n values were used as shown in Table 5.8. A simplex-centroid design for six components was used to analyze the effects of varying the proportion of α_{2k} (strategic) used in the model, and for four components to analyze the α_{3k} (tactical). The difference in the components arises because the tactical objective only contained four elements. This was again performed for the three alternatives previously described.

A comparison of the scores for the three alternatives is plotted in Figure 5.5 (strategic) and Figure 5.6 (tactical) for various combinations of α_{nk} . The com-

Table 5.12: Combinations of Weights for β_n

SET	β_1	β_2	β_3	CRNT	DEV	FULL
1	0.00	0.00	1.00	4.46	3.84	4.04
2	0.00	1.00	0.00	5.29	4.30	4.36
3	1.00	0.00	0.00	10.00	9.53	9.66
4	0.00	0.50	0.50	4.87	4.07	4.20
5	0.00	0.33	0.67	4.74	4.00	4.15
6	0.00	0.67	0.33	5.01	4.15	4.25
7	0.50	0.00	0.50	7.23	6.69	6.85
8	0.33	0.00	0.67	6.31	5.74	5.91
9	0.67	0.00	0.33	8.15	7.64	7.79
10	0.50	0.50	0.00	7.64	6.92	7.01
11	0.33	0.67	0.00	6.86	6.04	6.13
12	0.67	0.33	0.00	8.43	7.79	7.89
13	0.33	0.33	0.33	6.58	5.89	6.02
14	0.25	0.25	0.50	6.05	5.38	5.53
15	0.25	0.50	0.25	6.26	5.49	5.61
16	0.50	0.25	0.25	7.44	6.80	6.93
17	0.40	0.40	0.20	7.01	6.30	6.42
18	0.40	0.20	0.40	6.84	6.21	6.35
19	0.20	0.40	0.40	5.90	5.16	5.29

CRNT - Current. DEV - Development.
 FULL - Full.

Figure 5.5: Scores of Alternatives for Values of the Strategic Objective α_{2k}

binations of α_{nk} used in the plots are shown in Table 5.13 and Table 5.14 and represent the following variations of α_{nk} :

1. all the weight is in only one α_n (set # 1 - 6 for $n = 2$, set # 1 - 4 for $n = 3$).
2. the weight is split evenly between only two α_n 's (set # 7 - 21 for $n = 2$, set # 5 - 10 for $n = 3$).
3. the weight is split evenly between only three α_n 's (set # 22 - 41 for $n = 2$, set # 11 - 14 for $n = 3$).
4. the weight is split evenly between only four α_n 's (set # 42 - 56 for $n = 2$, not applicable for $n = 3$).
5. the weight is split evenly between only five α_n 's (set # 57 - 62 for $n = 2$, not applicable for $n = 3$).

Figure 5.6: Scores of Alternatives for Values of the Tactical Objective α_{3k}

6. the weight is split evenly between all α_n 's (set # 63 for $n = 2$, set # 15 for $n = 3$).

Results tend to be robust to the attribute weights. However, outcomes do highlight the strengths and weaknesses of each attribute. For the Strategic objective, the current operations' score is consistently higher, and the development and full system alternatives exhibit similar trends with respect to the weight of α_{nk} . The closest scores between the development and full system occur at data set 3 (pure Mission) and 18 (equal mix of Mission/Technology).

The fitted models for the analysis of the Strategic and Tactical weights are provided in Appendix M. Looking at the Strategic weights for three component interactions on the development and full systems, the largest coefficients occur when Internal Relations, Market Position, Mission, and Organization are in the model. On four component interactions, the highest coefficients for the devel-

Table 5.13: Combinations of Weights for Strategic Objective α_{2k}

SET	α_{21}	α_{22}	α_{23}	α_{24}	α_{25}	α_{26}	CRNT	DEV	FULL
1	1.00	0.00	0.00	0.00	0.00	0.00	68.2	63.2	65.3
2	0.00	1.00	0.00	0.00	0.00	0.00	67.7	62.4	63.5
3	0.00	0.00	1.00	0.00	0.00	0.00	69.1	61.2	61.2
4	0.00	0.00	0.00	1.00	0.00	0.00	68.9	62.4	64.9
5	0.00	0.00	0.00	0.00	1.00	0.00	67.6	61.8	62.7
6	0.00	0.00	0.00	0.00	0.00	1.00	69.5	59.7	60.8
7	0.50	0.50	0.00	0.00	0.00	0.00	67.9	62.8	64.4
8	0.50	0.00	0.50	0.00	0.00	0.00	68.7	62.2	63.4
9	0.50	0.00	0.00	0.50	0.00	0.00	68.5	62.6	65.1
10	0.50	0.00	0.00	0.00	0.50	0.00	67.9	62.5	64.1
11	0.50	0.00	0.00	0.00	0.00	0.50	68.9	61.5	63.2
12	0.00	0.50	0.50	0.00	0.00	0.00	68.4	61.9	62.4
13	0.00	0.50	0.00	0.50	0.00	0.00	68.3	62.4	64.2
14	0.00	0.50	0.00	0.00	0.50	0.00	67.6	62.1	63.1
15	0.00	0.50	0.00	0.00	0.00	0.50	68.6	61.1	62.2
16	0.00	0.00	0.50	0.50	0.00	0.00	69.0	61.8	63.2
17	0.00	0.00	0.50	0.00	0.50	0.00	68.4	61.5	62.0
18	0.00	0.00	0.50	0.00	0.00	0.50	69.3	60.5	61.0
19	0.00	0.00	0.00	0.50	0.50	0.00	68.3	62.1	63.8
20	0.00	0.00	0.00	0.50	0.00	0.50	69.2	61.1	63.0
21	0.00	0.00	0.00	0.00	0.50	0.50	68.6	60.8	61.8
22	0.33	0.33	0.33	0.00	0.00	0.00	68.3	62.3	63.4
23	0.33	0.33	0.00	0.33	0.00	0.00	68.3	62.7	64.6
24	0.33	0.33	0.00	0.00	0.33	0.00	67.8	62.5	63.9
25	0.33	0.33	0.00	0.00	0.00	0.33	68.5	61.8	63.3
26	0.33	0.00	0.33	0.33	0.00	0.00	68.7	62.3	63.9
27	0.33	0.00	0.33	0.00	0.33	0.00	68.3	62.1	63.2
28	0.33	0.00	0.33	0.00	0.00	0.33	68.9	61.4	62.6
29	0.33	0.00	0.00	0.33	0.33	0.00	68.2	62.5	64.3
30	0.33	0.00	0.00	0.33	0.00	0.33	68.9	61.8	63.8
31	0.33	0.00	0.00	0.00	0.33	0.33	68.5	61.6	63.1
32	0.00	0.33	0.33	0.33	0.00	0.00	68.5	62.0	63.3
33	0.00	0.33	0.33	0.00	0.33	0.00	68.1	61.9	62.5
34	0.00	0.33	0.33	0.00	0.00	0.33	68.8	61.2	61.9
35	0.00	0.33	0.00	0.33	0.33	0.00	68.1	62.2	63.7
36	0.00	0.33	0.00	0.33	0.00	0.33	68.7	61.6	63.2
37	0.00	0.33	0.00	0.00	0.33	0.33	68.3	61.4	62.4
38	0.00	0.00	0.33	0.33	0.33	0.00	68.5	61.8	63.0
39	0.00	0.00	0.33	0.33	0.00	0.33	69.2	61.2	62.4
40	0.00	0.00	0.33	0.00	0.33	0.33	68.8	61.0	61.6
41	0.00	0.00	0.00	0.33	0.33	0.33	68.7	61.4	62.9
42	0.25	0.25	0.25	0.25	0.00	0.00	68.5	62.3	63.6
43	0.25	0.25	0.25	0.00	0.25	0.00	68.2	62.2	63.2
44	0.25	0.25	0.25	0.00	0.00	0.25	68.6	61.7	62.8
45	0.25	0.25	0.00	0.25	0.25	0.00	68.1	62.5	64.1
46	0.25	0.25	0.00	0.25	0.00	0.25	68.6	62.0	63.7
47	0.25	0.25	0.00	0.00	0.25	0.25	68.3	61.8	63.2
48	0.25	0.00	0.25	0.25	0.25	0.00	68.5	62.2	63.6
49	0.25	0.00	0.25	0.25	0.00	0.25	68.9	61.7	63.2
50	0.25	0.00	0.25	0.00	0.25	0.25	68.6	61.5	62.6
51	0.25	0.00	0.00	0.25	0.25	0.25	68.6	61.8	63.5
52	0.00	0.25	0.25	0.25	0.25	0.00	68.3	62.0	63.1
53	0.00	0.25	0.25	0.25	0.00	0.25	68.8	61.5	62.7
54	0.00	0.25	0.25	0.00	0.25	0.25	68.5	61.3	62.1
55	0.00	0.25	0.00	0.25	0.25	0.25	68.4	61.6	63.0
56	0.00	0.00	0.25	0.25	0.25	0.25	68.8	61.3	62.5
57	0.20	0.20	0.20	0.20	0.20	0.00	68.3	62.2	63.6
58	0.20	0.20	0.20	0.20	0.00	0.20	68.7	61.8	63.3
59	0.20	0.20	0.20	0.00	0.20	0.20	68.4	61.7	62.8
60	0.20	0.20	0.00	0.20	0.20	0.20	68.4	62.0	63.5
61	0.20	0.00	0.20	0.20	0.20	0.20	68.7	61.7	63.1
62	0.00	0.20	0.20	0.20	0.20	0.20	68.6	61.6	62.7
63	0.17	0.17	0.17	0.17	0.17	0.17	68.5	61.8	63.2

CRNT - Current. DEV - Development. FULL - Full.

Table 5.14: Combinations of Weights for Tactical Objective α_{3k}

SET	α_{31}	α_{32}	α_{33}	α_{34}	CRNT	DEV	FULL
1	1.00	0.00	0.00	0.00	67.5	60.6	62.1
2	0.00	1.00	0.00	0.00	67.3	60.5	61.8
3	0.00	0.00	1.00	0.00	67.1	59.0	60.4
4	0.00	0.00	0.00	1.00	67.4	61.7	62.7
5	0.50	0.50	0.00	0.00	67.4	60.6	62.0
6	0.50	0.00	0.50	0.00	67.3	59.8	61.3
7	0.50	0.00	0.00	0.50	67.5	61.2	62.4
8	0.00	0.50	0.50	0.00	67.2	59.7	61.1
9	0.00	0.50	0.00	0.50	67.4	61.1	62.2
10	0.00	0.00	0.50	0.50	67.3	60.4	61.6
11	0.33	0.33	0.33	0.00	67.3	60.1	61.5
12	0.33	0.33	0.00	0.33	67.4	61.0	62.2
13	0.33	0.00	0.33	0.33	67.4	60.5	61.8
14	0.00	0.33	0.33	0.33	67.3	60.4	61.7
15	0.25	0.25	0.25	0.25	67.4	60.5	61.8

CRNT - Current. DEV - Development. FULL - Full.

opment system occur when Market Position, Mission, Organization, Public Relations, and Technology are in the model. For the full system, the highest coefficients occur when Market Position, Organization, Public Relations, and Technology are in the model. Therefore, the decision maker may wish to further to investigate the Market Position, Mission, and Organization attributes.

The deterministic analysis provides insight into the composition of the outcome, indicating the objectives and/or elements which play an important role in the model. Identification of these objectives/elements provides insight to the decision maker as to the important aspects of the alternatives, and what areas may require additional consideration in any further analysis that may be performed.

5.4 Risk Analysis

The analysis of risk is performed as described in Chapter 4. The riskiness of the alternatives is placed in the cash flows and qualitative flows by having the decision maker provide these flows in terms of pessimistic, most likely, and optimistic estimates. In addition, the interest rates are also given by the decision

Table 5.15: Mean and Variance for Final Scores $\tilde{\rho}$

ALTERNATIVE	MEAN	VARIANCE
Development System	57.50	1.40
Full System	58.45	2.33
Current Operations	62.97	12.15

Table 5.16: Mean and Variance for the Objectives

ALTERNATIVE	PECUNIARY		STRATEGIC		TACTICAL	
	MEAN	VAR	MEAN	VAR	MEAN	VAR
Development System	2,277.39	7,730.27	570.30	604.41	460.47	500.92
Full System	2,321.72	18,691.21	588.74	546.32	508.84	670.96
Current Operations	2,549.84	171,152.77	876.03	635.98	611.03	108.51

maker in this manner. This data is provided in Appendix M. A sample size of 1,000 is used, with 10 bins. The value of θ is taken to be 0.70, based upon experience of the decision maker and similar analyses performed in [17] and [16]. The remaining evaluation parameters, such as weights, tax rate, depreciation, etc. are as used for the deterministic analysis. The range of $\tilde{T}$ is from 2 to 8 years.

Frequency distributions used to analyze this case study were determined using the AMSTEP-R program. The frequency distributions for $\tilde{\rho}$ are provided in Figures 5.7 through 5.9. The frequency distributions for the objectives are provided in Appendix N. The mean and variance for the final score $\tilde{\rho}$ is provided in Table 5.15, for the objectives in Table 5.16, and for the attribute versus alternative matrix in Table 5.17.

Table 5.17: Mean and Variance for Attribute vs. Alternative Matrix

INDEX	CURRENT		DEVELOPMENT		FULL	
	Mean	Var	Mean	Var	Mean	Var
MI	-.6218	.0183	-.5384	.0009	-.5532	.0021
NI_1	-.0379	.0004	.0472	.0013	-.0413	.0008
NI_2	-.0649	.0014	.0985	.0006	.1028	.0008
NI_3	-.0879	.0015	.1735	.0025	.2617	.0024
NI_4	-.0712	.0006	.0983	.0030	.0102	.0021
NI_5	-.0010	.0003	.1427	.0005	.1580	.0005
NI_6	-.1228	.0008	.2770	.0023	.2749	.0021
NI_7	.0997	.0003	.2109	.0007	.1661	.0013
NI_8	.1102	.0002	.2092	.0015	.1792	.0019
NI_9	.1227	.0001	.3311	.0027	.2769	.0032
NI_{10}	.1043	.0002	.1663	.0007	.1420	.0003

Figure 5.7: Frequency Distribution of Final Score $\tilde{p}$ - Current Operations

Figure 5.8: Frequency Distribution of Final Score $\tilde{\rho}$ - Development System

Figure 5.9: Frequency Distribution of Final Score $\tilde{\rho}$ - Full System

The preferred alternative is the development system, followed by the full system and the current operations. The development system also is the alternative with the lowest variance, indicating less risk as compared to the other alternatives. The current operations showed the greatest variance. As can be seen from the frequency distribution in Figure 5.7, the scores for the current operations tend to be spread out.

Analyzing the attribute versus alternative matrix in Table 5.17, the cause of the high variability for the current operations is the $\tilde{M}I$. For the development system, the high variability elements are $\tilde{N}I_3$, $\tilde{N}I_4$, $\tilde{N}I_6$, and $\tilde{N}I_9$ which correspond to Mission, Organization, Technology, and Material respectively. This indicates that these elements add risk to the alternative, and should be analyzed further as to their impact on the alternative.

The full system has the same high variability elements as the development system. The difference is that Material tends to be riskier, but Organization is less risky for the full system. Further comparison of the variances between the development and full system indicate that the full system is a greater risk on the monetary end, and less risky in the Personnel attribute.

The risk analysis provides the decision maker with means and variances which can be used to investigate the potentials of the various alternatives. Means and Variances of the final score ($\tilde{\rho}$) provide a preference relationship, and the attribute versus alternative matrix provides insight into the attributes which contribute to the risk (high variability). The decision maker may wish to investigate these elements further before taking any action on a final recommendation.

5.5 Summary

This chapter presented a case study utilizing the AMST methodology developed in this research. The analysis was performed on a “real world” example, showing how the methodology could be used to evaluate AMST. A deterministic approach was initially performed to analyze the impact of the objectives, and then a risk analysis was performed to analyze the risk of the alternatives under consideration.

The preferred alternative based upon the analysis is the development system. This alternative had the lowest Composite Programming score, along with the lowest variance on the score. Thus, this is the least risky of the three alternatives. Additionally, the analysis provided insight into the elements which contribute most to risk. The decision maker may consider to evaluate these elements further before making a final decision.

Although this analysis was actually performed at Hughes using a more traditional financial approach (payback), a significant amount of work was done in investigating the qualitative benefits. These benefits were documented as part of the justification, and amounted to strictly textual information. This was difficult to review, and difficult to trade-off among the three alternatives. Additionally, risk was incorporated into the interest rate, and there was no way to show the costs/benefits of the qualitative issues over time.

Incidentally, the decision reached at Hughes was to select the development system, and it has turned out to be a worthwhile decision. Using the methodology presented herein, the results of the analysis would have been clearer to present, and more succinct. Additionally, the methodology (as described in Chapter 3) provides a mechanism to investigate the intangible costs/benefits, providing the

decision maker with a structured approach to solve what in other circumstances is an open ended problem.

Chapter 6

Evaluation and Extensions

“Don’t let what you cannot do interfere with what you can do” -

John Wooden [14]

This chapter provides an evaluation of the model presented in this dissertation, along with suggested extensions for further research.

6.1 Evaluation

The model presented in this research provides a decision maker with a methodology to evaluate AMST. The objectives of the model (Pecuniary, Strategic, and Tactical) allow the decision maker to break the evaluation down into monetary (Pecuniary) and nonmonetary (Strategic/Tactical) aspects. The nonmonetary aspects are further divided into those areas which relate to planning (Strategic) and those areas which relate to the operations (Tactical) of a company. These objectives are further broken down into attributes which define the objectives, and elements which define the attributes. Using this decomposition, the costs and benefits associated with AMST for a manufacturing enterprise can be evaluated. The structure assists the decision maker in analyzing all aspects of an AMST alternative and how the costs/benefits of an alternative affect the manufacturing enterprise.

The Monetary Index provides the necessary monetary evaluation. The Non-monetary Index provides the nonmonetary evaluation, incorporating the concept of qualitative flows. Qualitative flows allow the nonmonetary attributes/elements

to be evaluated over time. The Nonmonetary Index then discounts these qualitative flows to a present value, providing a qualitative assessment for the attributes/elements which covers the anticipated life of the project. Therefore, the qualitative benefits are not evaluated as a simple "one-time" cost/benefit.

Having identified the attributes/elements associated with a set of AMST alternatives and determined the cash flows and qualitative flows, the decision maker has available a portion of the necessary information to perform an evaluation. At this point the decision maker must use caution not to select an interest rate which includes adjustments for risk. Should the decision maker select a deterministic evaluation, the method of Composite Programming is used to trade-off the alternatives. Each objective is assigned a weight of importance, as is each attribute/element. This allows the priorities of the enterprise to be included in the model. The Composite Programming technique then provides a rank ordering of the alternatives. To assist the decision maker, this algorithm has been coded to execute on an IBM compatible PC - a resource commonly available today. To facilitate ease of use, input to the program is via files created with "LOTUS 1-2-3". Thus, after having performed the difficult task of identifying the attributes/elements, determining appropriate flows, and determining weights, the solution of the model is easy to determine. Analysis of the deterministic results can further be aided with the use of mixture experiments. This allows the decision maker to analyze the impact of each objective or attribute/element on the final result.

Finally, the issue of risk analysis is addressed. Due to the unknown nature of the distributions of cash flows, qualitative flows, and interest rates, an enumeration is performed. The decision maker specifies pessimistic, most likely, and optimistic

values for each cash flow, qualitative flow, and interest rate with respect to the anticipated life of the project. Additionally, pessimistic, most likely, and optimistic project lives are specified. In doing this and removing risk adjustments from the interest rate, an accurate assessment of risk can be attained.

The Composite Programming technique is again employed for the enumeration, which results in a distribution of scores, objectives $\tilde{M}I$, and $\tilde{N}I_k$. Dependencies of the cash flows, qualitative flows, and interest rates, with respect to time, are also captured by assuming a multivariate normal distribution for each. The distributions resulting from the enumeration are then used to determine means and variances. The variances are used to identify the riskiness of the alternatives. The variances of the $\tilde{N}I_k$ provide management with insight to the risky attributes/elements of an alternative, which provides the decision maker with areas they may wish to further investigate.

Therefore, the model provides the decision maker with a means to evaluate AMST alternatives including qualitative factors, study the effects of the attributes/elements on the outcome, and address the riskiness of various alternatives without adjusting the interest rate for risk.

6.2 Extensions

As with many research projects, the more one becomes involved with the work, the more one discovers additional areas to investigate and improve upon, and this effort is no different. The extensions identified are broken down into the deterministic analysis, risk analysis, and software developed.

6.2.1 Deterministic

An extension on the deterministic analysis is to incorporate this methodology into areas other than manufacturing. One example would be the health care field. With the close scrutiny of health care costs and the advent of newer and more complicated (and costly) equipment, it is becoming difficult for health care providers to acquire new and modern equipment. It seems that several of the difficulties faced in the health care field are similar to those in the manufacturing environment. Primarily, there is no adequate way to incorporate the intangible costs/benefits of new equipment into an evaluation. The physicians I have spoken with all indicated a need for a methodology similar to that of this research for use in the health care field. This would require determination of a different set of attributes/elements for the three objectives which would address the health care enterprise. Having defined these attributes/elements, the remaining model would be the same as for the AMST.

6.2.2 Risk

There are two primary extensions in the risk evaluation methodology. These are incorporating dependencies between the attributes/elements, and use of an input distribution other than the triangular and normal.

Although dependence has been modeled for the cash flows, qualitative flows, and interest rates along time, dependencies may exist between the attributes/elements of cash flows, qualitative flows, and/or interest rates. For example, a decline in Public Relations of a company may have an effect on the Internal Relations, also leading them to decline. Such dependencies, should they exist, would then need to be captured in the model.

The cash flows, qualitative flows, and interest rates for the risk analysis model were in the form of a triangular distribution. Another distribution which is commonly used in the absence of data is the beta distribution. The beta distribution can also be defined in terms of pessimistic, most likely, and optimistic values, and its use may provide more accurate results, especially in the tails of the distribution. Additionally, the assumption of the multivariate normal distribution for dependency might be relaxed, and another dependence model used that would not require the input distributions to be symmetrical. This would allow cases where estimates may be skewed one direction or another. An example of such an instance is software development costs, which experience shows tend to run over estimates rather than below.

6.2.3 Software

Although the software programs developed in this research are easy to use, several improvements can be made to them. The mixture experiment analysis requires several computational steps which could be incorporated into the deterministic program, which would provide a more concise output in a form that is directly useable for evaluation. Additionally, the results of the risk determination are stored in ASCII files, and require an extra processing step to produce the frequency distributions. This could be incorporated into the program by either writing the results as "LOTUS 1-2-3" files, or adding graphical output routines.

The current risk determination program is not very efficient in its memory utilization. Several improvements can be made to better use memory, which would allow larger models to be analyzed. There are also some computational improvements which could be made in the algorithm in order to improve upon the execution time of the program.

These extensions would all be an improvement upon this work, and they would surely lead to additional extensions, refinements, and improvements.

Chapter 7

Summary and Conclusions

“Success is getting what you want. Happiness is liking what you get.” [14]

As we approach the “postmodern” factory of 1999, new approaches will be required in order to adequately evaluate AMST [32]. The shortcomings of the current approaches include:

1. Inability to account for intangible costs/benefits.
2. Failure to properly evaluate all alternatives, including the “do-nothing”.
3. Inappropriately including risk in the interest rate versus in the cash/qualitative flows.
4. Changing cost patterns, from direct to indirect.

This research proposes a model which overcomes the shortcomings of the traditional financial techniques.

The model developed consists of three objectives. There is a Pecuniary objective, which addresses the monetary aspects of the evaluation. Incorporation of the intangible costs/benefits are provided via a Strategic objective and a Tactical objective. These objectives consist of attributes/elements which have been shown to map into a typical manufacturing organization. A trade-off of these objectives for several alternatives is then performed using Composite Programming, however other methodologies may be employed.

The results of the deterministic analysis provide a rank order of the alternatives under investigation. Coupled with a mixture experiment, it is possible to

graphically portray the contours of each alternative as the importance of the three objectives vary.

The deterministic analysis assumes a risk free environment, indicating that future events are known for certain. This is not the case in a real world setting. Therefore, the deterministic model is augmented to allow the decision maker to specify interest rates, cash/qualitative flows, and time periods in ranges which signify the uncertain nature of future events. Through an enumeration, including dependencies of interest rates and cash/qualitative flows over time, a distribution of final scores is determined. This provides the decision maker with a mean and variance of the final scores, indicating the riskiness of the alternatives being evaluated. Further insight on the attributes which contribute to risk is obtained from analysis of the distributions of the attributes. Those attributes exhibiting large variances tend to contribute more toward risk.

Therefore, the model accounts for intangible costs/benefits of AMST. The methodology includes analysis of not implementing any of the alternatives under consideration, and points out that not implementing any of the alternatives is not necessarily one of status-quo operations, but deteriorating operations. Risk is removed from the interest rate and placed in the cash/qualitative flows. And the definition of the attributes makes no assumption of direct/indirect labor, but views costs/benefits from where they occur.

Additionally, the models have been developed into software programs which allow ease of use and provide assistance in the analysis for the decision maker.

Appendix A

Proofs

Theorem 3.1 *The Monetary Index $MI_j = \frac{NPV_j}{R_{MI}}$ yields a result in the range $[-1, +1]$.*

PROOF: In order to prove this result, three cases are analyzed:

1. NPV_{MAX} and NPV_{MIN} are both positive.
2. NPV_{MAX} is positive and NPV_{MIN} is negative.
3. NPV_{MAX} and NPV_{MIN} are both negative.

Case 1: When both NPV_{MAX} and NPV_{MIN} are positive, the R_{MI} will simply be NPV_{MAX} . In this case, $MI_j = \frac{NPV_j}{NPV_{MAX}}$ and the MI_j will range between 0 and 1.

Case 2: When NPV_{MAX} is positive and NPV_{MIN} is negative, the R_{MI} will be $\max(|NPV_{MIN}|, NPV_{MAX})$. In this situation, $MI_j = \frac{NPV_j}{\max(|NPV_{MIN}|, NPV_{MAX})}$. Since $\max(|NPV_{MIN}|, NPV_{MAX}) \geq |NPV_j|$, the MI_j must be between -1 and $+1$.

Case 3: When NPV_{MAX} and NPV_{MIN} are both be negative, R_{MI} will be $|NPV_{MIN}|$. This will yield $MI_j = \frac{NPV_j}{|NPV_{MIN}|}$ and MI_j will range between -1 and 0 .

Therefore, the MI_j is either $[0, +1]$, $[-1, +1]$, or $[-1, 0]$, and as such the MI_j will be in the range $[-1, +1]$ $\square$.

Theorem 3.2 *The Nonmonetary Index $NI_{kj} = \frac{NPQF_{kj}}{R_{NI}}$ yields a result in the range $[-1, +1]$.*

PROOF: In order to prove this result, three cases are again analyzed:

1. All of the Q_{tkj} 's are positive.
2. The Q_{tkj} 's vary between positive and negative values.
3. All of the Q_{tkj} 's are negative.

Case 1: When all of the Q_{tkj} 's are positive, the $NPQF_{kj}$ is positive. In this case the smallest value is achieved when all of the Q_{tkj} are zero, the $NPQF_{kj}$ is zero, and the NI_{kj} is zero. The largest value is achieved when all of the Q_{tkj} are at the upper bound of 100. Then, $NPQF_{kj} = \sum_{t=1}^T 100(1+h)^{-t} = 100 \sum_{t=1}^T (1+h)^{-t}$, and the NI_{kj} is one.

Case 2: When the Q_{tkj} vary between positive and negative values, the $NPQF_{kj}$ will be between $-100 \sum_{t=1}^T (1+h)^{-t}$ and $100 \sum_{t=1}^T (1+h)^{-t}$, and thus the NI_{kj} will be between -1 and $+1$.

Case 3: Finally, when all of the Q_{tkj} are negative, the $NPQF_{kj}$ is negative. The smallest value is achieved when all the Q_{tkj} are at the lower bound of -100. Then, $NPQF_{kj} = \sum_{t=1}^T -100(1+h)^{-t} = -100 \sum_{t=1}^T (1+h)^{-t}$, and the $NI_{kj} = -1$. The largest value is achieved when the Q_{tkj} are all zero, $NPQF_{kj}$ is zero, and the NI_{kj} is zero.

Therefore, the NI_{kj} is either $[0, +1]$, $(-1, +1)$, or $[-1, 0]$, and as such the NI_{kj} will be in the range $[-1, +1]$ $\square$.

Appendix B

AMSTEP-D Program Listing

```

/*
/*  AMSTEP-D: Advanced Manufacturing System Technology Evaluation Program
/*
/*                      Deterministic
/*
/*
/*                      Johann G. Demmel
/*                      copyright (c) 1991
/*
/*                      Compiler: Power C by MIX Software
/*
/*
#include <bios.h>
#include <conio.h>
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define MAX_ALTS 5

FILE *ACRS_in, *Fp, *Out;

int ACRS_type, Num_alts, Proj_len, Type;

float Monetary_rate[20], Nonmonetary_rate[20], Obj_weight[3];
float Factors[20], ACRS[21];
float Tax_rate, P, Q;
float MI[MAX_ALTS], NI[MAX_ALTS][12], Score[MAX_ALTS];

double NPV_max, NPV_min, NPV[MAX_ALTS], Depreciation[21];
double NPQF_s[MAX_ALTS][6], NPQF_t[MAX_ALTS][6];

char Input_files[MAX_ALTS][13], Alt_title[MAX_ALTS][25], Title[40];
char Prefix_name[9] = "amstep ";

struct {
    int pecuniary;
    int strategic;
    int tactical;
} Num_attrib;

struct {

```

```

    char description[15]; /* Attribute description.      */
    double cash_flow[21]; /* Cash flows for attribute.    */
} Monetary[20];

struct { /* Structure for nonmonetary data. */
    char attribute[20]; /* Attribute description.      */
    float weight; /* Attribute weight.          */
    double qual_flow[21]; /* Qualitative flows for attribute. */
} Strategic[6], Tactical[6];

double comp_prog();
void depreciation(void);
double distance();
void echo_inputs();
void factors();
void fill_real();
double get_IEEE_real();
void get_ACRS(void);
int get_parameters();
void ignore_bytes();
void indices();
void initialize(void);
float interest();
int lotus_read();
void norm_weights(void);
void opening_menu(void);
void prepare(void);
void rankings(void);
int read_data();
void store_input();
void print_array();

/* FUNCTION: main */
/* DESCRIPTION: */
/* Controls the execution of the functions which comprise AMSTEP. */

main(int argc, char *argv[])
{
    int i;

    prepare();
    opening_menu();
    clrscrn();
    poscurs(5,22);
    fprintf(stderr,"<< OBTAINING ANALYSIS PARAMETERS >>");
    if (get_parameters(argc,argv[1])) {
        exit(1);
    }
    norm_weights();
    echo_inputs();

```

```

    for (i = 0; i < Num_alts; ++i) {
        initialize();
        clrscrn();
        poscurs(5,21);
        fprintf(stderr,"<< OBTAINING DATA FOR ALTERNATIVE %d >>",i);
        read_data(i);
        clrscrn();
        poscurs(5,16);
        fprintf(stderr,"<< PERFORMING CALCULATIONS FOR ALTERNATIVE %d >>",i);
        npv(i);
        npqf('s',i);
        npqf('t',i);
        indices(i);
        Score[i] = comp_prog(i);
        print_array(i);
    }

    rankings();
    poscurs(25,0);
}

/*  FUNCTION: prepare                                     */
/*  DESCRIPTION:                                         */
/*      Initializes program variables.                   */
/*  */

void prepare(void)
{
    int i, j;

    Num_alts = 0;
    for (i = 0; i < 3; ++i)
        Obj_weight[i] = 0.;
    for (j = 0; j < 20; ++j)
        Monetary_rate[j] = Nonmonetary_rate[j] = 0.;
}

/*  FUNCTION: initialize                                 */
/*  DESCRIPTION:                                         */
/*      Initializes variables dependent upon alternative. */
/*  */

void initialize(void)
{
    int i, k;

    for (i = 0; i < 21; ++i)
        Depreciation[i] = 0.;

    for (i = 0; i < 6; ++i) {
        for (k = 0; k < 21; ++k) {
            Strategic[i].qual_flow[k] = 0.;

```

```

        Tactical[i].qual_flow[k] = 0.;
    }
}
for (i = 0; i < 20; ++i) {
    Monetary[i].description[0] = '\0';
    for (k = 0; k < 21; ++k) {
        Monetary[i].cash_flow[k] = 0.;
    }
}
}
/*  FUNCTION: opening_menu                                     */
/*  DESCRIPTION:                                             */
/*  Displays an opening message to the user.                */
*/

void opening_menu(void)
{
    int i;

    cursoff();
    clrscrn();
    poscurs(3,30);
    fprintf(stderr,"+-----+");
    poscurs(13,30);
    fprintf(stderr,"+-----+");
    for (i = 0; i < 9; ++i) {
        poscurs(i+4,30);
        fprintf(stderr,"|                |");
    }
    poscurs(5,33);
    fprintf(stderr,"A dvanced");
    poscurs(6,33);
    fprintf(stderr,"M anufacturing");
    poscurs(7,33);
    fprintf(stderr,"S ystem");
    poscurs(8,33);
    fprintf(stderr,"T echnology");
    poscurs(9,33);
    fprintf(stderr,"E valuation");
    poscurs(10,33);
    fprintf(stderr,"P rogram");
    poscurs(11,33);
    fprintf(stderr,"D eterministic");
    poscurs(16,31);
    fprintf(stderr,"copyright (c) 1991");
    poscurs(17,32);
    fprintf(stderr,"Johann G. Demmel");
    poscurs(23,25);
    fprintf(stderr,"< strike any key to continue >");
    while (!kbhit());
    getch();
}

```

```

    cursoron();
}
/*  FUNCTION: get_parameters                                */
/*  DESCRIPTION:                                           */
/*    Obtains analysis parameters from a LOTUS 1-2-3 input file. */

int get_parameters(int argc, char parm_file)
{
    int col, i, int_val, j, opcode, parm_code = -1, parms_found = 16383, row;
    int base2, base_row, range;
    char label[240];
    double real_val;
    char parm_names[14][17] = {
        "title      ",
        "project length ",
        "input files   ",
        "acrs          ",
        "monetary rate  ",
        "nonmonetary rate",
        "tax rate       ",
        "npv min        ",
        "npv max        ",
        "strategic weight",
        "tactical weight ",
        "pecuniary weight",
        "p factor       ",
        "q factor       " };
    char strat_attrib[6][19] = {
        "Internal Relations",
        "Market Position   ",
        "Mission           ",
        "Organization      ",
        "Public Relations  ",
        "Technology        " };
    char tact_attrib[6][15] = {
        "Design          ",
        "Flexibility      ",
        "Integration      ",
        "Material         ",
        "Personnel        ",
        "Produceability" };

    if (argc == 1) {
        poscurs(8,26);
        fprintf(stderr,"ERROR: must supply file name");
        return 1;
    }
    else {
        Fp = fopen(parm_file,"rb");
        if (Fp == NULL) {

```



```

    poscurs(8,26);
    fprintf(stderr,"ERROR: opening %s",parm_file);
    return 1;
}
Num_attrib.strategic = 0;
Num_attrib.tactical = 0;
poscurs(9,18);
strupr(parm_file);
fprintf(stderr,"Processing Parameter File %s ...",parm_file);
do {
    opcode = lotus_read(&row, &col, &int_val, &real_val, label);
    switch (opcode) {
        case 12 : /* blank cell, skip. */
            if (col == 0) {
                range += 1;
            }
            break;
        case 13 : /* integer value. */
            if ((col == 1) && (row != base_row))
                range += 1;
            real_val = int_val;
            store_input(parm_code,real_val,range);
            break;
        case 14 : /* real value. */
            if ((col == 1) && (row != base_row))
                range += 1;
            store_input(parm_code,real_val,range);
            break;
        case 15 : /* label. */
            if (col == 0) {
                range = 0;
                base_row = row;
                base2 = 1;
                parm_code = -1;
                j = 0;
                do {
                    if (!strnicmp(parm_names[j],label,strlen(label))) {
                        parm_code = j;
                        parms_found = parms_found ^ base2;
                    }
                    base2 = base2 * 2;
                    ++j;
                } while ((parm_code == -1) && (j < 14));
                if (parm_code == -1) {
                    for (i = 0; i < 6; ++i) {
                        if (strnicmp(strat_attrib[i],label,strlen(label)) == 0) {
                            j = Num_attrib.strategic;
                            strncpy(Strategic[j].attribute,label,strlen(label));
                            Num_attrib.strategic += 1;
                            parm_code = 14;
                        }
                    }
                }
            }
    }
} while (1);

```

```

        break;
    }
    else {
        if (strnicmp(tact_attrib[i],label,strlen(label)) == 0) {
            j = Num_attrib.tactical;
            strncpy(Tactical[j].attribute,label,strlen(label));
            Num_attrib.tactical += 1;
            parm_code = 15;
            break;
        }
    }
}
}
}
else {
    switch (parm_code) {
        case -1 :
            break;
        case 0 :
            j = strlen(label);
            if (j > 40)
                j = 40;
            strncpy(Title,label,j);
            break;
        case 2 :
            strncpy(Input_files[Num_alts],label,strlen(label));
            Num_alts += 1;
            break;
        default :
            poscurs(20,26);
            fprintf(stderr,"ERROR: parm_code not defined");
            return 2;
    }
}
break;
case 16 : /* real value in formula. */
    if ((col == 1) && (row != base_row))
        range += 1;
    store_input(parm_code,real_val,range);
    break;
default : /* ignore all other opcodes. */
    break;
}
} while (opcode != 1);
fclose(Fp);
if (parms_found) {
    base2 = 1;
    poscurs(11,25);
    fprintf(stderr,"Required parameters not found");
    poscurs(12,37);
}

```

```

    fprintf(stderr,"%d",parms_found);
    poscurs(13,28);
    fprintf(stderr,"Missing Parameters are:");
    j = 1;
    for (i = 1; i <= 14; ++i) {
        parm_code = parms_found & base2;
        base2 = base2 * 2;
        if (parm_code) {
            poscurs(13+j,31);
            fprintf(stderr,"%s",parm_names[i-1]);
            ++j;
        }
    }
    return 3;
}
else
    return 0;
}
}
/*  FUNCTION: store_input                                     */
/*  DESCRIPTION:                                             */
/*    Stores the analysis parameters from the input file into appropriate */
/*    variables.                                             */
void store_input(int code, double value, int range)
{
    int i = 0;
    static int mcnt, ncnt;

    switch (code) {
        case -1 :
            break;
        case 1 : /*  project length.  */
            Proj_len = value;
            break;
        case 3 : /*  ACRS depreciation.  */
            ACRS_type = value;
            get_ACRS();
            break;
        case 4 : /*  monetary interest rate.  */
            if (Monetary_rate[0] == 0.)
                mcnt = 0;
            Monetary_rate[mcnt] = value;
            mcnt += 1;
            break;
        case 5 : /*  nonmonetary interest rate.  */
            if (Nonmonetary_rate[0] == 0.)
                ncnt = 0;
            Nonmonetary_rate[ncnt] = value;
            ncnt += 1;
    }
}

```

```

        break;
    case 6 : /* tax rate. */
        Tax_rate = value/100.;
        break;
    case 7 : /* minimum NPV. */
        NPV_min = value;
        break;
    case 8 : /* maximum NPV. */
        NPV_max = value;
        break;
    case 9 : /* strategic weight. */
        Obj_weight[1] = value;
        break;
    case 10 : /* tactical weight. */
        Obj_weight[2] = value;
        break;
    case 11 : /* pecuniary weight. */
        Obj_weight[0] = value;
        break;
    case 12 : /* p-factor. */
        P = value;
        break;
    case 13 : /* q-factor. */
        Q = value;
        break;
    case 14 : /* Strategic attribute weights. */
        Strategic[Num_attrib.strategic-1].weight = value;
        break;
    case 15 : /* Tactical attribute weights. */
        Tactical[Num_attrib.tactical-1].weight = value;
        break;
    default : /* error. */
        poscurs(20,18);
        fprintf(stderr,"ERROR: Invalid parameter code (%d) in store_input",
                    code);
        break;
    }
}

/* FUNCTION: get_ACRS */
/* DESCRIPTION: */
/* Obtains ACRS values from an input file. */

void get_ACRS(void)
{
    unsigned short int i, skip;

    ACRS_in = fopen("acrs.dat","r");
    if (ACRS_in == NULL) {
        poscurs(20,28);
    }
}

```

```

    fprintf(stderr, "ERROR: Opening ACRS.DAT");
    exit(1);
}
switch (ACRS_type) {
    case 3 :
        skip = 0;
        break;
    case 5 :
        skip = 4;
        break;
    case 7 :
        skip = 10;
        break;
    case 10 :
        skip = 18;
        break;
    case 15 :
        skip = 29;
        break;
    case 20 :
        skip = 45;
        break;
    default :
        poscurs(20,17);
        fprintf(stderr, "ERROR: Incorrect ACRS type input %d", ACRS_type);
        exit(1);
}
for (i = 0; i < skip; ++i)
    fscanf(ACRS_in, "%f", &ACRS[i]);
for (i = 0; i < ACRS_type + 1; ++i)
    fscanf(ACRS_in, "%f", &ACRS[i]);
fclose(ACRS_in);
}

/*  FUNCTION: read_data                                     */
/*  DESCRIPTION:                                           */
/*    Reads the cash flow and qualitative flow data from the input file */
/*    specified by the user.                               */

int read_data(int alt)
{
    int process = 0, old_row;
    int base_row, col = 0, i, int_val, label_len, opcode, pos = -1, row = 0;
    double real_val;
    char label[240];

    /*  Determine the number of values to input based upon the type of
       analysis to be performed, and open the input file.  If risk, input
       required is pessimistic, most likely, and optimistic.  Otherwise, only
       one input is required. */

```

```

Fp = fopen(Input_files[alt],"rb");
if (Fp == NULL) {
    fprintf(stderr,"\nERROR: opening %s\n",Input_files[alt]);
    return 1;
}

/*  Read input data from a LOTUS 1-2-3 file.  Fill arrays used in this
    program with data read from the file. */

strupr(Input_files[alt]);
poscurs(9,21);
fprintf(stderr,"Processing data from %s ...",Input_files[alt]);
do {
    opcode = lotus_read(&row, &col, &int_val, &real_val, label);
    switch (opcode) {
        case 12 : /* Blank cell - zero value if part of attribute input. */
            if (old_row == row)
                break;
            if (col == 0) {
                base_row = row;
            }
            break;
            if ((process >= 1) && (process <= 3))
                fill_real(row,col,process,0.,pos);
            break;
        case 13 : /* Integer input - convert to real double. */
            if (old_row == row)
                break;
            if (row != base_row) {
                base_row = row;
            }
            real_val = int_val;
            fill_real(row,col,process,real_val,pos);
            break;
        case 14 : /* Real input - process as double. */
            if (old_row == row)
                break;
            if (row != base_row) {
                base_row = row;
            }
            fill_real(row,col,process,real_val,pos);
            break;
        case 15 : /* Label input - contains key for processing objectives. */
            if ((col > 0) && (row == base_row))
                break;
            if (col == 0) {
                base_row = row;
            }
            label_len = strlen(label);
    }
}

```

```

if (strncmp("Pecuniary",label,label_len) == 0) {
    process = 1;
    Num_attrib.pecuniary = 0;
    old_row = row;
    break;
}
if (strncmp("Strategic",label,label_len) == 0) {
    process = 2;
    old_row = row;
    break;
}
if (strncmp("Tactical",label,label_len) == 0) {
    process = 3;
    old_row = row;
    break;
}
switch (process) {
    case 0:
        strncpy(Alt_title[alt],label,label_len);
        Alt_title[alt][label_len] = '\0';
        break;
    case 1:
        pos = Num_attrib.pecuniary;
        strncpy(Monetary[pos].description,label,label_len);
        Monetary[pos].description[label_len] = '\0';
        Num_attrib.pecuniary += 1;
        break;
    case 2:
        if (strncmp("Strategic",label,label_len) != 0) {
            pos = -1;
            for (i = 0; i < Num_attrib.strategic; ++i) {
                if (strnicmp(Strategic[i].attribute,label,label_len) == 0) {
                    pos = i;
                }
            }
            if (pos == -1) {
                poscurs(20,20);
                fprintf(stderr,"ERROR: Strategic attribute not defined");
                poscurs(21,10);
                fprintf(stderr,"Attrib: %s\n",label);
            }
            for (i = 0; i < Num_attrib.strategic; ++i)
                fprintf(stderr,"%s %4.0d\n",Strategic[i].attribute,Strategic[i].weight);
            exit(1);
        }
        break;
    case 3:
        if (strncmp("Tactical",label,label_len) != 0) {
            pos = -1;
            for (i = 0; i < Num_attrib.tactical; ++i) {

```

```

        if (strnicmp(Tactical[i].attribute,label,label_len) == 0) {
            pos = i;
        }
    }
    if (pos == -1) {
        poscurs(20,20);
        fprintf(stderr,"ERROR: Tactical attribute not defined");
        fprintf(stderr,"Attrib: %s\n",label);
    }
    for (i = 0; i < Num_attrib.tactical; ++i)
        fprintf(stderr,"%s %4.0d\n",Tactical[i].attribute,Tactical[i].weight);
        exit(1);
    }
}
break;
}
break;
case 16 : /* Formula input - contains real value. */
    if (old_row == row)
        break;
    if (row != base_row) {
        base_row = row;
    }
    fill_real(row,col,process,real_val,pos);
    break;
default :
    break;
}
} while (opcode != 1);
fclose(Fp);
}

/*  FUNCTION: fill_real                                     */
/*  DESCRIPTION:                                           */
/*  Fills the appropriate arrays with cash flows or qualitative flows. */

void fill_real(row, col, process, real_val, pos)
int row, col, process, pos;
double real_val;
{
    switch (process) {
        case 1:
            Monetary[pos].cash_flow[col-1] = real_val;
            break;
        case 2:
            Strategic[pos].qual_flow[col-1] = real_val;
            break;
        case 3:
            Tactical[pos].qual_flow[col-1] = real_val;
            break;
        default:

```



```

        fprintf(stderr, "ERROR process %d incorrect in fill_real");
        exit(1);
        break;
    }
}

/*  FUNCTION: lotus_read                                     */
/*  DESCRIPTION:                                             */
/*  Reads input data from the LOTUS files.                  */
/*  */

int lotus_read(row, col, int_val, real_val, label)
    int *row, *col, *int_val;
    double *real_val;
    char label[240];
{
    int end_col, end_row, format_key;
    int format_type, formula_opcode, i, label_byte, length, opcode;
    int mode, protect, size, start_row, start_col;

    opcode = getc(Fp) + (getc(Fp) * 256);
    length = getc(Fp) + (getc(Fp) * 256);
    switch (opcode) {
        case 0 : /* Beginning of file */
            if (start_processing(length) != 0)
                opcode = 1;
            break;
        case 1 : /* End of file */
            break;
        case 2 : /* Calculation Method */
        case 3 : /* Calculation Order */
        case 4 : /* Type of Window Split */
        case 5 : /* Synchronize windows to cursor movement */
            ignore_bytes(length);
            break;
        case 6 : /* Range */
            start_col = getc(Fp) + (getc(Fp) * 256);
            start_row = getc(Fp) + (getc(Fp) * 256);
            end_col = getc(Fp) + (getc(Fp) * 256);
            end_row = getc(Fp) + (getc(Fp) * 256);
            break;
        case 7 : /* Description of Window #1 */
        case 8 : /* Defines column width */
        case 9 : /* Description of Window #2 */
        case 10 : /* Defines column width */
        case 11 : /* Range name */
            ignore_bytes(length);
            break;
        case 12 : /* Blank Cell */
            mode = getc(Fp);
            *col = getc(Fp) + (getc(Fp) * 256);
    }
}

```

```

    *row = getc(Fp) + (getc(Fp) * 256);
    break;
case 13 : /* Integer Value */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    *int_val = getc(Fp) + (getc(Fp) * 256);
    break;
case 14 : /* Floating Point Value */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    *real_val = get_IEEE_real(*row,*col);
    break;
case 15 : /* Label */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    i = 5;
    label_byte = getc(Fp);
    while ((i < length) && (label_byte != 0)) {
        label_byte = label[i-5] = getc(Fp);
        i += 1;
    }
    label[i-5] = '\0';
    break;
case 16 : /* Formula */
    mode = getc(Fp);
    protect = mode >> 7;
    format_type = (mode >> 4) & 7;
    format_key = mode & 15;
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    *real_val = get_IEEE_real(*row,*col);
    size = getc(Fp) + (getc(Fp) * 256);
    formula_opcode = getc(Fp);
    for(i = 16; i < length; ++i)
        getc(Fp);
    break;
case 24 : /* Table Range */
case 25 : /* Query Range */
case 26 : /* Print Range */
case 27 : /* Sort Range */
case 28 : /* Fill Range */
case 29 : /* Primary Sort Key Range */
case 32 : /* Distribution Range */
case 35 : /* Secondary Sort Key Range */
case 36 : /* Global Protection */
case 37 : /* Footer Print */
case 38 : /* Header Print */

```

```

    case 39 : /* Print Setup */
    case 40 : /* Margins */
    case 41 : /* Label Alignment */
    case 42 : /* Borders */
    case 45 : /* Graph Settings */
    case 46 : /* Named Current Graph Settings */
    case 47 : /* Iteration Count */
    case 48 : /* Unformatted print */
    case 49 : /* Cursor Location */
    case 75 : /* Worksheet Password */
    case 100 : /* Hidden Columns Record 1 */
    case 101 : /* Hidden Columns Record 2 */
    case 102 : /* Parse Ranges */
    case 103 : /* Linear Regression Ranges */
    case 105 : /* Matrix Mathematics Ranges */
    case 150 : /* Cell Pointer Index */
        ignore_bytes(length);
        break;
    default : /* Other Code is an Error */
        fprintf(stderr,"ERROR: Opcode %d not defined\n",opcode);
        ignore_bytes(length);
}
return(opcode);
}

/*  FUNCTION: ignore_bytes                                     */
/*  DESCRIPTION:                                             */
/*      Reads and ignores data from the input file.         */

void ignore_bytes(int length)
{
    int i;

    for (i = 0; i < length; ++i)
        getc(Fp);
}

/*  FUNCTION: start_processing                               */
/*  DESCRIPTION:                                             */
/*      Displays message to the user of the type of LOTUS file being read. */

int start_processing(int length)
{
    int i, file_format = 0;

    for (i = 0; i < length; ++i)
        file_format += (getc(Fp) * pow(256,i));
    switch (file_format) {
        case 1028 : /* File type is 1-2-3 */
            poscurs(7,28);

```

```

        fprintf(stderr,"Format type is 1-2-3.");
        return(0);
    case 1029 : /* File type is Symphony - do not process */
        poscurs(7,16);
        fprintf(stderr,"Format type is SYMPHOMY and cannot be processed");
        return(1);
    case 1030 : /* File type is 1-2-3 version 2 */
        poscurs(7,24);
        fprintf(stderr,"Format type is 1-2-3 version 2.");
        return(0);
    default : /* Unknown file type */
        poscurs(7,25);
        fprintf(stderr,"Format type is unknown (%04X).",file_format);
        poscurs(9,29);
        fprintf(stderr,"processing terminated");
        return(1);
}
}

/*  FUNCTION: get_IEEE_real                                     */
/*  DESCRIPTION:                                                */
/*    Converts the input from a 64 bit IEEE real storage into a useable */
/*    form for the program.                                     */
/*

double get_IEEE_real(int row, int col)
{
    int i, j, neg_exp, sign, word;
    double exponent, mantissa, value, one_bit;
    long int temp;

    neg_exp = 52;
    value = 0.;
    for (i = 0; i < 7; ++i) {
        word = 8;
        temp = getc(Fp);
        if (temp != 0) {
            if (i == 6)
                word = 4;
            for(j = 0; j < word; ++j) {
                one_bit = temp & 1;
                value += (one_bit * (1/pow(2,neg_exp)));
                neg_exp -= 1;
                temp = temp >> 1;
            }
        }
        else
            neg_exp -= 8;
    }
    exponent = temp;
    temp = getc(Fp);

```

```

    exponent += ((temp & 15) * 16);
    temp = temp >> 4;
    exponent += ((temp & 7) * 256);
    mantissa = value;
    sign = ((temp >> 3) & 1);
    if (sign == 1)
        sign = -1;
    else
        sign = 1;
    if (exponent == 2047.) {
        if (mantissa != 0.)
            fprintf(stderr, "Value at row %d col %d is not a valid number\n", row, col);
        else
            fprintf(stderr, "Value at row %d col %d is infinity\n", row, col);
        return(NULL);
    }
    if (exponent == 0.) {
        if (mantissa != 0.) {
            exponent = pow(2, -1022.);
            return(sign * exponent * mantissa);
        }
        else
            return(0.);
    }
    if ((exponent > 0.) && (exponent < 2047.)) {
        exponent = pow(2, (exponent-1023.));
        mantissa += 1.;
        return(sign * exponent * mantissa);
    }
    fprintf(stderr, "*** ERROR ** Real format not converted at row %d col %d",
            row, col);
    return(NULL);
}

/*  FUNCTION: factors                                     */
/*  DESCRIPTION:                                         */
/*      Determines the interest factors used in the analysis. */

void factors(char fac_type)
{
    int i;
    float rate;

    rate = 1.;
    switch (fac_type) {
        case 'm' :
            Factors[0] = 1.;

```

```

        for (i = 1; i <= Proj_len; ++i) {
            rate = rate * (1 + interest(fac_type,i-1));
            Factors[i] = 1. / rate;
        }
        break;
    case 'n' :
        Factors[0] = 1.;
        for (i = 1; i <= Proj_len; ++i) {
            rate = rate * (1 + interest(fac_type,i-1));
            Factors[i] = 1. / rate;
        }
        break;
    }
}

/*  FUNCTION: interest                                     */
/*  DESCRIPTION:                                           */
/*    Determines the interest rate to use for the analysis. */

float interest(char fac_type, int limit)
{
    float temp_interest;
    int mult = 0;

    switch (fac_type) {
        case 'm' :
            return Monetary_rate[limit]/100.;
        case 'n' :
            return Nonmonetary_rate[limit]/100.;
    }
}

/*  FUNCTION: npv                                         */
/*  DESCRIPTION:                                           */
/*    Determines the NPV of the Monetary cash flows.      */

npv(int alt)
{
    int j, k;
    double cash_flow;

    factors('m');
    NPV[alt] = 0.;
    depreciation();
    for (k = 0; k <= Proj_len; ++k) {
        cash_flow = 0.;
        for (j = 0; j < Num_attrib.pecuniary; ++j)
            cash_flow += Monetary[j].cash_flow[k];
    }
}

```

```

        if (k != 0)
            cash_flow = (cash_flow * (1 - Tax_rate)) + (Depreciation[k] * Tax_rate);
        NPV[alt] += (cash_flow * Factors[k]);
    }
}

/*  FUNCTION: depreciation                                     */
/*  DESCRIPTION:                                              */
/*      Determines the deprecitation schedule of the investment. */

void depreciation(void)
{
    short int pos = -1;
    int ACRS_limit, i, j;

    for (i = 0; i < Num_attrib.pecuniary; ++i) {
        if (strnicmp(Monetary[i].description,"depr investment",15) == 0) {
            pos = i;
            break;
        }
    }
    if (pos >= 0) {
        for (i = 0; i <= Proj_len; ++i) {
            ACRS_limit = i + ACRS_type + 2;
            if (ACRS_limit > Proj_len)
                ACRS_limit = Proj_len + 1;
            for (j = i+1; j < ACRS_limit; ++j) {
                Depreciation[j] += (-Monetary[pos].cash_flow[i] * ACRS[j-(i+1)]);
            }
        }
    }
}

/*  FUNCTION: npqf                                           */
/*  DESCRIPTION:                                              */
/*      Determines the NPQF of the Nonmonetary cash flows.   */

npqf(char objective, int alt)
{
    int i, j;

    factors('n');
    switch (objective) {
        case 's' :
            for (j = 0; j < Num_attrib.strategic; ++j) {
                NPQF_s[alt][j] = 0.;
                for (i = 1; i <= Proj_len; ++i)
                    NPQF_s[alt][j] += Strategic[j].qual_flow[i] * Factors[i];
            }
            break;
    }
}

```

```

    case 't' :
        for (j = 0; j < Num_attrib.tactical; ++j) {
            NPQF_t[alt][j] = 0.;
            for (i = 1; i <= Proj_len; ++i)
                NPQF_t[alt][j] += Tactical[j].qual_flow[i] * Factors[i];
            }
        break;
    }
}

/*  FUNCTION: norm_weights                                     */
/*  DESCRIPTION:                                              */
/*      Normalizes the weights for the nonmonetary attributes, and the */
/*      objectives.                                           */
void norm_weights(void)
{
    int i;
    float sum;

    sum = 0.;
    for (i = 0; i < 3; ++i)
        sum += Obj_weight[i];
    for (i = 0; i < 3; ++i)
        Obj_weight[i] = (Obj_weight[i] / sum) * 100.;
    sum = 0.;
    for (i = 0; i < Num_attrib.strategic; ++i)
        sum += Strategic[i].weight;
    for (i = 0; i < Num_attrib.strategic; ++i)
        Strategic[i].weight = (Strategic[i].weight / sum) * 100.;
    sum = 0.;
    for (i = 0; i < Num_attrib.tactical; ++i)
        sum += Tactical[i].weight;
    for (i = 0; i < Num_attrib.tactical; ++i)
        Tactical[i].weight = (Tactical[i].weight / sum) * 100.;
}

/*  FUNCTION: indices                                         */
/*  DESCRIPTION:                                              */
/*      Calculates the Monetary and Nonmonetary indices.     */
void indices(int alt)
{
    int i, j;
    float r_ni;

    MI[alt] = NPV[alt] / (NPV_max - NPV_min);
    r_ni = 0.;
    factors('n');
}

```



```

    for (i = 1; i <= Proj_len; ++i)
        r_ni += Factors[i];
    for (i = 0; i < Num_attrib.strategic; ++i)
        NI[alt][i] = NPQF_s[alt][i] / (100. * r_ni);
    j = Num_attrib.strategic + Num_attrib.tactical;
    for (i = Num_attrib.strategic; i < j; ++i)
        NI[alt][i] = NPQF_t[alt][i-Num_attrib.strategic] / (100. * r_ni);
}

/*  FUNCTION: comp_prog                                     */
/*  DESCRIPTION:                                           */
/*    Calculates the Composite Programming score for an alternative. */

double comp_prog(int alt)
{
    int i, j;
    float power, score, term;

    power = Q/P;
    term = 0.;
    score = 100. * distance(MI[alt]);
    score = Obj_weight[0] * pow(score,power);
    for (i = 0; i < Num_attrib.strategic; ++i)
        term += Strategic[i].weight * distance(NI[alt][i]);
    score += Obj_weight[1] * pow(term,power);
    term = 0.;
    j = Num_attrib.strategic + Num_attrib.tactical;
    for (i = Num_attrib.strategic; i < j; ++i)
        term += Tactical[i-Num_attrib.strategic].weight * distance(NI[alt][i]);
    score += Obj_weight[2] * pow(term,power);
    return pow(score,(1./Q));
}

/*  FUNCTION: distance                                     */
/*  DESCRIPTION:                                           */
/*    Calculates the distance an attribute is from the ideal. */

double distance(float term)
{
    float results;

    results = ((1. - term) / 2.);
    return pow(results,P);
}

/*  FUNCTION: echo_inputs                                  */
/*  DESCRIPTION:                                           */
/*    Prints the inputs to the program specified by the user. */

```

```

void echo_inputs()
{
    int j;

    Out = fopen("amstep.inp","w");
    if (Out == NULL) {
        fprintf(stderr,"\nERROR: opening AMSTEP.OUT\n");
        exit(1);
    }

    fprintf(Out,"%s\n",Title);
    fprintf(Out,"Tax rate %5.2f\n",Tax_rate*100.);
    fprintf(Out,"Project Length %d\n",Proj_len);
    fprintf(Out,"ACRS Type %d ",ACRS_type);
    fprintf(Out,"\nMonetary Rate ");
    for (j = 0; j < Proj_len; ++j)
        fprintf(Out,"%5.2f ",Monetary_rate[j]);
    fprintf(Out,"\n");
    fprintf(Out,"Nonmonetary Rate ");
    for (j = 0; j < Proj_len; ++j)
        fprintf(Out,"%5.2f ",Nonmonetary_rate[j]);
    fprintf(Out,"\n");
    fprintf(Out,"Pecuniary Weight %4.1f\n",Obj_weight[0]);
    fprintf(Out,"Strategic Weight %4.1f\n",Obj_weight[1]);
    fprintf(Out,"Tactical Weight %4.1f\n",Obj_weight[2]);
    fprintf(Out,"NPV min %12.2f\n",NPV_min);
    fprintf(Out,"NPV max %12.2f\n\n",NPV_max);
    fclose(Out);
}

/*  FUNCTION: print_array                                     */
/*  DESCRIPTION:                                             */
/*    Prints the contents of the arrays containing cash flows and */
/*    qualitative flows.                                     */
/*  */

void print_array(int alt)
{
    int i, j, k;
    char digit[4], filename[14];

    itoa(alt,digit,10);
    Prefix_name[6] = digit[0];
    Prefix_name[7] = '\0';
    strcpy(filename,Prefix_name);
    Out = fopen(strncat(filename,".res",4),"w");
    if (Out == NULL) {
        fprintf(stderr,"\nERROR: opening %s\n",filename);
        exit(1);
    }
    fprintf(Out,"%25s\n",Alt_title[alt]);
    fprintf(Out,"\nPECUNIARY");

```

```

for (k = 0; k < Num_attrib.pecuniary; ++k) {
    fprintf(Out, "\n%15s", Monetary[k].description);
    for (j = 0; j <= Proj_len; ++j)
        fprintf(Out, "\t%15.2f", Monetary[k].cash_flow[j]);
}
fprintf(Out, "\n  Depreciation");
for (j = 0; j <= Proj_len; ++j)
    fprintf(Out, "\t%15.2f", Depreciation[j]);
fprintf(Out, "\n\nSTRATEGIC");
for (k = 0; k < Num_attrib.strategic; ++k) {
    fprintf(Out, "\n%20s ", Strategic[k].attribute);
    fprintf(Out, "%4.0f ", Strategic[k].weight);
    for (j = 0; j <= Proj_len; ++j)
        fprintf(Out, "\t%8.0f", Strategic[k].qual_flow[j]);
}
fprintf(Out, "\n\nTACTICAL");
for (k = 0; k < Num_attrib.tactical; ++k) {
    fprintf(Out, "\n%20s ", Tactical[k].attribute);
    fprintf(Out, "%4.0f ", Tactical[k].weight);
    for (j = 0; j <= Proj_len; ++j)
        fprintf(Out, "\t%8.0f", Tactical[k].qual_flow[j]);
}
fprintf(Out, "\n\n");
/* */
fprintf(Out, "Alterntaive %d\n\n", alt);
fprintf(Out, "Net Present Value \t%12.2f\n", NPV[alt]);
fprintf(Out, "Net Present Qualitative Flows\n");
for (k = 0; k < Num_attrib.strategic; ++k)
    fprintf(Out, "%20s \t %7.2f\n", Strategic[k].attribute, NPQF_s[alt][k]);
for (k = 0; k < Num_attrib.tactical; ++k)
    fprintf(Out, "%20s \t %7.2f\n", Tactical[k].attribute, NPQF_t[alt][k]);
fprintf(Out, "\nMoneatry Index \t\t%8.4f\n", MI[alt]);
fprintf(Out, "Nonmonetary Indices\n");
for (k = 0; k < Num_attrib.strategic; ++k)
    fprintf(Out, "%20s \t %6.4f\n", Strategic[k].attribute, NI[alt][k]);
for (k = 0; k < Num_attrib.tactical; ++k)
    fprintf(Out, "%20s \t %6.4f\n", Tactical[k].attribute,
        NI[alt][k+Num_attrib.strategic]);
fprintf(Out, "\nScore: %4.0f\n", Score[alt]);
fclose(Out);
}

/*  FUNCTION: rankings                                     */
/*  DESCRIPTION:                                           */
/*  Determines the final rankings of the alternatives.     */
/*                                                         */

void rankings(void)
{
    int i, j, pos;
    float large = 1000000., temp;

```

```

struct {
    int pos;
    float score;
} rank[MAX_ALTS];

for (j = 0; j < Num_alts; ++j) {
    temp = Score[0];
    for (i = 0; i < Num_alts; ++i) {
        if (Score[i] <= temp) {
            temp = Score[i];
            pos = i;
        }
    }
    Score[pos] = large;
    rank[j].pos = pos;
    rank[j].score = temp;
}

clrscrn();
poscurs(5,30);
fprintf(stderr,"<< FINAL RANKINGS >>");
poscurs(7,21);
fprintf(stderr,"RANK          ALTERNATIVE          SCORE");
poscurs(8,21);
fprintf(stderr,"----          -----          -----");
for (i = 0; i < Num_alts; ++i) {
    poscurs(10+i,22);
    fprintf(stderr,"%d",i+1);
    poscurs(10+i,27);
    j = rank[i].pos;
    fprintf(stderr,"%s",Alt_title[j]);
    poscurs(10+i,54);
    fprintf(stderr,"%5.1f",rank[i].score);
}
}

```

Appendix C

Mixture Experiments

This appendix provides a background on the methodology of mixture experiments and is largely taken from Cornell [26]. Additional information can also be found in [27].

The primary objective of a mixture experiment is to study the effects of a set of components on a measurable response in order to determine the composition of the components which produces an optimal response. The purpose of the mixture experiment within this research is to obtain some measure of the effect which each weight (component) has on the evaluation score (response). The components are taken singly and in combination with other components.

In a mixture experiment, the experimental region is all of the points of a regular $(r - 1)$ -dimensional simplex, where r is the number of components. When $r = 2$ components, the experimental region is a line in two dimensional space. When $r = 3$, the experimental region is an equilateral triangle as shown in Figure C.1. For four components ($r = 4$) the experimental region is a tetrahedron as shown in Figure C.2.

The coordinate system of a mixture problem is referred to as a simplex coordinate system. When $r = 3$, the coordinates can be plotted on triangular graph paper. The vertices of the triangle represent pure components. The interior points of the triangle represent mixtures which include a portion of all three components. For example, the centroid of the triangle is the point where the mixture is made up of equal proportions of all three components.

For mixture experiments, it is assumed that there exists a relationship

$$\eta = \Psi(x_1, x_2, \dots, x_r)$$

Figure C.1: Simplex Triangle Experimental Region

Figure C.2: Simplex Tetrahedron Experimental Region

which defines the dependence of the response η on the proportions of $x_1, x_2, \dots, x_r$ of the r components, where

$$\begin{aligned} x_i &\geq 0 \quad i = 1, \dots, r \\ \sum_{i=1}^r x_i &= 1 \end{aligned}$$

The response function of a system containing r components can be modeled as first-degree polynomial such as:

$$\eta = b_0 + \sum_{i=1}^r b_i x_i$$

or a second-degree polynomial such as :

$$\eta = b_0 + \sum_{i=1}^r b_i x_i + \sum_{i,j=1}^r b_{ij} x_i x_j$$

Although a cubic equation may be used, most mixture experiments are reparameterized forms of these general polynomials.

In a mixture experiment, the experimental program consists of N observations of the value of a response. Each response is observed from a known set of components, and usually more than one response is observed for each component mixture. The observed value of the response is y_u and it is assumed that y_u in the u^{th} trial varies about a mean of η with common variance σ^2 for all $u = 1, 2, \dots, N$. The observed value is fully denoted by

$$y_u = \eta + \epsilon_u \quad 1 \leq u \leq N$$

where ϵ_u is an experimental error. ϵ_u is assumed to be uncorrelated, identically distributed with mean zero and common variance σ^2 . Thus, $E(y_u) = \eta$ for all $u = 1, 2, \dots, N$.

The design used to support a polynomial equation which represents the response over an entire simplex region is the simplex-centroid. The simplex-centroid

Figure C.3: Design Points of the Simplex-Centroid for $r = 3$

design for r components consists of $2^r - 1$ design points. The points consist of the r pure blends, $\binom{r}{2}$ permutations of $(y_1, y_2, 0, 0, \dots)$, $\binom{r}{3}$ permutations of $(y_1, y_2, y_3, 0, 0, \dots)$, etc., until $(y_r, y_r, \dots, y_r)$. These points are shown in Figure C.3 for $r = 3$.

Cornell derives the polynomial model which can be fitted to the data collected at the design points of the simplex-centroid as follows [26]. Assume a model for two components, x_1 and x_2 , where $x_1 + x_2 = 1$. The first degree model is written as:

$$\eta = b_0 + b_1x_1 + b_2x_2$$

Replace b_0 with $b_0(x_1 + x_2)$:

$$\begin{aligned} \eta &= b_0(x_1 + x_2) + b_1x_1 + b_2x_2 \\ &= (b_0 + b_1)x_1 + (b_0 + b_2)x_2 \\ &= b'_1x_1 + b'_2x_2 \end{aligned}$$

In this manner, the constant term b_0 has been removed from the model. For a second-degree polynomial, replace b_0 with $b_0(x_1 + x_2)$, x_1^2 with $x_1(1 - x_2)$, and x_2^2 with $x_2(1 - x_1)$. This yields:

$$\begin{aligned}\eta &= b_0(x_1 + x_2) + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1(1 - x_2) + b_{22}x_2(1 - x_1) \\ &= (b_0 + b_1 + b_{11})x_1 + (b_0 + b_2 + b_{22})x_2 + (b_{12} - b_{11} - b_{22})x_1x_2 \\ &= b'_1x_1 + b'_2x_2 + b'_{12}x_1x_2\end{aligned}$$

and the terms $b_{11}x_1^2$ and $b_{22}x_2^2$ are removed from the model, along with b_0 . Therefore, the polynomial model of the simplex-centroid, with primes removed from the b_i 's, is:

$$\eta = \sum_{i=1}^r b_i x_i + \sum_{\substack{i,j=1 \\ i < j}}^r b_{ij} x_i x_j + \sum_{\substack{i,j,k=1 \\ i < j < k}}^r b_{ijk} x_i x_j x_k + \cdots + b_{12\dots r} \prod_{i=1}^r x_i \quad (\text{C.1})$$

The parameter b_i is the expected response to the pure component i . b_{ij} is the contrast of the responses to blends of two components, b_{ijk} is the contrast of the responses to blends of three components, etc. Note that the mixture model has fewer terms than the standard polynomial.

When values of the response are collected only at the points of the simplex-centroid, the estimators of the coefficients are simple functions of the observed values of the response. For example, let y_i be the observed value of the response to the pure component i ($x_i = 1, x_j = 0, i \neq j$), and y_{ij} the observed value of the response to the equal 50-50 mixture of components i and j ($x_i = \frac{1}{2}, x_j = \frac{1}{2}, x_k = 0, i < j < k$). Suppose n_i observations are collected for the pure components and n_{ij} observations for the 50-50 mixture, and the average responses for these observed values are denoted by $\bar{y}_i$ and $\bar{y}_{ij}$ respectively. Now, the formulas for calculating the estimates of the coefficients ($\hat{b}_i, \hat{b}_{ij}$) for a second-degree model are

determined by substituting the values of $\bar{y}_i$, $\bar{y}_{ij}$, and x_i into a second-degree form of equation C.1.

As an example, consider an experiment of two components ($r = 2$). Observations are collected at the following (x_1, x_2) points: $(1,0)$, $(0,1)$, and $(\frac{1}{2}, \frac{1}{2})$. The average response for the pure component x_1 is $\bar{y}_1 = 1\hat{b}_1 + 0\hat{b}_2$ and for the pure component x_2 is $\bar{y}_2 = 0\hat{b}_1 + 1\hat{b}_2$ where $\hat{b}$ is the estimate of b . For the mixture $(\frac{1}{2}, \frac{1}{2})$ the observed response is $\bar{y}_{12} = \frac{1}{2}b_1 + \frac{1}{2}b_2 + (\frac{1}{2})^2b_{12}$. Solving these equations for $\hat{b}_1$, $\hat{b}_2$, and $\hat{b}_{12}$ yields:

$$\begin{aligned}\hat{b}_1 &= \bar{y}_1 \\ \hat{b}_2 &= \bar{y}_2 \\ \hat{b}_{12} &= 4\bar{y}_{12} - 2(\bar{y}_1 + \bar{y}_2)\end{aligned}$$

Cornell provides formulas for up to $r = 4$ [26]. The polynomial for $r = 4$ is:

$$\eta = \sum_{i=1}^4 b_i x_i + \sum_{\substack{i,j=1 \\ i < j}}^4 b_{ij} x_i x_j + \sum_{\substack{i,j,k=1 \\ i < j < k}}^4 b_{ijk} x_i x_j x_k + b_{1234} x_1 x_2 x_3 x_4$$

The observed data values are:

$$\begin{array}{llll} y_i & \text{at} & x_i = 1, x_j = 0 & j \neq i \\ y_{ij} & \text{at} & x_i = x_j = \frac{1}{2}, x_k = 0 & i < j, k \neq i, j \\ y_{ijk} & \text{at} & x_i = x_j = x_k = \frac{1}{3}, x_l = 0 & i < j < k, l \neq i, j, k \\ y_{ijkl} & \text{at} & x_i = x_j = x_k = x_l = \frac{1}{4} & \end{array}$$

where $i, j, k = 1, 2, 3, 4$. The coefficient estimates are calculated using:

$$\begin{aligned}\hat{b}_i &= \bar{y}_i \quad i < j \\ \hat{b}_{ij} &= 4\bar{y}_{ij} - 2(\bar{y}_i + \bar{y}_j) \quad i < j \\ \hat{b}_{ijk} &= 27\bar{y}_{ijk} - 12(\bar{y}_{ij} + \bar{y}_{ik} + \bar{y}_{jk}) + 3(\bar{y}_i + \bar{y}_j + \bar{y}_k) \quad i < j < k \\ \hat{b}_{1234} &= 256\bar{y}_{1234} - 108(\bar{y}_{123} + \bar{y}_{124} + \bar{y}_{134} + \bar{y}_{234}) + \\ &\quad 32(\bar{y}_{12} + \bar{y}_{13} + \bar{y}_{14} + \bar{y}_{23} + \bar{y}_{24} + \bar{y}_{34}) - 4(\bar{y}_1 + \bar{y}_2 + \bar{y}_3 + \bar{y}_4)\end{aligned}$$

Appendix D

Simplex-Centroid Design for Six Components

Formulas for calculating the coefficient estimates of the simplex-centroid design for up to four components are provided by Cornell [26] and were given in Appendix C. Using the methodology described in Appendix C, formulas for calculations of the simplex-centroid design for five and six components are provided in this appendix.

The polynomial model which is fitted to the data collected at the design points for $r = 5$ is:

$$\eta = \sum_{i=1}^5 b_i x_i + \sum_{\substack{i,j=1 \\ i < j}}^5 b_{ij} x_i x_j + \sum_{\substack{i,j,k=1 \\ i < j < k}}^5 b_{ijk} x_i x_j x_k + \sum_{\substack{i,j,k,l=1 \\ i < j < k < l}}^5 b_{ijkl} x_i x_j x_k x_l + b_{12345} x_1 x_2 x_3 x_4 x_5 \quad (\text{D.1})$$

Observations are made only at the points of the simplex-centroid design. The observed data values are collected as follows, where $i, j, k, l, m \in [1, 2, 3, 4, 5]$:

$$\begin{aligned} y_i & \text{ at } x_i = 1, \quad x_j = 0 \\ & j \neq i \\ y_{ij} & \text{ at } x_i = x_j = \frac{1}{2}, \quad x_k = 0 \\ & i < j \quad k \neq i, j \\ y_{ijk} & \text{ at } x_i = x_j = x_k = \frac{1}{3}, \quad x_l = 0 \\ & i < j < k, \quad l \neq i, j, k \\ y_{ijkl} & \text{ at } x_i = x_j = x_k = x_l = \frac{1}{4}, \quad x_m = 0 \\ & i < j < k < l, \quad m \neq i, j, k, l \end{aligned}$$

$$y_{ijklm} \quad \text{at} \quad x_i = x_j = x_k = x_l = x_m = \frac{1}{5}$$

Let $\bar{y}_i$, $\bar{y}_{ij}$, $\bar{y}_{ijk}$, $\bar{y}_{ijkl}$, and $\bar{y}_{ijklm}$ be the average values of the responses described above. Substituting the $\bar{y}$'s and x 's into equation D.1 yields:

$$\begin{aligned} \bar{y}_{ijklm} = & \left(\frac{1}{5}\right)(\hat{b}_i + \hat{b}_j + \hat{b}_k + \hat{b}_l + \hat{b}_m) + \\ & \left(\frac{1}{5}\right)^2(\hat{b}_{ij} + \hat{b}_{ik} + \hat{b}_{il} + \hat{b}_{im} + \hat{b}_{jk} + \hat{b}_{jl} + \hat{b}_{jm} + \hat{b}_{kl} + \hat{b}_{km} + \hat{b}_{lm}) + \\ & \left(\frac{1}{5}\right)^3(\hat{b}_{ijk} + \hat{b}_{ijl} + \hat{b}_{ijm} + \hat{b}_{ikl} + \hat{b}_{ikm} + \hat{b}_{ilm} + \hat{b}_{jkl} + \hat{b}_{jkm} + \\ & \quad \hat{b}_{jlm} + \hat{b}_{klm}) + \\ & \left(\frac{1}{5}\right)^4(\hat{b}_{ijkl} + \hat{b}_{ijkm} + \hat{b}_{ijlm} + \hat{b}_{iklm} + \hat{b}_{jklm}) + \\ & \left(\frac{1}{5}\right)^5(\hat{b}_{ijklm}) \end{aligned}$$

Rewriting to solve for $\hat{b}_{ijklm}$:

$$\begin{aligned} \hat{b}_{ijklm} = & 3125\bar{y}_{ijklm} - \\ & 625(\hat{b}_i + \hat{b}_j + \hat{b}_k + \hat{b}_l + \hat{b}_m) + \\ & 125(\hat{b}_{ij} + \hat{b}_{ik} + \hat{b}_{il} + \hat{b}_{im} + \hat{b}_{jk} + \hat{b}_{jl} + \hat{b}_{jm} + \hat{b}_{kl} + \hat{b}_{km} + \hat{b}_{lm}) + \\ & 25(\hat{b}_{ijk} + \hat{b}_{ijl} + \hat{b}_{ijm} + \hat{b}_{ikl} + \hat{b}_{ikm} + \hat{b}_{ilm} + \hat{b}_{jkl} + \hat{b}_{jkm} + \\ & \quad \hat{b}_{jlm} + \hat{b}_{klm}) + \\ & 5(\hat{b}_{ijkl} + \hat{b}_{ijkm} + \hat{b}_{ijlm} + \hat{b}_{iklm} + \hat{b}_{jklm}) \end{aligned}$$

Each $\hat{b}$ term is expanded according to its known polynomial form from Appendix C. For example, $\hat{b}_i = \bar{y}_i$ and $\hat{b}_{ij} = 4\bar{y}_{ij} - 2(\bar{y}_i + \bar{y}_j)$. Using these relationships, the simplex-centroid model for five components is:

$$\begin{aligned} \hat{b}_{ijklm} = & 3125\bar{y}_{ijklm} - \\ & 1280(\bar{y}_{ijkl} + \bar{y}_{ijkm} + \bar{y}_{ijlm} + \bar{y}_{iklm} + \bar{y}_{jklm}) + \end{aligned}$$

$$\begin{aligned}
& 405(\bar{y}_{ijk} + \bar{y}_{ijl} + \bar{y}_{ijm} + \bar{y}_{ikl} + \bar{y}_{ikm} + \bar{y}_{ilm} + \bar{y}_{jkl} + \bar{y}_{jkm} + \\
& \quad \bar{y}_{jlm} + \bar{y}_{klm}) - \\
& 80(\bar{y}_{ij} + \bar{y}_{ik} + \bar{y}_{il} + \bar{y}_{im} + \bar{y}_{jk} + \bar{y}_{jl} + \bar{y}_{jm} + \bar{y}_{kl} + \bar{y}_{km} + \bar{y}_{lm}) + \\
& 5(\bar{y}_i + \bar{y}_j + \bar{y}_k + \bar{y}_l + \bar{y}_m)
\end{aligned}$$

For six components ($r = 6$) the polynomial model which is fitted to the data collected is:

$$\begin{aligned}
\eta = & \sum_{i=1}^6 b_i x_i + \sum_{\substack{i,j=1 \\ i < j}}^6 b_{ij} x_i x_j + \sum_{\substack{i,j,k=1 \\ i < j < k}}^6 b_{ijk} x_i x_j x_k + \sum_{\substack{i,j,k,l=1 \\ i < j < k < l}}^6 b_{ijkl} x_i x_j x_k x_l + \\
& \sum_{\substack{i,j,k,l,m=1 \\ i < j < k < l < m}}^6 b_{ijklm} x_i x_j x_k x_l x_m + b_{123456} x_1 x_2 x_3 x_4 x_5 x_6
\end{aligned} \tag{D.2}$$

Observations are again made only at the points of the simplex-centroid design. The observed data values collected are the same as for the five component model, with the following modification to the term y_{ijklm} and the addition of the term y_{ijklmn} where $i, j, k, l, m, n \in [1, 2, 3, 4, 5, 6]$:

$$\begin{aligned}
y_{ijklm} \quad \text{at} \quad x_i = x_j = x_k = x_l = x_m = \frac{1}{5}, \quad x_n = 0 \\
i < j < k < l < m, \quad n \neq i, j, k, l, m \\
y_{ijklmn} \quad \text{at} \quad x_i = x_j = x_k = x_l = x_m = x_n = \frac{1}{6}
\end{aligned}$$

Let $\bar{y}_i$, $\bar{y}_{ij}$, $\bar{y}_{ijk}$, $\bar{y}_{ijkl}$, $\bar{y}_{ijklm}$, and $\bar{y}_{ijklmn}$ be the average values of the responses described above. Substituting the $\bar{y}$'s and x 's into equation D.2 yields:

$$\begin{aligned}
\bar{y}_{ijklmn} = & \left(\frac{1}{6}\right) (\hat{b}_i + \hat{b}_j + \hat{b}_k + \hat{b}_l + \hat{b}_m + \hat{b}_n) + \\
& \left(\frac{1}{6}\right)^2 (\hat{b}_{ij} + \hat{b}_{ik} + \hat{b}_{il} + \hat{b}_{im} + \hat{b}_{in} + \hat{b}_{jk} + \hat{b}_{jl} + \hat{b}_{jm} + \hat{b}_{jn} + \\
& \hat{b}_{kl} + \hat{b}_{km} + \hat{b}_{kn} + \hat{b}_{lm} + \hat{b}_{ln} + \hat{b}_{mn}) +
\end{aligned}$$

$$\begin{aligned}
& \left(\frac{1}{6}\right)^3 (\hat{b}_{ijk} + \hat{b}_{ijl} + \hat{b}_{ijm} + \hat{b}_{ijn} + \hat{b}_{ikl} + \hat{b}_{ikm} + \hat{b}_{ikn} + \hat{b}_{ilm} + \\
& \quad \hat{b}_{iln} + \hat{b}_{imn} + \hat{b}_{jkl} + \hat{b}_{jkm} + \hat{b}_{jkn} + \hat{b}_{jlm} + \hat{b}_{jln} + \hat{b}_{jmn} + \\
& \quad \hat{b}_{klm} + \hat{b}_{kln} + \hat{b}_{kmn} + \hat{b}_{lmn}) + \\
& \left(\frac{1}{6}\right)^4 (\hat{b}_{ijkl} + \hat{b}_{ijkm} + \hat{b}_{ijkn} + \hat{b}_{ijlm} + \hat{b}_{ijln} + \hat{b}_{ijmn} + \hat{b}_{iklm} + \\
& \quad \hat{b}_{ikln} + \hat{b}_{ikmn} + \hat{b}_{jklm} + \hat{b}_{jkl n} + \hat{b}_{jkmn} + \hat{b}_{jlmn} + \hat{b}_{klmn}) + \\
& \left(\frac{1}{6}\right)^5 (\hat{b}_{ijklm} + \hat{b}_{ijkln} + \hat{b}_{ijkmn} + \hat{b}_{ijlmn} + \hat{b}_{iklmn} + \hat{b}_{jklmn}) + \\
& \left(\frac{1}{6}\right)^6 (\hat{b}_{ijklmn})
\end{aligned}$$

Solving for $\hat{b}_{ijklmn}$:

$$\begin{aligned}
\hat{b}_{ijklmn} = & 46656\bar{y}_{ijklm} - \\
& 7776(\hat{b}_i + \hat{b}_j + \hat{b}_k + \hat{b}_l + \hat{b}_m + \hat{b}_n) + \\
& 1296(\hat{b}_{ij} + \hat{b}_{ik} + \hat{b}_{il} + \hat{b}_{im} + \hat{b}_{in} + \hat{b}_{jk} + \hat{b}_{jl} + \hat{b}_{jm} + \hat{b}_{jn} + \\
& \quad \hat{b}_{kl} + \hat{b}_{km} + \hat{b}_{kn} + \hat{b}_{lm} + \hat{b}_{ln} + \hat{b}_{mn}) + \\
& 216(\hat{b}_{ijk} + \hat{b}_{ijl} + \hat{b}_{ijm} + \hat{b}_{ijn} + \hat{b}_{ikl} + \hat{b}_{ikm} + \hat{b}_{ikn} + \hat{b}_{ilm} + \\
& \quad \hat{b}_{iln} + \hat{b}_{imn} + \hat{b}_{jkl} + \hat{b}_{jkm} + \hat{b}_{jkn} + \hat{b}_{jlm} + \hat{b}_{jln} + \hat{b}_{jmn} + \\
& \quad \hat{b}_{klm} + \hat{b}_{kln} + \hat{b}_{kmn} + \hat{b}_{lmn}) + \\
& 36(\hat{b}_{ijkl} + \hat{b}_{ijkm} + \hat{b}_{ijkn} + \hat{b}_{ijlm} + \hat{b}_{ijln} + \hat{b}_{ijmn} + \hat{b}_{iklm} + \\
& \quad \hat{b}_{ikln} + \hat{b}_{ikmn} + \hat{b}_{jklm} + \hat{b}_{jkl n} + \hat{b}_{jkmn} + \hat{b}_{jlmn} + \hat{b}_{klmn}) + \\
& 6(\hat{b}_{ijklm} + \hat{b}_{ijkln} + \hat{b}_{ijkmn} + \hat{b}_{ijlmn} + \hat{b}_{iklmn} + \hat{b}_{jklmn})
\end{aligned}$$

Expanding each term according to its known polynomial form from Appendix C and the previously derived five component form yields the simplex-centroid model for six components:

$$\hat{b}_{ijklmn} = 46656\bar{y}_{ijklmn} -$$

$$\begin{aligned}
& 18750(\bar{y}_{ijklm} + \bar{y}_{ijkln} + \bar{y}_{ijkmn} + \bar{y}_{ijlmn} + \bar{y}_{iklmn} + \bar{y}_{jklmn}) + \\
& 6144(\bar{y}_{ijkl} + \bar{y}_{ijkm} + \bar{y}_{ijkn} + \bar{y}_{ijlm} + \bar{y}_{ijln} + \bar{y}_{ijmn} + \bar{y}_{iklm} + \\
& \quad \bar{y}_{ikln} + \bar{y}_{ikmn} + \bar{y}_{jklm} + \bar{y}_{jkl n} + \bar{y}_{jkmn} + \bar{y}_{jlmn} + \bar{y}_{klmn}) - \\
& 1458(\bar{y}_{ijk} + \bar{y}_{ijl} + \bar{y}_{ijm} + \bar{y}_{ijn} + \bar{y}_{ikl} + \bar{y}_{ikm} + \bar{y}_{ikn} + \bar{y}_{ilm} + \\
& \quad \bar{y}_{iln} + \bar{y}_{imn} + \bar{y}_{jkl} + \bar{y}_{jkm} + \bar{y}_{jkn} + \bar{y}_{jlm} + \bar{y}_{jln} + \bar{y}_{jmn} + \\
& \quad \bar{y}_{klm} + \bar{y}_{kln} + \bar{y}_{kmn} + \bar{y}_{lmn}) + \\
& 192(\bar{y}_{ij} + \bar{y}_{ik} + \bar{y}_{il} + \bar{y}_{im} + \bar{y}_{in} + \bar{y}_{jk} + \bar{y}_{jl} + \bar{y}_{jm} + \bar{y}_{jn} + \\
& \quad \bar{y}_{kl} + \bar{y}_{km} + \bar{y}_{kn} + \bar{y}_{lm} + \bar{y}_{ln} + \bar{y}_{mn}) + \\
& 6(\bar{y}_i + \bar{y}_j + \bar{y}_k + \bar{y}_l + \bar{y}_m + \bar{y}_n)
\end{aligned}$$

D.1 Fitted Simplex-Centroid Model for Six Components

Recall that α_{nk} is the weighting factor for the importance of the attributes/elements of the Strategic or Tactical objective in the model. The following simplex-centroid models were derived using the data presented in Table 3.17 and 3.18. The fitted simplex-centroid model for six components for the Strategic objective ($n = 2$) of the Semi-Automatic alternative is:

$$\begin{aligned}
\hat{y}_{semi-auto.} = & 35.3\alpha_{21} + 34.8\alpha_{22} + 31.9\alpha_{23} + 35.7\alpha_{24} + 31.1\alpha_{25} + 32.9\alpha_{26} + \\
& 0.2\alpha_{21}\alpha_{22} + 0.4\alpha_{21}\alpha_{23} + 0\alpha_{21}\alpha_{24} + 0.8\alpha_{21}\alpha_{25} + 0.4\alpha_{21}\alpha_{26} + \\
& 0.2\alpha_{22}\alpha_{23} + 0.2\alpha_{22}\alpha_{24} + 0.6\alpha_{22}\alpha_{25} + 0.2\alpha_{22}\alpha_{26} + 0.8\alpha_{23}\alpha_{24} + \\
& 0\alpha_{23}\alpha_{25} + 0\alpha_{23}\alpha_{26} + 0.8\alpha_{24}\alpha_{25} + 0.4\alpha_{24}\alpha_{26} + 0\alpha_{25}\alpha_{26} - \\
& 24.9\alpha_{21}\alpha_{22}\alpha_{23} - 44.1\alpha_{21}\alpha_{22}\alpha_{24} - 0.3\alpha_{21}\alpha_{22}\alpha_{25} - 0.6\alpha_{21}\alpha_{22}\alpha_{26} - \\
& 0.9\alpha_{21}\alpha_{23}\alpha_{24} + 0\alpha_{21}\alpha_{23}\alpha_{25} + 1.2\alpha_{21}\alpha_{23}\alpha_{26} - 0.3\alpha_{21}\alpha_{24}\alpha_{25} -
\end{aligned}$$

$$\begin{aligned}
& 0.6\alpha_{21}\alpha_{24}\alpha_{26} - 0.9\alpha_{21}\alpha_{25}\alpha_{26} + 0.9\alpha_{22}\alpha_{23}\alpha_{24} + 0.3\alpha_{22}\alpha_{23}\alpha_{25} + \\
& 1.5\alpha_{22}\alpha_{23}\alpha_{26} - 1.2\alpha_{22}\alpha_{24}\alpha_{25} - 1.5\alpha_{22}\alpha_{24}\alpha_{26} - 0.6\alpha_{22}\alpha_{25}\alpha_{26} + \\
& 0.6\alpha_{23}\alpha_{24}\alpha_{25} - 0.9\alpha_{23}\alpha_{24}\alpha_{26} + 0.9\alpha_{23}\alpha_{25}\alpha_{26} + 0.9\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 9.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24} - 4.4\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25} - 14.4\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{26} + \\
& 11.6\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25} - 4.0\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{26} - 6.4\alpha_{21}\alpha_{22}\alpha_{25}\alpha_{26} + \\
& 8.8\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25} + 11.2\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{26} - 4.8\alpha_{21}\alpha_{23}\alpha_{25}\alpha_{26} + \\
& 3.6\alpha_{21}\alpha_{24}\alpha_{25}\alpha_{26} - 12.0\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} - 9.6\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} - \\
& 18.0\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 19.2\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} - 12.4\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 12.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} + 46.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} + \\
& 149.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 2.5\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 107.0\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + 116.5\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 2018.4\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26}
\end{aligned}$$

The fitted simplex-centroid model for 6 components for the Strategic objective ($n = 2$) of the Automatic alternative is:

$$\begin{aligned}
\hat{y}_{automatic} = & 34.5\alpha_{21} + 31.3\alpha_{22} + 25.8\alpha_{23} + 32.0\alpha_{24} + 26.7\alpha_{25} + 27.0\alpha_{26} + \\
& 0.4\alpha_{21}\alpha_{22} + 3.8\alpha_{21}\alpha_{23} + 0.2\alpha_{21}\alpha_{24} + 2.8\alpha_{21}\alpha_{25} + 2.6\alpha_{21}\alpha_{26} + \\
& 1.8\alpha_{22}\alpha_{23} - 0.2\alpha_{22}\alpha_{24} + 1.2\alpha_{22}\alpha_{25} + 1.0\alpha_{22}\alpha_{26} + 2.4\alpha_{23}\alpha_{24} + \\
& 0.2\alpha_{23}\alpha_{25} + 0\alpha_{23}\alpha_{26} + 1.4\alpha_{24}\alpha_{25} + 1.2\alpha_{24}\alpha_{26} - 0.2\alpha_{25}\alpha_{26} - \\
& 51.6\alpha_{21}\alpha_{22}\alpha_{23} + 59.1\alpha_{21}\alpha_{22}\alpha_{24} - 0.6\alpha_{21}\alpha_{22}\alpha_{25} + 0.6\alpha_{21}\alpha_{22}\alpha_{26} - \\
& 2.1\alpha_{21}\alpha_{23}\alpha_{24} + 3.9\alpha_{21}\alpha_{23}\alpha_{25} + 2.4\alpha_{21}\alpha_{23}\alpha_{26} + 1.2\alpha_{21}\alpha_{24}\alpha_{25} - \\
& 0.3\alpha_{21}\alpha_{24}\alpha_{26} + 3.3\alpha_{21}\alpha_{25}\alpha_{26} - 1.2\alpha_{22}\alpha_{23}\alpha_{24} + 0.3\alpha_{22}\alpha_{23}\alpha_{25} + \\
& 1.5\alpha_{22}\alpha_{23}\alpha_{26} + 0.9\alpha_{22}\alpha_{24}\alpha_{25} - 0.6\alpha_{22}\alpha_{24}\alpha_{26} + 1.2\alpha_{22}\alpha_{25}\alpha_{26} - \\
& 0.3\alpha_{23}\alpha_{24}\alpha_{25} + 0.9\alpha_{23}\alpha_{24}\alpha_{26} + 0\alpha_{23}\alpha_{25}\alpha_{26} + 1.8\alpha_{24}\alpha_{25}\alpha_{26} +
\end{aligned}$$

$$\begin{aligned}
& 0.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24} + 8.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25} + 4.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{26} - \\
& 8.8\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25} - 11.2\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{26} - 8.4\alpha_{21}\alpha_{22}\alpha_{25}\alpha_{26} - \\
& 17.2\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25} + 6.0\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{26} - 6.4\alpha_{21}\alpha_{23}\alpha_{25}\alpha_{26} - \\
& 11.2\alpha_{21}\alpha_{24}\alpha_{25}\alpha_{26} + 7.6\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} - 5.6\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} + \\
& 0.8\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 6.0\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + 19.2\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 104.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} + 171.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} + \\
& 41.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 205.5\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + \\
& 165.5\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + 22.5\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 3639.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26}
\end{aligned}$$

The fitted simplex-centroid model for six components for the Tactical objective ($n = 3$) of the Manual alternative is:

$$\begin{aligned}
\hat{y}_{manual} = & 30.3\alpha_{31} + 32.1\alpha_{32} + 33.6\alpha_{33} + 42.9\alpha_{34} + 33.0\alpha_{35} + 30.7\alpha_{36} + \\
& 0.4\alpha_{31}\alpha_{32} + 0.6\alpha_{31}\alpha_{33} + 4.8\alpha_{31}\alpha_{34} + 0.2\alpha_{31}\alpha_{35} + 0\alpha_{31}\alpha_{36} + \\
& 0.2\alpha_{32}\alpha_{33} + 3.6\alpha_{32}\alpha_{34} + 0.2\alpha_{32}\alpha_{35} + 0\alpha_{32}\alpha_{36} + 2.6\alpha_{33}\alpha_{34} + \\
& 0\alpha_{33}\alpha_{35} + 0.2\alpha_{33}\alpha_{36} + 2.6\alpha_{34}\alpha_{35} + 4.4\alpha_{34}\alpha_{36} + 0.2\alpha_{35}\alpha_{36} - \\
& 59.7\alpha_{31}\alpha_{32}\alpha_{33} + 135.0\alpha_{31}\alpha_{32}\alpha_{34} + 0.3\alpha_{31}\alpha_{32}\alpha_{35} + 0.6\alpha_{31}\alpha_{32}\alpha_{36} + \\
& 0.3\alpha_{31}\alpha_{33}\alpha_{34} + 0.3\alpha_{31}\alpha_{33}\alpha_{35} - 0.6\alpha_{31}\alpha_{33}\alpha_{36} + 4.2\alpha_{31}\alpha_{34}\alpha_{35} + \\
& 3.9\alpha_{31}\alpha_{34}\alpha_{36} + 0.6\alpha_{31}\alpha_{35}\alpha_{36} - 0.3\alpha_{32}\alpha_{33}\alpha_{34} - 1.2\alpha_{32}\alpha_{33}\alpha_{35} + \\
& 0.6\alpha_{32}\alpha_{33}\alpha_{36} + 2.4\alpha_{32}\alpha_{34}\alpha_{35} + 2.1\alpha_{32}\alpha_{34}\alpha_{36} + 0.6\alpha_{32}\alpha_{35}\alpha_{36} + \\
& 0.6\alpha_{33}\alpha_{34}\alpha_{35} + 1.8\alpha_{33}\alpha_{34}\alpha_{36} + 0.6\alpha_{33}\alpha_{35}\alpha_{36} + 1.8\alpha_{34}\alpha_{35}\alpha_{36} + \\
& 30.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34} - 6.8\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{35} - 39.6\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{36} - \\
& 7.6\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{35} + 16.0\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{36} - 5.2\alpha_{31}\alpha_{32}\alpha_{35}\alpha_{36} - \\
& 2.4\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{35} + 13.6\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{36} + 2.8\alpha_{31}\alpha_{33}\alpha_{35}\alpha_{36} +
\end{aligned}$$

$$\begin{aligned}
& 12.4\alpha_{31}\alpha_{34}\alpha_{35}\alpha_{36} + 0.4\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35} + 5.6\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{36} - \\
& 2.4\alpha_{32}\alpha_{33}\alpha_{35}\alpha_{36} + 7.6\alpha_{32}\alpha_{34}\alpha_{35}\alpha_{36} + 12.8\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} + \\
& 124.5\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35} - 245.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{36} - \\
& 81.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{35}\alpha_{36} - 93.5\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{35}\alpha_{36} + \\
& 16.5\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - 95.0\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - \\
& 1236.6\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36}
\end{aligned}$$

The fitted simplex-centroid model for six components for the Tactical objective ($n = 3$) of the Semi-Automatic alternative is:

$$\begin{aligned}
\hat{y}_{semi-auto.} = & 30.2\alpha_{31} + 30.5\alpha_{32} + 49.9\alpha_{33} + 38.2\alpha_{34} + 34.8\alpha_{35} + 46.5\alpha_{36} - \\
& 0.2\alpha_{31}\alpha_{32} + 11.4\alpha_{31}\alpha_{33} + 3.2\alpha_{31}\alpha_{34} + 1.2\alpha_{31}\alpha_{35} + 9.0\alpha_{31}\alpha_{36} + \\
& 10.8\alpha_{32}\alpha_{33} + 2.6\alpha_{32}\alpha_{34} + 1.0\alpha_{32}\alpha_{35} + 8.4\alpha_{32}\alpha_{36} + 3.4\alpha_{33}\alpha_{34} + \\
& 5.8\alpha_{33}\alpha_{35} + 0.4\alpha_{33}\alpha_{36} + 0.4\alpha_{34}\alpha_{35} + 1.8\alpha_{34}\alpha_{36} + 4.2\alpha_{35}\alpha_{36} + \\
& 110.7\alpha_{31}\alpha_{32}\alpha_{33} - 186.6\alpha_{31}\alpha_{32}\alpha_{34} + 1.2\alpha_{31}\alpha_{32}\alpha_{35} + 9.6\alpha_{31}\alpha_{32}\alpha_{36} - \\
& 0.9\alpha_{31}\alpha_{33}\alpha_{34} + 6.9\alpha_{31}\alpha_{33}\alpha_{35} - 8.4\alpha_{31}\alpha_{33}\alpha_{36} - 0.9\alpha_{31}\alpha_{34}\alpha_{35} - \\
& 1.5\alpha_{31}\alpha_{34}\alpha_{36} + 3.6\alpha_{31}\alpha_{35}\alpha_{36} + 2.7\alpha_{32}\alpha_{33}\alpha_{34} + 6.6\alpha_{32}\alpha_{33}\alpha_{35} - \\
& 7.5\alpha_{32}\alpha_{33}\alpha_{36} - 1.2\alpha_{32}\alpha_{34}\alpha_{35} - 0.6\alpha_{32}\alpha_{34}\alpha_{36} + 3.3\alpha_{32}\alpha_{35}\alpha_{36} + \\
& 4.5\alpha_{33}\alpha_{34}\alpha_{35} - 2.4\alpha_{33}\alpha_{34}\alpha_{36} - 2.4\alpha_{33}\alpha_{35}\alpha_{36} + 1.5\alpha_{34}\alpha_{35}\alpha_{36} + \\
& 6.8\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34} + 24.8\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{35} - 60.8\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{36} + \\
& 7.6\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{35} + 9.2\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{36} + 12.4\alpha_{31}\alpha_{32}\alpha_{35}\alpha_{36} - \\
& 3.2\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{35} - 4.8\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{36} - 11.6\alpha_{31}\alpha_{33}\alpha_{35}\alpha_{36} - \\
& 1.2\alpha_{31}\alpha_{34}\alpha_{35}\alpha_{36} + 13.6\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35} + 8.8\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{36} - \\
& 9.6\alpha_{32}\alpha_{33}\alpha_{35}\alpha_{36} + 0.8\alpha_{32}\alpha_{34}\alpha_{35}\alpha_{36} - 17.6\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - \\
& 268.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35} - 178.5\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{36} -
\end{aligned}$$

$$\begin{aligned}
& 218.5\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{35}\alpha_{36} + 18.5\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{35}\alpha_{36} + \\
& 29.5\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} + 120.0\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - \\
& 258.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36}
\end{aligned}$$

The fitted simplex-centroid model for six components for the Tactical objective ($n = 3$) of the Automatic alternative is:

$$\begin{aligned}
\hat{y}_{automatic} = & 33.6\alpha_{31} + 36.5\alpha_{32} + 34.7\alpha_{33} + 31.5\alpha_{34} + 34.8\alpha_{35} + 33.6\alpha_{36} + \\
& 0.2\alpha_{31}\alpha_{32} + 0.2\alpha_{31}\alpha_{33} + 0.2\alpha_{31}\alpha_{34} + 0\alpha_{31}\alpha_{35} + 0\alpha_{31}\alpha_{36} + \\
& 0\alpha_{32}\alpha_{33} + 0.8\alpha_{32}\alpha_{34} - 0.2\alpha_{32}\alpha_{35} + 0.2\alpha_{32}\alpha_{36} + 0.4\alpha_{33}\alpha_{34} - \\
& 0.2\alpha_{33}\alpha_{35} - 0.2\alpha_{33}\alpha_{36} + 0.2\alpha_{34}\alpha_{35} + 0.2\alpha_{34}\alpha_{36} + 0\alpha_{35}\alpha_{36} + \\
& 36.6\alpha_{31}\alpha_{32}\alpha_{33} - 36.0\alpha_{31}\alpha_{32}\alpha_{34} + 0.9\alpha_{31}\alpha_{32}\alpha_{35} - 0.3\alpha_{31}\alpha_{32}\alpha_{36} - \\
& 1.5\alpha_{31}\alpha_{33}\alpha_{34} + 0.9\alpha_{31}\alpha_{33}\alpha_{35} + 0.9\alpha_{31}\alpha_{33}\alpha_{36} + 1.5\alpha_{31}\alpha_{34}\alpha_{35} - \\
& 1.2\alpha_{31}\alpha_{34}\alpha_{36} + 0\alpha_{31}\alpha_{35}\alpha_{36} + 0.9\alpha_{32}\alpha_{33}\alpha_{34} + 0.3\alpha_{32}\alpha_{33}\alpha_{35} - \\
& 0.9\alpha_{32}\alpha_{33}\alpha_{36} + 1.2\alpha_{32}\alpha_{34}\alpha_{35} + 0\alpha_{32}\alpha_{34}\alpha_{36} + 0.9\alpha_{32}\alpha_{35}\alpha_{36} - \\
& 0.3\alpha_{33}\alpha_{34}\alpha_{35} - 0.3\alpha_{33}\alpha_{34}\alpha_{36} - 0.6\alpha_{33}\alpha_{35}\alpha_{36} - 1.2\alpha_{34}\alpha_{35}\alpha_{36} + \\
& 3.2\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34} - 10.8\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{35} + 0.8\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{36} - \\
& 8.0\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{35} + 6.0\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{36} + 10.0\alpha_{31}\alpha_{32}\alpha_{35}\alpha_{36} - \\
& 2.4\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{35} + 8.4\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{36} + 4.8\alpha_{31}\alpha_{33}\alpha_{35}\alpha_{36} + \\
& 0.4\alpha_{31}\alpha_{34}\alpha_{35}\alpha_{36} + 7.6\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35} + 10.8\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{36} + \\
& 7.6\alpha_{32}\alpha_{33}\alpha_{35}\alpha_{36} + 2.8\alpha_{32}\alpha_{34}\alpha_{35}\alpha_{36} + 16.0\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - \\
& 10.5\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35} + 66.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{36} + \\
& 100.0\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{35}\alpha_{36} + 11.5\alpha_{31}\alpha_{32}\alpha_{34}\alpha_{35}\alpha_{36} - \\
& 3.5\alpha_{31}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - 124.0\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36} - \\
& 827.4\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\alpha_{35}\alpha_{36}
\end{aligned}$$

Appendix E

Goal Programming Results

The Goal Programming (GP) model is a linear mathematical model which is the weighted sum of all deviations from given constraints. The constraints, decision variables, and objective function are determined by the decision environment. The general GP formulation is [80]:

$$\min \sum_{n=1}^N \sum_{i=1}^I K_n (w_{in}^- d_i^- + w_{in}^+ d_i^+)$$

subject to:

$$\sum_{j=1}^J a_{ij} X_j + d_i^- - d_i^+ = b_i \quad (i = 1, \dots, I)$$

$$X_j, d_i^-, d_i^+ \geq 0$$

where:

- K_n - preemptive priority weight assigned to goal k .
- w_{in}^-, w_{in}^+ - differential weights assigned to the deviational variables of goal i at a given priority level n .
- d_i^-, d_i^+ - negative and positive deviations.
- X_j - decision variable.
- a_{ij} - technological coefficient of X_j in goal i .
- b_j - the i^{th} goal level.

System constraints usually are also included, and they are the absolute restrictions imposed by the decision environment on the model. An example of a

system constraint is that there are only seven days in a week. These must be satisfied before any goal constraints can be considered. The goal constraints are those functions that present desired levels of certain measurements. An example is the desired market share for each product that a company produces. For an ordinal solution to be achieved, negative and/or positive deviations about the goal are to be minimized based upon the preemptive priority weights assigned to them. Therefore, lower priority goals are only considered after higher priority goals.

The following pages provide the results of solving the example problem of Chapter 3 using Goal Programming. The software package "STORM Personal Version 2.0" for the personal computer was used [34]. Note that ALT 1, ALT 2, and ALT 3 correspond to the manual, semi-automatic, and automatic alternatives, respectively.

Chapter 3 Example - Goal Programming Solution, iteration 1
DETAILED LP REPORT FOR
OPTIMAL SOLUTION

The following variables are fixed

ALT 1	0
ALT 2	0
ALT 3	1

OPTIMAL SOLUTION - DETAILED REPORT

	Variable	Value	Cost	Red. cost	Status
1	ALT 1	0.0000	0.0000	33.2107	Lower bound
2	ALT 2	0.0000	0.0000	-3326.1310	Lower bound
3	ALT 3	1.0000	0.0000	-4145.1130	Lower bound
4	D1-	0.8618	544.0000	0.0000	Basic
5	D1+	0.0000	0.0000	544.0000	Lower bound
6	D2-	0.6620	640.0000	0.0000	Basic
7	D2+	0.0000	0.0000	640.0000	Lower bound
8	D3-	0.3208	608.0000	0.0000	Basic
9	D3+	0.0000	0.0000	608.0000	Lower bound
10	D4-	0.7038	480.0000	0.0000	Basic
11	D4+	0.0000	0.0000	480.0000	Lower bound
12	D5-	0.3724	416.0000	0.0000	Basic
13	D5+	0.0000	0.0000	416.0000	Lower bound
14	D6-	0.3904	576.0000	0.0000	Basic
15	D6+	0.0000	0.0000	576.0000	Lower bound
16	D7-	0.8000	480.0000	0.0000	Basic
17	D7+	0.0000	0.0000	480.0000	Lower bound
18	D8-	0.6452	608.0000	0.0000	Basic
19	D8+	0.0000	0.0000	608.0000	Lower bound
20	D9-	0.6931	576.0000	0.0000	Basic
21	D9+	0.0000	0.0000	576.0000	Lower bound
22	D10-	0.6579	480.0000	0.0000	Basic
23	D10+	0.0000	0.0000	480.0000	Lower bound
24	D11-	0.6171	512.0000	0.0000	Basic
25	D11+	0.0000	0.0000	512.0000	Lower bound
26	D12-	0.6002	608.0000	0.0000	Basic
27	D12+	0.0000	0.0000	608.0000	Lower bound
28	D13-	0.5571	3600.0000	0.0000	Basic
29	D13+	0.0000	0.0000	3600.0000	Lower bound

	Variable	Value	Cost	Red. cost	Status
Artificial Variables					
57	ONE PROJ	0.0000	0.0000	0.0000	Basic

	Constraint	Type	RHS	Slack	Shadow price
1	NPV	=	1.0000	0.0000	3600.0000
2	NPQF1	=	1.0000	0.0000	544.0000
3	NPQF2	=	1.0000	0.0000	640.0000
4	NPQF3	=	1.0000	0.0000	608.0000
5	NPQF4	=	1.0000	0.0000	480.0000
6	NPQF5	=	1.0000	0.0000	416.0000
7	NPQF6	=	1.0000	0.0000	576.0000
8	NPQF7	=	1.0000	0.0000	480.0000
9	NPQF8	=	1.0000	0.0000	608.0000
10	NPQF9	=	1.0000	0.0000	576.0000
11	NPQF10	=	1.0000	0.0000	480.0000
12	NPQF11	=	1.0000	0.0000	512.0000
13	NPQF12	=	1.0000	0.0000	608.0000
14	ONE PROJ	=	1.0000	0.0000	0.0000

Objective Function Value = 5982.887

Chapter 3 Example - Goal Programming Solution, iteration 2
 DETAILED LP REPORT FOR
 OPTIMAL SOLUTION

The following variables are fixed

ALT 1	0
ALT 2	1

OPTIMAL SOLUTION - DETAILED REPORT

	Variable	Value	Cost	Red. cost	Status
1	ALT 1	0.0000	0.0000	33.2107	Lower bound
2	ALT 2	1.0000	0.0000	-3326.1310	Lower bound
3	D1-	0.8618	544.0000	0.0000	Basic
4	D1+	0.0000	0.0000	544.0000	Lower bound
5	D2-	0.8300	640.0000	0.0000	Basic
6	D2+	0.0000	0.0000	640.0000	Lower bound
7	D3-	0.6467	608.0000	0.0000	Basic
8	D3+	0.0000	0.0000	608.0000	Lower bound
9	D4-	0.8874	480.0000	0.0000	Basic
10	D4+	0.0000	0.0000	480.0000	Lower bound
11	D5-	0.5948	416.0000	0.0000	Basic
12	D5+	0.0000	0.0000	416.0000	Lower bound
13	D6-	0.7084	576.0000	0.0000	Basic
14	D6+	0.0000	0.0000	576.0000	Lower bound
15	D7-	1.0000	480.0000	0.0000	Basic
16	D7+	0.0000	0.0000	480.0000	Lower bound
17	D8-	0.8868	608.0000	0.0000	Basic
18	D8+	0.0000	0.0000	608.0000	Lower bound
19	D9-	0.8702	576.0000	0.0000	Basic
20	D9+	0.0000	0.0000	576.0000	Lower bound
21	D10-	0.7610	480.0000	0.0000	Basic
22	D10+	0.0000	0.0000	480.0000	Lower bound
23	D11-	0.5569	512.0000	0.0000	Basic
24	D11+	0.0000	0.0000	512.0000	Lower bound
25	D12-	0.8187	608.0000	0.0000	Basic
26	D12+	0.0000	0.0000	608.0000	Lower bound
27	D13-	0.4607	3600.0000	0.0000	Basic
28	D13+	0.0000	0.0000	3600.0000	Lower bound

	Variable	Value	Cost	Red. cost	Status
Artificial Variables					
56	ONE PROJ	0.0000	0.0000	0.0000	Basic

	Constraint	Type	RHS	Slack	Shadow price
1	NPV	=	1.0000	0.0000	3600.0000
2	NPQF1	=	1.0000	0.0000	544.0000
3	NPQF2	=	1.0000	0.0000	640.0000
4	NPQF3	=	1.0000	0.0000	608.0000
5	NPQF4	=	1.0000	0.0000	480.0000
6	NPQF5	=	1.0000	0.0000	416.0000
7	NPQF6	=	1.0000	0.0000	576.0000
8	NPQF7	=	1.0000	0.0000	480.0000
9	NPQF8	=	1.0000	0.0000	608.0000
10	NPQF9	=	1.0000	0.0000	576.0000
11	NPQF10	=	1.0000	0.0000	480.0000
12	NPQF11	=	1.0000	0.0000	512.0000
13	NPQF12	=	1.0000	0.0000	608.0000
14	ONE PROJ	=	1.0000	0.0000	0.0000

Objective Function Value = 6801.869

Appendix F

MCQA-II Results

Multicriteria Q-Analysis (MCQA) is a multiobjective technique based upon the principles of Q-analysis and polyhedral dynamics [112]. Q-analysis provides a measure between the structure of two sets, and how they are related. In order to more clearly summarize the results obtained from Q-analysis, MCQA was developed to apply Q-analysis to MCDM problems.

For an MCDM problem, the two sets which are used for comparison are the sets of criteria and alternatives. An incidence matrix between these two sets is utilized to define a relationship between criteria and alternatives. If a specific criterion i is related to a specific alternative j , a 1 is entered into the matrix at (i, j) . If no relationship exists, a zero is entered. Relationships usually do not exhibit a binary nature, and as such a threshold (slicing level) may be used to generate a binary matrix.

Two versions of MCQA are available, MCQA I and MCQA II. MCQA I views a decision problem from a concordance view, and provides a method to rank alternatives using Q-analysis and the concepts of a Project Satisfaction Index (PSI) and a Project Comparison Index (PCI) [55]. The PSI represents the decision makers level of satisfaction toward a given alternative, and does not involve global comparison with other alternatives in the set. The PSI, by itself only a value, is defined as:

$$PSI(j) = \sum_{s=1}^S a_s X(a_s)$$

where:

j - the alternative number under consideration, $j = 1, \dots, J$.

S - the number of slicing levels.

a_s - a particular slicing level.

$X(a_s)$ - sum of all the weights of a satisfied criteria.

In order to achieve a comparison with respect to the other alternatives on a global basis, the PCI is introduced. The PCI, which establishes a relative ranking between the alternatives, is defined as:

$$PCI(j) = \sum_{s=1}^S a_s d_s$$

where:

d_s - $q_{MAX} - q_{MIN}$.

q_{MAX} - maximum q-level for the alternative of interest.

q_{MIN} - q-level where another alternative appears in the ranking with the alternative of interest. (may be the same as q_{MAX}).

With the PSI and PCI, the MCDM problem becomes a trade-off between the value of an alternative and the relative ranking of the alternatives. The PSI and PCI are combined through an L_p -Norm to achieve an ordinal ranking of the alternatives. This is the Project Rating Index (PRI), which is defined as:

$$PRI(j) = \left(\left| 1 - \frac{PSI(j)}{PSI_{MAX}} \right|^p + \left| 1 - \frac{PCI(j)}{PCI_{MAX}} \right|^p \right)^{1/p}$$

When $p = 2$, the L_p -Norm is simply the Euclidean distance between the alternatives (PSI, PCI) and some ideal vector $(1, 1)$.

MCQA I is strictly a concordance measure, and does not include any measure of the decision makers discomfort of choosing one alternative over another. MCQA II includes a discordance measure which allows alternatives to be more realistically

ranked according to the decision makers preferences. The Project Discordance Index (PDI) is determined in the same manner as the PCI, except it is set up to measure displeasure between criteria and alternatives. A complementary incidence matrix now replaces the original incidence matrix. The complementary incidence matrix is defined to contain ones where the original incidence matrix contained zeros, and visa versa. The PDI is defined as:

$$PDI(j) = \sum_{s=1}^S a_s d'_s$$

where:

$$d'_s = q'_{MAX} - q'_{MIN}.$$

$$q'_{MAX} = \text{maximum } q\text{-level for the alternative of interest.}$$

$$q'_{MIN} = \text{q-level where another alternative appears in the ranking with the alternative of interest. (may be the same as } q'_{MAX} \text{).}$$

In order to achieve a complete outranking using the PDI, along with the PSI and PCI from MCQA I, another L_p -Norm is used to create a second Project Rating Index, PRI2. This is defined to be:

$$PRI2(j) = \left(\left| 1 - \frac{PSI(j)}{PSI_{MAX}} \right|^p + \left| 1 - \frac{PCI(j)}{PCI_{MAX}} \right|^p + \left| \frac{PDI(j)}{PDI_{MAX}} \right|^p \right)^{1/p}$$

This index trades off the decision makers satisfaction of alternatives, along with a concordance and discordance ranking of the alternatives. As before, the lower the PRI2 result, the better the rank. A step by step procedure for MCQA II is given by Hiessl et al. [55].

The following pages list the results obtained using MCQA II on the problem presented in Chapter 3.

PECUNIARY OBJECTIVE

 MULTI CRITERIA Q-ANALYSIS WITH DISCORDANCE MEASUREMENT

NUMBER OF ALTERNATIVES : 3
 NUMBER OF CRITERIA : 1

PAY-OFF MATRIX :

CRIT. NO : 1
 ALT. 1 : .64
 ALT. 2 : .54
 ALT. 3 : .44

WEIGHT :100.00

RATINGS :

WORST : -1.00
 BEST : 1.00

PREFERENCE MATRIX :

CRIT. NO : 1
 ALT. 1 : .82
 ALT. 2 : .77
 ALT. 3 : .72

WEIGHT :100.00

RANKING WITH P = 2.0 :

PROJ.	PSI	PCI	PDI	PRI1	PRI2
1	225.000	.800	.000	.000	.000
2	145.000	.000	.000	1.061	1.061
3	70.000	.000	.750	1.214	1.573

STRATEGIC OBJECTIVE

 MULTI CRITERIA Q-ANALYSIS WITH DISCORDANCE MEASUREMENT

NUMBER OF ALTERNATIVES : 3
 NUMBER OF CRITERIA : 6

PAY-OFF MATRIX :

CRIT. NO :	1	2	3	4	5	6
ALT. 1 :	-.30	-.24	-.49	-.50	-.27	-.90
ALT. 2 :	.14	.17	.35	.11	.40	.29
ALT. 3 :	.14	.34	.68	.30	.62	.61

WEIGHT : 17.00 20.00 19.00 15.00 13.00 18.00

RATINGS :

WURST : -1.00 -1.00 -1.00 -1.00 -1.00 -1.00

BEST : 1.00 1.00 1.00 1.00 1.00 1.00

PREFERENCE MATRIX :

CRIT. NO :	1	2	3	4	5	6
ALT. 1 :	.35	.38	.25	.25	.37	.05
ALT. 2 :	.57	.58	.68	.56	.70	.64
ALT. 3 :	.57	.67	.84	.65	.81	.81

WEIGHT : 17.00 20.00 19.00 15.00 13.00 18.00

RANKING WITH P = 2.0 :

PROJ.	PSI	PCI	PDI	PRI1	PRI2
1	21.000	.000	6.650	1.323	1.659
2	131.500	.000	.000	1.013	1.013
3	157.400	1.400	.000	.000	.000

TACTICAL OBJECTIVE

 MULTI CRITERIA Q-ANALYSIS WITH DISCORDANCE MEASUREMENT

NUMBER OF ALTERNATIVES : 3
 NUMBER OF CRITERIA : 6

PAY-OFF MATRIX :

CRIT. NO :	1	2	3	4	5	6
ALT. 1 :	.00	-.60	-.38	-.14	.11	-.39
ALT. 2 :	.00	.11	.13	.24	.44	.18
ALT. 3 :	.20	.35	.31	.34	.38	.40

WEIGHT : 15.00 19.00 18.00 15.00 16.00 19.00

RATINGS :

WORST : -1.00 -1.00 -1.00 -1.00 -1.00 -1.00

BEST : 1.00 1.00 1.00 1.00 1.00 1.00

PREFERENCE MATRIX :

CRIT. NO :	1	2	3	4	5	6
ALT. 1 :	.50	.20	.31	.43	.56	.31
ALT. 2 :	.50	.56	.56	.62	.72	.59
ALT. 3 :	.60	.68	.65	.67	.69	.70

WEIGHT : 15.00 19.00 18.00 15.00 16.00 19.00

RANKING WITH P = 2.0 :

PROJ.	PSI	PCI	PDI	PRI1	PRI2
1	47.950	.000	4.350	1.191	1.555
2	125.350	.700	.000	.447	.447
3	135.700	1.250	.000	.000	.000

OBJECTIVE FUNCTION

 MULTI CRITERIA Q-ANALYSIS WITH DISCORDANCE MEASUREMENT

NUMBER OF ALTERNATIVES : 3
 NUMBER OF CRITERIA : 3

PAY-OFF MATRIX :

CRIT. NO :	1	2	3
ALT. 1 :	.00	1.66	1.55
ALT. 2 :	1.06	1.01	.45
ALT. 3 :	1.57	.00	.00

WEIGHT : 36.00 32.00 32.00

RATINGS :

WORST :	3.00	3.00	3.00
BEST :	.00	.00	.00

PREFERENCE MATRIX :

CRIT. NO :	1	2	3
ALT. 1 :	1.00	.45	.48
ALT. 2 :	.65	.66	.85
ALT. 3 :	.48	1.00	1.00

WEIGHT : 36.00 32.00 32.00

RANKING WITH P = 2.0 :

PROJ.	PSI	PCI	PDI	PRI1	PRI2
1	111.600	1.650	2.400	.541	1.137
2	129.000	.600	1.650	.828	1.076
3	189.000	2.550	.600	.000	.250

Appendix G

Risk Independence Derivations

This appendix presents the derivations of $E[\tilde{M}I]$ and $V[\tilde{M}I]$ as presented in Chapter 4.

Recall that the moment generating function of the Monetary Index is:

$$\phi_{\tilde{M}I}(r) = \sum_{t=0}^{\infty} \left[\prod_{n=0}^t \phi_{\tilde{A}_n}(M_1 r) \right] p\{T = t\}$$

The expected value of the Monetary Index is:

$$\begin{aligned} E[\tilde{M}I] &= \phi'_{\tilde{M}I}(r) \\ &= \frac{d}{dr} \phi_{\tilde{M}I}(r) \Big|_{r=0} \\ &= \frac{d}{dr} \left[\sum_{t=0}^{\infty} \left[\prod_{n=0}^t \phi_{\tilde{A}_n}(M_1 r) \right] p\{T = t\} \right]_{r=0} \end{aligned}$$

Expanding the summation yields:

$$\begin{aligned} E[\tilde{M}I] &= \frac{d}{dr} \left[\prod_{n=0}^0 \phi_{\tilde{A}_n}(M_1 r) p\{T = 0\} + \prod_{n=0}^1 \phi_{\tilde{A}_n}(M_1 r) p\{T = 1\} + \right. \\ &\quad \left. \prod_{n=0}^2 \phi_{\tilde{A}_n}(M_1 r) p\{T = 2\} + \prod_{n=0}^3 \phi_{\tilde{A}_n}(M_1 r) p\{T = 3\} + \cdots + \right. \\ &\quad \left. \prod_{n=0}^{\infty} \phi_{\tilde{A}_n}(M_1 r) p\{T = \infty\} \right]_{r=0} \\ &= \frac{d}{dr} \left[\prod_{n=0}^0 \phi_{\tilde{A}_n}(M_1 r) p\{T = 0\} \right]_{r=0} + \frac{d}{dr} \left[\prod_{n=0}^1 \phi_{\tilde{A}_n}(M_1 r) p\{T = 1\} \right]_{r=0} + \\ &\quad \frac{d}{dr} \left[\prod_{n=0}^2 \phi_{\tilde{A}_n}(M_1 r) p\{T = 2\} \right]_{r=0} + \frac{d}{dr} \left[\prod_{n=0}^3 \phi_{\tilde{A}_n}(M_1 r) p\{T = 3\} \right]_{r=0} + \\ &\quad \cdots + \frac{d}{dr} \left[\prod_{n=0}^{\infty} \phi_{\tilde{A}_n}(M_1 r) p\{T = \infty\} \right]_{r=0} \end{aligned}$$

Looking at the first term from above we have:

$$\begin{aligned} \frac{d}{dr} \left[\prod_{n=0}^0 \phi_{\tilde{A}_n}(M_1 r) p\{T=0\} \right]_{r=0} &= \frac{d}{dr} [\phi_{\tilde{A}_0}(M_1 r)] p\{T=0\}|_{r=0} \\ &= M_1 \phi'_{\tilde{A}_0}(0) p\{T=0\} \end{aligned}$$

The second term is:

$$\begin{aligned} \frac{d}{dr} \left[\prod_{n=0}^1 \phi_{\tilde{A}_n}(M_1 r) p\{T=1\} \right]_{r=0} &= \frac{d}{dr} [\phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r)] p\{T=1\}|_{r=0} \\ &= [M_1 \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) + M_1 \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r)] p\{T=1\}|_{r=0} \\ &= M_1 [\phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) + \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0)] p\{T=1\} \end{aligned}$$

The third term is:

$$\begin{aligned} \frac{d}{dr} \left[\prod_{n=0}^2 \phi_{\tilde{A}_n}(M_1 r) p\{T=2\} \right]_{r=0} &= \frac{d}{dr} [\phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r)] p\{T=2\}|_{r=0} \\ &= [M_1 \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) + M_1 \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) + \\ &\quad M_1 \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r)] p\{T=2\}|_{r=0} \\ &= M_1 [\phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) + \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) + \\ &\quad \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0)] p\{T=2\} \end{aligned}$$

The fourth term is:

$$\begin{aligned} \frac{d}{dr} \left[\prod_{n=0}^3 \phi_{\tilde{A}_n}(M_1 r) p\{T=3\} \right]_{r=0} &= \frac{d}{dr} [\phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r)] p\{T=3\}|_{r=0} \\ &= [M_1 \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\ &\quad M_1 \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\ &\quad M_1 \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\ &\quad M_1 \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r)] p\{T=3\}|_{r=0} \end{aligned}$$

$$\begin{aligned}
& M_1 \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& M_1 \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) \Big] p\{T = 3\} \Big|_{r=0} \\
= & M_1 \Big[\phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \\
& \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \\
& \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \\
& \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi'_{\tilde{A}_3}(0) \Big] p\{T = 3\}
\end{aligned}$$

The trend continues for subsequent higher terms.

Combining terms yields:

$$\begin{aligned}
E[\tilde{M}I] = & M_1 \phi'_{\tilde{A}_0}(0) p\{T = 0\} + \\
& M_1 \Big[\phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) + \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \Big] p\{T = 1\} + \\
& M_1 \Big[\phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) + \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) + \\
& \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \Big] p\{T = 2\} + \\
& M_1 \Big[\phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \\
& \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \\
& \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi'_{\tilde{A}_3}(0) \Big] p\{T = 3\} + \cdots \tag{G.1}
\end{aligned}$$

Factoring for like derivative terms:

$$\begin{aligned}
E[\tilde{M}I] = & M_1 \phi'_{\tilde{A}_0}(0) p\{T = 0\} + \\
& M_1 \phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) p\{T = 1\} + M_1 \phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) p\{T = 2\} + \\
& M_1 \phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) p\{T = 3\} + \cdots + \\
& M_1 \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) p\{T = 1\} + M_1 \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) p\{T = 2\} + \\
& M_1 \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) p\{T = 3\} + \cdots + \\
& M_1 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) p\{T = 2\} +
\end{aligned}$$

$$M_1 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) p\{T = 3\} + \dots +$$

$$M_1 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi'_{\tilde{A}_3}(0) p\{T = 3\} + \dots$$

Simplifying the equation results in:

$$E[\tilde{M}I] = M_1 \phi'_{\tilde{A}_0}(0) \left[\sum_{t=0}^{\infty} \left(\prod_{n=1}^t \phi_{\tilde{A}_n}(0) \right) p\{T = t\} \right] +$$

$$M_1 \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \left[\sum_{t=1}^{\infty} \left(\prod_{n=2}^t \phi_{\tilde{A}_n}(0) \right) p\{T = t\} \right] +$$

$$M_1 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \left[\sum_{t=2}^{\infty} \left(\prod_{n=3}^t \phi_{\tilde{A}_n}(0) \right) p\{T = t\} \right] + \dots$$

And carrying the simplification one step further yields:

$$E[\tilde{M}I] = M_1 \sum_{t=0}^{\infty} \left[\phi'_{\tilde{A}_t}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m \phi_{\tilde{A}_n}(0) \right) p\{T = m\} \right] \right]$$

The variance of the Monetary Index is:

$$V[\tilde{M}I] = \phi''_{\tilde{M}I}(r) - [\phi'_{\tilde{M}I}(r)]^2$$

$$= \left. \frac{d^2}{dr^2} \phi_{\tilde{M}I}(r) \right|_{r=0} - \left[\left. \frac{d}{dr} \phi_{\tilde{M}I}(r) \right]^2 \right|_{r=0}$$

Since the second term above is simply $E[\tilde{M}I]^2$, further derivation of only the second moment is necessary, which is:

$$\left. \frac{d^2}{dr^2} \phi_{\tilde{M}I}(r) \right|_{r=0}$$

$$\frac{d}{dr} \left[M_1 \sum_{t=0}^{\infty} \left[\phi'_{\tilde{A}_t}(M_1 r) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m \phi_{\tilde{A}_n}(M_1 r) \right) P_T \right] \right] \right] \right]_{r=0}$$

where $P_T = p\{T = m\}$. The derivation of the second moment begins with the first derivative results of equation G.1 prior to evaluation at $r = 0$, and differentiating this to obtain the following:

$$\phi''_{\tilde{M}I}(r) = M_1^2 \phi''_{\tilde{A}_0}(M_1 r) p\{T = 0\} +$$

$$\begin{aligned}
& M_1^2 \left[\phi''_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) + \phi'_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) + \right. \\
& \quad \left. \phi'_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) + \phi_{\tilde{A}_0}(M_1 r) \phi''_{\tilde{A}_1}(M_1 r) \right] p\{T = 1\} + \\
& M_1^2 \left[\phi''_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) + \phi'_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) + \right. \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) + \phi'_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi''_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) + \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) + \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) + \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) + \\
& \quad \left. \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi''_{\tilde{A}_2}(M_1 r) \right] p\{T = 2\} + \\
& M_1^2 \left[\phi''_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \right. \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi''_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi''_{\tilde{A}_2}(M_1 r) \phi_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi'_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) + \\
& \quad \phi_{\tilde{A}_0}(M_1 r) \phi'_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) + \\
& \quad \left. \phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi'_{\tilde{A}_2}(M_1 r) \phi'_{\tilde{A}_3}(M_1 r) \right]
\end{aligned}$$

$$\phi_{\tilde{A}_0}(M_1 r) \phi_{\tilde{A}_1}(M_1 r) \phi_{\tilde{A}_2}(M_1 r) \phi''_{\tilde{A}_3}(M_1 r) \Big] p\{T = 3\} + \dots \Big|_{r=0}$$

Factoring for like derivative terms and evaluating:

$$\begin{aligned} \phi''_{\tilde{M}I}(0) &= M_1^2 \phi''_{\tilde{A}_0}(0) p\{T = 0\} + \\ &M_1^2 \phi''_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) p\{T = 1\} + M_1^2 \phi''_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) p\{T = 2\} + \\ &M_1^2 \phi''_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) p\{T = 3\} + \dots + \\ &M_1^2 \phi_{\tilde{A}_0}(0) \phi''_{\tilde{A}_1}(0) p\{T = 1\} + M_1^2 \phi_{\tilde{A}_0}(0) \phi''_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) p\{T = 2\} + \\ &M_1^2 \phi_{\tilde{A}_0}(0) \phi''_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) p\{T = 3\} + \dots + \\ &M_1^2 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi''_{\tilde{A}_2}(0) p\{T = 2\} + \\ &M_1^2 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi''_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) p\{T = 3\} + \dots + \\ &M_1^2 \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0)'' p\{T = 3\} + \dots + \\ &2M_1^2 \phi'_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) p\{T = 1\} + \\ &2M_1^2 \left[\phi'_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) + \phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) + \right. \\ &\quad \left. \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \right] p\{T = 2\} + \\ &2M_1^2 \left[\phi'_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \right. \\ &\quad \phi'_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi'_{\tilde{A}_3}(0) + \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \phi_{\tilde{A}_3}(0) + \\ &\quad \phi_{\tilde{A}_0}(0) \phi'_{\tilde{A}_1}(0) \phi_{\tilde{A}_2}(0) \phi'_{\tilde{A}_3}(0) + \\ &\quad \left. \phi_{\tilde{A}_0}(0) \phi_{\tilde{A}_1}(0) \phi'_{\tilde{A}_2}(0) \phi'_{\tilde{A}_3}(0) \right] p\{T = 3\} + \dots \end{aligned}$$

Simplifying to final result yields:

$$\begin{aligned} V[\tilde{M}I] &= M_1^2 \sum_{t=0}^{\infty} \left[\phi''_{\tilde{A}_t}(0) \left[\sum_{m=t}^{\infty} \left(\prod_{\substack{n=0 \\ n \neq t}}^m \phi_{\tilde{A}_n}(0) \right) p\{T = m\} \right] \right] + \\ &2M_1^2 \sum_{t=1}^{\infty} \left[\sum_{\substack{v,w=0 \\ v \neq w}}^t \phi'_{\tilde{A}_v}(0) \phi'_{\tilde{A}_w}(0) \prod_{s \neq v,w} \phi_{\tilde{A}_s}(0) \right] p\{T = t\} - E[\tilde{M}I]^2 \end{aligned}$$

Appendix H

Data for Independent Risk

Table H.1: Evaluation Parameters

PARAMETER	VALUE	PARAMETER	VALUE
Tax rate	34.00%	p factor	2
ACRS	7 years	q factor	2

Table H.2: Attribute Weights

ATTRIBUTE	WEIGHT	NORMALIZED
Monetary	100	100
Internal Relations	80	17
Market Position	95	20
Mission	90	19
Organization	70	15
Public Relations	60	13
Technology	85	18
Design	75	15
Flexibility	95	19
Integration	90	18
Material	75	15
Personnel	80	16
Produceability	95	19

Table H.3: Objective Weights

OBJECTIVE	WEIGHT	NORMALIZED
Pecuniary	90	36
Strategic	80	32
Tactical	80	32

Table H.4: Interest Rates in Percent

PARAMETER	YEAR/RATE		
monetary rate	1	3	8
	13.00	13.00	14.60
	13.40	13.40	15.40
	13.60	13.60	16.20
	1	3	10
	13.00	13.00	15.00
	13.40	13.40	15.60
	13.60	13.60	16.20
	1	3	12
	13.00	13.00	15.40
	13.40	13.40	16.00
	13.60	13.60	16.60
nonmonetary rate	1	3	8
	7.80	7.80	8.50
	7.90	7.90	9.00
	8.00	8.00	9.50
	1	3	10
	7.90	7.90	8.70
	8.00	8.00	9.20
	8.10	8.10	9.70
	1	3	12
	8.00	8.00	9.00
	8.10	8.10	9.50
	8.20	8.20	10.00

Table H.5: Manual Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW			
Labor	1	3	6	8
	(\$114,660)	(\$136,500)	(\$169,260)	(\$158,340)
	(\$109,200)	(\$130,000)	(\$161,200)	(\$150,800)
	(\$103,740)	(\$123,500)	(\$153,140)	(\$143,260)
	1	3	6	10
	(\$114,660)	(\$136,500)	(\$169,260)	(\$147,420)
	(\$109,200)	(\$130,000)	(\$161,200)	(\$140,400)
	(\$103,740)	(\$123,500)	(\$153,140)	(\$133,380)
	1	3	6	12
	(\$114,660)	(\$136,500)	(\$169,260)	(\$136,500)
	(\$109,200)	(\$130,000)	(\$161,200)	(\$130,000)
	(\$103,740)	(\$123,500)	(\$153,140)	(\$123,500)
Maintenance	1	3	5	8
	(\$2,100)	(\$2,310)	(\$2,541)	(\$2,795)
	(\$2,000)	(\$2,200)	(\$2,420)	(\$2,662)
	(\$1,900)	(\$2,090)	(\$2,299)	(\$2,529)
	1	3	5	8
	(\$2,100)	(\$2,310)	(\$2,541)	(\$2,795)
	(\$2,000)	(\$2,200)	(\$2,420)	(\$2,662)
	(\$1,900)	(\$2,090)	(\$2,299)	(\$2,529)
	1	3	5	8
	(\$2,100)	(\$2,310)	(\$2,541)	(\$2,795)
	(\$2,000)	(\$2,200)	(\$2,420)	(\$2,662)
	(\$1,900)	(\$2,090)	(\$2,299)	(\$2,529)
Training	1	3	6	8
	(\$1,500)	(\$1,984)	(\$3,017)	(\$2,624)
	(\$1,000)	(\$1,323)	(\$2,011)	(\$1,749)
	(\$500)	(\$661)	(\$1,006)	(\$875)
	1	3	6	8
	(\$1,500)	(\$1,984)	(\$3,017)	(\$2,624)
	(\$1,000)	(\$1,323)	(\$2,011)	(\$1,749)
	(\$500)	(\$661)	(\$1,006)	(\$875)
	1	3	6	8
	(\$1,500)	(\$1,984)	(\$3,017)	(\$2,624)
	(\$1,000)	(\$1,323)	(\$2,011)	(\$1,749)
	(\$500)	(\$661)	(\$1,006)	(\$875)
Documentation	1	3	6	8
	(\$5,500)			
	(\$5,000)			
	(\$4,500)			
	1	3	6	8
	(\$5,500)			
	(\$5,000)			
	(\$4,500)			
	1	3	6	8
	(\$5,500)			
	(\$5,000)			
	(\$4,500)			
Space	1	3	4	7
	(\$5,350)	(\$5,350)	(\$10,700)	(\$16,050)
	(\$5,000)	(\$5,000)	(\$10,000)	(\$15,000)
	(\$4,650)	(\$4,650)	(\$9,300)	(\$13,950)
	1	3	4	7
	(\$5,350)	(\$5,350)	(\$10,700)	(\$16,050)
	(\$5,000)	(\$5,000)	(\$10,000)	(\$15,000)
	(\$4,650)	(\$4,650)	(\$9,300)	(\$13,950)
	1	3	4	7
	(\$5,350)	(\$5,350)	(\$10,700)	(\$16,050)
	(\$5,000)	(\$5,000)	(\$10,000)	(\$15,000)
	(\$4,650)	(\$4,650)	(\$9,300)	(\$13,950)
Rework	1	3	6	8
	(\$86,940)	(\$106,280)	(\$140,070)	(\$136,335)
	(\$75,600)	(\$92,400)	(\$121,800)	(\$118,552)
	(\$64,260)	(\$78,540)	(\$103,530)	(\$100,769)
	1	3	6	10
	(\$86,940)	(\$106,280)	(\$140,070)	(\$132,600)
	(\$75,600)	(\$92,400)	(\$121,800)	(\$115,304)
	(\$64,260)	(\$78,540)	(\$103,530)	(\$98,010)
	1	3	6	12
	(\$86,940)	(\$106,280)	(\$140,070)	(\$128,864)
	(\$75,600)	(\$92,400)	(\$121,800)	(\$112,056)
	(\$64,260)	(\$78,540)	(\$103,530)	(\$95,248)

Table H.5: Manual Operations Cash Flows - cont'd.

ATTRIBUTE	YEAR/CASH FLOW			
Transportation	1	4	5	8
	(\$10,700)	(\$10,700)	(\$16,050)	(\$16,050)
	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)
	(\$9,300)	(\$9,300)	(\$13,950)	(\$13,950)
	1	4	5	8
	(\$10,700)	(\$10,700)	(\$16,050)	(\$16,050)
	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)
	(\$9,300)	(\$9,300)	(\$13,950)	(\$13,950)
	1	4	5	8
	(\$10,700)	(\$10,700)	(\$16,050)	(\$16,050)
	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)
	(\$9,300)	(\$9,300)	(\$13,950)	(\$13,950)
Cash Inflow	1	6	8	
	\$652,800	\$1,052,160	\$1,024,102	
	\$816,000	\$1,315,200	\$1,280,128	
	\$979,200	\$1,578,240	\$1,536,153	
	1	6	10	
	\$652,800	\$1,052,160	\$996,045	
	\$816,000	\$1,315,200	\$1,245,056	
	\$979,200	\$1,578,240	\$1,494,067	
	1	6	12	
	\$652,800	\$1,052,160	\$987,987	
	\$816,000	\$1,315,200	\$1,209,984	
	\$979,200	\$1,578,240	\$1,451,981	

Table H.6: Semi-Automatic Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW			
Investment	0			
	(\$30,000)			
	(\$30,000)			
	(\$24,000)			
	0			
	(\$30,000)			
	(\$30,000)			
	(\$24,000)			
	0			
	(\$30,000)			
	(\$30,000)			
	(\$24,000)			
Depr Investment	0			
	(\$144,000)			
	(\$120,000)			
	(\$96,000)			
	0			
	(\$144,000)			
	(\$120,000)			
	(\$96,000)			
	0			
	(\$144,000)			
	(\$120,000)			
	(\$96,000)			
Salvage value	8			
	\$6,375			
	\$7,500			
	\$8,625			
	10			
	\$4,675			
	\$5,500			
	\$6,325			
	12			
	\$2,975			
	\$3,500			
	\$4,025			
Labor	1	3	6	8
	(\$297,440)	(\$320,320)	(\$388,960)	(\$366,080)
	(\$270,400)	(\$291,200)	(\$353,600)	(\$332,800)
	(\$243,360)	(\$262,080)	(\$318,240)	(\$299,520)
	1	3	6	10
	(\$297,440)	(\$320,320)	(\$388,960)	(\$343,200)
	(\$270,400)	(\$291,200)	(\$353,600)	(\$312,000)
	(\$243,360)	(\$262,080)	(\$318,240)	(\$280,800)
	1	3	6	12
	(\$297,440)	(\$320,320)	(\$388,960)	(\$320,320)
	(\$270,400)	(\$291,200)	(\$353,600)	(\$291,200)
	(\$243,360)	(\$262,080)	(\$318,240)	(\$262,080)
Maintenance	1			
	(\$7,659)			
	(\$6,660)			
	(\$5,661)			
	1			
	(\$7,659)			
	(\$6,660)			
	(\$5,661)			
	1			
	(\$7,659)			
	(\$6,660)			
	(\$5,661)			
Training	1	3	8	
	(\$30,000)	(\$22,500)	(\$15,000)	
	(\$20,000)	(\$15,000)	(\$10,000)	
	(\$10,000)	(\$7,500)	(\$5,000)	
	1	3	8	
	(\$30,000)	(\$22,500)	(\$15,000)	
	(\$20,000)	(\$15,000)	(\$10,000)	
	(\$10,000)	(\$7,500)	(\$5,000)	
	1	3	8	
	(\$30,000)	(\$22,500)	(\$15,000)	
	(\$20,000)	(\$15,000)	(\$10,000)	
	(\$10,000)	(\$7,500)	(\$5,000)	

Table H.6: Semi-Automatic Operations Cash Flows - cont'd

ATTRIBUTE	YEAR/CASH FLOW		
Documentation	1		
	(\$3,000)		
	(\$2,500)		
	(\$2,000)		
	1		
	(\$3,000)		
	(\$2,500)		
	(\$2,000)		
	1		
	(\$3,000)		
	(\$2,500)		
	(\$2,000)		
Space	1		
	(\$6,688)		
	(\$6,250)		
	(\$5,813)		
	1		
	(\$6,688)		
	(\$6,250)		
	(\$5,813)		
	1		
	(\$6,688)		
	(\$6,250)		
	(\$5,813)		
Rework	1	2	8
	(\$86,940)	(\$85,008)	(\$74,575)
	(\$75,600)	(\$73,920)	(\$64,848)
	(\$64,260)	(\$62,832)	(\$55,120)
	1	2	10
	(\$86,940)	(\$85,008)	(\$71,088)
	(\$75,600)	(\$73,920)	(\$61,824)
	(\$64,260)	(\$62,832)	(\$52,550)
	1	2	12
	(\$86,940)	(\$85,008)	(\$67,020)
	(\$75,600)	(\$73,920)	(\$58,800)
	(\$64,260)	(\$62,832)	(\$49,980)
Programming	1	3	4
	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$15,000)	(\$10,000)
Cash Inflow	1	6	8
	\$645,120	\$1,098,240	\$1,068,954
	\$806,400	\$1,372,800	\$1,336,192
	\$967,680	\$1,647,360	\$1,603,430
	1	6	10
	\$645,120	\$1,098,240	\$1,039,667
	\$806,400	\$1,372,800	\$1,299,584
	\$967,680	\$1,647,360	\$1,559,500
	1	6	12
	\$645,120	\$1,098,240	\$1,010,381
	\$806,400	\$1,372,800	\$1,262,976
	\$967,680	\$1,647,360	\$1,515,571

Table H.7: Automatic Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW		
Investment	0		
	(\$60,000)		
	(\$50,000)		
	(\$40,000)		
	0		
	(\$60,000)		
	(\$50,000)		
	(\$40,000)		
	0		
	(\$60,000)		
	(\$50,000)		
	(\$40,000)		
Depr Investment	0		
	(\$720,000)		
	(\$600,000)		
	(\$480,000)		
	0		
	(\$720,000)		
	(\$600,000)		
	(\$480,000)		
	0		
	(\$720,000)		
	(\$600,000)		
	(\$480,000)		
Salvage value	8		
	\$46,000		
	\$40,000		
	\$34,000		
	10		
	\$34,500		
	\$30,000		
	\$25,500		
	12		
	\$23,000		
	\$20,000		
	\$17,000		
Labor	1	3	6
	(\$400,400)	(\$331,760)	(\$331,760)
	(\$364,000)	(\$301,600)	(\$301,600)
	(\$327,600)	(\$271,440)	(\$271,440)
	1	3	6
	(\$400,400)	(\$331,760)	(\$331,760)
	(\$364,000)	(\$301,600)	(\$301,600)
	(\$327,600)	(\$271,440)	(\$271,440)
	1	3	6
	(\$400,400)	(\$331,760)	(\$331,760)
	(\$364,000)	(\$301,600)	(\$301,600)
	(\$327,600)	(\$271,440)	(\$271,440)
Maintenance	1		
	(\$18,400)		
	(\$16,000)		
	(\$13,600)		
	1		
	(\$18,400)		
	(\$16,000)		
	(\$13,600)		
	1		
	(\$18,400)		
	(\$16,000)		
	(\$13,600)		
Training	1	3	4
	(\$60,000)	(\$45,000)	(\$30,000)
	(\$40,000)	(\$30,000)	(\$20,000)
	(\$20,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$60,000)	(\$45,000)	(\$30,000)
	(\$40,000)	(\$30,000)	(\$20,000)
	(\$20,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$60,000)	(\$45,000)	(\$30,000)
	(\$40,000)	(\$30,000)	(\$20,000)
	(\$20,000)	(\$15,000)	(\$10,000)

Table H.7: Automatic Operations Cash Flows - cont'd

ATTRIBUTE	YEAR/CASH FLOW			
	1	2		
Documentation	1	2		
	(\$6,000)	(\$3,600)		
	(\$5,000)	(\$3,000)		
	(\$4,000)	(\$2,400)		
	1	2		
	(\$6,000)	(\$3,600)		
	(\$5,000)	(\$3,000)		
	(\$4,000)	(\$2,400)		
	1	2		
	(\$6,000)	(\$3,600)		
	(\$5,000)	(\$3,000)		
	(\$4,000)	(\$2,400)		
Space	1			
	(\$6,688)			
	(\$6,250)			
	(\$5,813)			
	1			
	(\$6,688)			
	(\$6,250)			
	(\$5,813)			
	1			
	(\$6,688)			
	(\$6,250)			
	(\$5,813)			
Rework	1	5	6	8
	(\$86,940)	(\$65,205)	(\$35,018)	(\$33,810)
	(\$75,800)	(\$56,700)	(\$30,450)	(\$29,400)
	(\$64,260)	(\$48,195)	(\$25,883)	(\$24,990)
	1	5	6	10
	(\$86,940)	(\$65,205)	(\$35,018)	(\$31,153)
	(\$75,800)	(\$56,700)	(\$30,450)	(\$27,090)
	(\$64,260)	(\$48,195)	(\$25,883)	(\$23,027)
	1	5	6	10
	(\$86,940)	(\$65,205)	(\$35,018)	(\$31,153)
	(\$75,800)	(\$56,700)	(\$30,450)	(\$27,090)
	(\$64,260)	(\$48,195)	(\$25,883)	(\$23,027)
Programming	1	2	3	4
	(\$75,000)	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$25,000)	(\$15,000)	(\$10,000)
	1	2	3	4
	(\$75,000)	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$25,000)	(\$15,000)	(\$10,000)
	1	2	3	4
	(\$75,000)	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$25,000)	(\$15,000)	(\$10,000)
Cash Inflow	1	6	8	
	\$622,080	\$1,105,920	\$1,076,428	
	\$777,600	\$1,382,400	\$1,345,536	
	\$933,120	\$1,658,880	\$1,614,643	
	1	6	10	
	\$622,080	\$1,105,920	\$1,046,937	
	\$777,600	\$1,382,400	\$1,308,672	
	\$933,120	\$1,658,880	\$1,570,407	
	1	6	12	
	\$622,080	\$1,105,920	\$1,017,446	
	\$777,600	\$1,382,400	\$1,271,808	
	\$933,120	\$1,658,880	\$1,526,170	

Table H.8: Manual Operations Qualitative Flows

ATTRIBUTE	STRATEGIC YEAR/QUAL. FLOW				ATTRIBUTE	TACTICAL YEAR/QUAL. FLOW			
Internal Relations	1	3	6	7	Design	1			
	10	-35	-35	-55		-5			
	15	-30	-30	-50		0			
	20	-25	-25	-45		5			
	1	3	6	7		1			
	10	-35	-35	-55		-5			
	15	-30	-30	-50		0			
	20	-25	-25	-45		5			
	1	3	6	7		1			
	10	-35	-35	-55		-5			
Market Position	15	-30	-30	-50	Flexibility	0			
	20	-25	-25	-45		5			
	1	4	8			1	4	5	8
	0	-20	-95			-55	-55	-95	-95
	20	0	-75			-40	-40	-80	-80
	40	20	-55			-25	-25	-65	-65
	1	4	8	10		1	4	5	8
	0	-20	-95	-98		-55	-55	-95	-95
	20	0	-75	-83		-40	-40	-80	-80
	40	20	-55	-63		-25	-25	-65	-65
Mission	1	4	8	12	Integration	1	4	5	8
	0	-20	-95	-100		-55	-55	-95	-95
	20	0	-75	-90		-40	-40	-80	-80
	40	20	-55	-70		-25	-25	-65	-65
	1	2	8			1	8		
	10	-40	-55			-27	-72		
	15	-30	-45			-15	-60		
	20	-20	-35			-3	-48		
	1	2	8	10		1	8	10	
	10	-40	-55	-95		-27	-72	-92	
Organization	15	-30	-45	-85	Material	-15	-60	-80	
	20	-20	-35	-75		-3	-48	-68	
	1	2	8	10		1	8	10	12
	10	-40	-55	-95		-27	-72	-92	-100
	15	-30	-45	-85		-15	-60	-80	-90
	20	-20	-35	-75		-3	-48	-68	-78
	1					1	3	4	8
	-55					19	-6	-26	-46
	-50					25	0	-20	-40
	-45					31	6	-14	-34
Public Relations	1				Personnel	1	3	4	8
	-55					19	-6	-26	-46
	-50					25	0	-20	-40
	-45					31	6	-14	-34
	1					1	3	4	8
	-55					19	-6	-26	-46
	-50					25	0	-20	-40
	-45					31	6	-14	-34
	1	2	8			1	8		
	13	-7	-67			27	-3	-23	
Technology	20	0	-60		Produceability	35	5	-15	
	27	7	-53			43	13	-7	
	1	2	8	10		1	6	8	10
	13	-7	-67	-87		27	-3	-23	-43
	20	0	-60	-80		35	5	-15	-35
	27	7	-53	-73		43	13	-7	-27
	1	2	8	10		1	6	8	10
	13	-7	-67	-87		27	-3	-23	-43
	20	0	-60	-80		35	5	-15	-35
	27	7	-53	-83		43	13	-7	-32
	1					1	8		
	-100					-31	-60		
	-90					-20	-55		
	-80					-9	-44		
	1					1	8	10	
	-100					-31	-66	-76	
	-90					-20	-55	-65	
	-80					-9	-44	-54	
	1					1	8	10	12
	-100					-31	-66	-76	-81
	-90					-20	-55	-65	-70
	-80					-9	-44	-54	-59

Table H.9: Semi-Automatic Operations Qualitative Flows

STRATEGIC					TACTICAL				
ATTRIBUTE	YEAR/QUAL. FLOW				ATTRIBUTE	YEAR/QUAL. FLOW			
Strategic Internal Relations	1	3	7		Tactical Design	1			
	-40	0	35			-5			
	-35	5	40			0			
	-30	10	45			5			
	1	3	7	10		1			
	-40	0	35	55		-5			
	-35	5	40	60		0			
	-30	10	45	65		5			
	1	3	7	10		1			
	-40	0	35	55		-5			
	-35	5	40	60		0			
	-30	10	45	65		5			
Market Position	1	2	3	8	Flexibility	1	5	8	
	-10	-40	-20	15		-35	0	15	
	10	-20	0	35		-20	15	30	
	30	0	20	55		-15	30	45	
	1	2	3	8		1	5	8	10
	-10	-40	-20	15		-35	0	15	25
	10	-20	0	35		-20	15	30	40
	30	0	20	55		-15	30	45	55
	1	2	3	8		1	5	8	10
	-10	-40	-20	15		-35	0	15	25
	10	-20	0	35		-20	15	30	40
	30	0	20	55		-15	30	45	55
Mission	1	3	4	8	Integration	1	3	8	
	20	20	25	30		-27	-7	18	
	30	30	35	40		-15	5	30	
	40	40	45	50		-3	17	42	
	1	3	4	8		1	3	8	10
	20	20	25	30		-27	-7	18	28
	30	30	35	40		-15	5	30	40
	40	40	45	50		-3	17	42	52
	1	3	4	8		1	3	8	10
	20	20	25	30		-27	-7	18	28
	30	30	35	40		-15	5	30	40
	40	40	45	50		-3	17	42	52
Organization	1	3	8		Material	1	3	8	
	-40	5	35			-16	9	44	
	-35	10	40			-10	15	50	
	-30	15	45			-4	21	56	
	1	3	8			1	3	8	
	-40	5	35			-16	9	44	
	-35	10	40			-10	15	50	
	-30	15	45			-4	21	56	
	1	3	8			1	2	8	
	-40	5	35			-16	9	44	
	-35	10	40			-10	15	50	
	-30	15	45			-4	21	56	
Public Relations	1	7			Personnel	1	6	8	
	18	48				27	37	35	
	25	55				35	45	43	
	32	62				43	53	51	
	1	7				1	6	8	
	18	48				27	37	35	
	25	55				35	45	43	
	32	62				43	53	51	
	1	7				1	6	8	
	18	48				27	37	35	
	25	55				35	45	43	
	32	62				43	53	51	
Technology	1	4	5		Produceability	1	4	8	
	0	20	30			-38	4	34	
	10	30	40			-25	15	45	
	20	40	50			-14	26	56	
	1	4	5			1	4	8	10
	0	20	30			-38	4	34	44
	10	30	40			-25	15	45	55
	20	40	50			-14	26	56	66
	1	4	5	11		1	4	8	10
	0	20	30	45		-38	4	34	44
	10	30	40	50		-25	15	45	55
	20	40	50	55		-14	26	56	66

Table H.10: Automatic Operations Qualitative Flows

ATTRIBUTE	STRATEGIC YEAR/QUAL. FLOW				ATTRIBUTE	TACTICAL YEAR/QUAL. FLOW			
Strategic Internal Relations	1	3	8		Tactical Design	1			
	-40	0	35			15			
	-35	5	40			20			
	-30	10	45			25			
	1	3	8	10		1			
	-40	0	35	55		15			
	-35	5	40	60		20			
	-30	10	45	65		25			
	1	3	8	10		1			
	-40	0	35	55		15			
Market Position	-35	5	40	60	Flexibility	20			
	-30	10	45	65		25			
	1	2	3	7		1	3	6	8
	-10	-40	-10	60		-35	-5	35	75
	10	-20	10	80		-20	10	50	90
	30	0	30	100		-5	25	65	100
	1	2	3	7		1	3	6	8
	-10	-40	-10	60		-35	-5	35	75
	10	-20	10	80		-20	10	50	90
	30	0	30	100		-5	25	65	100
Mission	1	2	3	7	Integration	1	3	6	8
	-10	-40	-10	60		-35	-5	35	75
	10	-20	10	80		-20	10	50	90
	30	0	30	100		-5	25	65	100
	1	4	6	8		1	3	5	7
	30	50	70	80		-27	-7	18	43
	40	60	80	90		-15	5	30	55
	50	70	90	100		-3	17	42	67
	1	4	6	8		1	3	5	7
	30	50	70	80		-27	-7	18	43
Organization	40	60	80	90	Material	-15	5	30	55
	50	70	90	100		-3	17	42	67
	1	4	6	8		1	3	5	7
	30	50	70	80		-27	-7	18	43
	40	60	80	90		-15	5	30	55
	50	70	90	100		-3	17	42	67
	1	4	6	8		1	3	5	7
	30	50	70	80		-27	-7	18	43
	40	60	80	90		-15	5	30	55
	50	70	90	100		-3	17	42	67
Public Relations	1	3	5	8	Personnel	1	2	3	6
	-40	5	20	80		-16	4	9	39
	-35	10	25	85		-10	10	15	45
	-30	15	30	90		-4	16	21	51
	1	3	5	8		1	2	3	6
	-40	5	20	80		-16	4	9	39
	-35	10	25	85		-10	10	15	45
	-30	15	30	90		-4	16	21	51
	1	3	5	8		1	2	3	6
	-40	5	20	80		-16	4	9	39
Technology	-35	10	25	85	Produceability	-10	10	15	45
	-30	15	30	90		-4	16	21	51
	1	4	7	8		1	6	8	
	38	48	68	78		-28	47	45	
	45	55	75	85		-20	55	53	
	52	62	82	92		-12	63	61	
	1	4	7	8		1	6	8	10
	38	48	68	78		-28	47	45	60
	45	55	75	85		-20	55	53	68
	52	62	82	92		-12	63	61	76
	1	4	7	8		1	6	8	10
	38	48	68	78		-28	47	45	60
	45	55	75	85		-20	55	53	68
	52	62	82	92		-12	63	61	76
	1	4	7	8		1	6	8	10
	38	48	68	78		-28	47	45	60
	45	55	75	85		-20	55	53	68
	52	62	82	92		-12	63	61	76
	1	4	7	8		1	6	8	10
	38	48	68	78		-28	47	45	60

Appendix I

AMSTEP-R Program Listing

```

/*
/* AMSTEP-R: Advanced Manufacturing System Technology Evaluation Program
/*
/* Risk
/*
/*
/* Johann G. Demmel
/*
/* copyright (c) 1991
/*
/*
/* Compiler: Power C by MIX Software
/*
/* compile with /ml option
/*
/* link with [64K,15K,] option
/*
/*
#include <bios.h>
#include <conio.h>
#include <malloc.h>
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define MAX_ALTS 5
#define YR_LEN 2000L

FILE *In, *Compr, *Fp, *Objout, *Out;

unsigned short int Num_alts, Proj_len[3], ACRS_type, Sample, Bins;

int (far *Years)[];

float Obj_weight[3];
float Distribution[12][10], Factors[20], ACRS[21];
float Tax_rate, P, Q, Corr_coef;

double NPV_max, NPV_min, Depreciation[21], Flows[21];
double Max[MAX_ALTS][13], Min[MAX_ALTS][13];
/* #include "minmax.h" */

char Input_files[MAX_ALTS][13], Alt_title[MAX_ALTS][25], Title[40];
char Prefix_name[9] = "amstep-r";

struct Depend {          /* Structure for Cash/Qual flows */

```

```

    int points;           /* Number of data points.      */
    int yr_brk[5];        /* Years for breaks in curve.    */
    double rate[3][5];    /* Flow values.                  */

    struct { /* Structure for number of attributes. */
        unsigned short int pecuniary; /* Pecuniary. */
        unsigned short int strategic; /* Strategic.  */
        unsigned short int tactical;  /* Tactical.   */
    } Num_attrib;

    struct { /* Structure for monetary input. */
        char description[20]; /* Attribute Description. */
        struct Depend data[3];
    } Mon_inp[20];

    struct { /* Structure for nonmonetary input. */
        char attribute[20]; /* Attribute Description. */
        float weight;       /* Attribute weight.      */
        struct Depend data[3];
    } Str_inp[6], Tac_inp[6];

    struct Depend Mon_int[3], Nonmon_int[3]; /* Structure for interest data. */

double chol_prod();
double chol_sqr();
void comp_prog(void);
void compromise();
void det_pos();
float distance();
double drand();
void expand();
void factors();
void fill_points();
void fill_real();
void get_ACRS(void);
void get_distn();
double get_IEEE_real();
int get_parameters();
void ignore_bytes();
void initialize(void);
int lotus_read();
float mean();
void ni_index();
void ni_distn();
void non_recurring();
void norm_weights(void);
void npqf();
void npv();

```

```

void opening_menu(void);
void prepare(void);
void print_input();
void print_parms(void);
int read_data();
void srand();
void stdnorm();
void store_input();
float tri();
double var();

/*  FUNCTION: main                                     */
/*  DESCRIPTION:                                       */
/*    Controls the execution of the functions which comprise AMSTEP. */

main(int argc, char *argv[])
{
    unsigned short int i;
    unsigned long farmem;
    int years;
    char digit[4];
    float a, b, c, frac, temp;

    prepare();
    opening_menu();
    clrscrn();
    poscurs(5,22);
    fprintf(stderr,"<< OBTAINING ANALYSIS PARAMETERS >>");
    if (get_parameters(argc,argv[1])) {
        exit(1);
    }
    print_parms();

/*  Determine the length of the project.                */

    srand(1);
    farmem = farcoreleft();
    Years = farcalloc(YR_LEN,(unsigned long) sizeof(int));
    if(Years == NULL) {
        poscurs(20,18);
        fprintf(stderr,"Insufficient Far Memory for Years");
        poscurs(21,15);
        fprintf(stderr,"%lu bytes remaining prior to attempted allocation",farmem);
        exit(1);
    }
    a = Proj_len[0];
    c = Proj_len[1];
    b = Proj_len[2];

```

```

for (i = 0; i < Sample; ++i) {
    temp = tri(a,c,b);
    years = temp;
    frac = temp - years;
    if ((frac > 0.5) && (years < Proj_len[2]))
        years += 1;
    (*Years)[i] = years;
}
norm_weights();
for (i = 0; i < Num_alts; ++i) {
    itoa(i,digit,10);
    Prefix_name[6] = digit[0];
    Prefix_name[7] = '\0';
    clrscrn();
    poscurs(5,21);
    fprintf(stderr,"<< OBTAINING DATA FOR ALTERNATIVE %d >>",i);
    initialize();
    read_data(i);
    print_input(i);
    clrscrn();
    poscurs(5,16);
    fprintf(stderr,"<< PERFORMING CALCULATIONS FOR ALTERNATIVE %d >>",i);
    srand(1);
    npv(i);
    srand(1);
    npqf('s',i);
    srand(1);
    npqf('t',i);
}
farfree(Years);
clrscrn();
comp_prog();
clrscrn();
poscurs(5,29);
fprintf(stderr,"<< PROGRAM COMPLETE >>");
poscurs(25,0);
}

/*  FUNCTION: prepare                                     */
/*  DESCRIPTION:                                         */
/*      Initializes program variables.                   */
/*                                                         */

void prepare(void)
{
    unsigned short int i, j, k;

    Num_alts = 0;
    for (i = 0; i < 3; ++i) {

```

```

    Mon_int[i].points = Nonmon_int[i].points = 0;
    Proj_len[i] = 0;
    Obj_weight[i] = 0.;
    for (k = 0; k < 5; ++k) {
        Mon_int[i].yr_brk[k] = Nonmon_int[i].yr_brk[k] = 0.;
        for (j = 0; j < 3; ++j)
            Mon_int[i].rate[j][k] = Nonmon_int[i].rate[j][k] = 0.;
    }
}
for (i = 0; i < 6; ++i)
    Str_inp[i].weight = Tac_inp[i].weight = 0.;
}

/*  FUNCTION: opening_menu                                     */
/*  DESCRIPTION:                                             */
/*    Displays an opening message to the user.              */
/*                                                           */

void opening_menu(void)
{
    unsigned short int i;

    cursoff();
    clrscrn();
    poscurs(3,30);
    fprintf(stderr,"+-----+");
    poscurs(14,30);
    fprintf(stderr,"+-----+");
    for (i = 0; i < 10; ++i) {
        poscurs(i+4,30);
        fprintf(stderr,"|          |");
    }
    poscurs(5,33);
    fprintf(stderr,"A dvanced");
    poscurs(8,33);
    fprintf(stderr,"M anufacturing");
    poscurs(7,33);
    fprintf(stderr,"S ystem");
    poscurs(8,33);
    fprintf(stderr,"T echnology");
    poscurs(9,33);
    fprintf(stderr,"E valuation");
    poscurs(10,33);
    fprintf(stderr,"P rogram");
    poscurs(11,33);
    fprintf(stderr,"|");
    poscurs(12,33);
    fprintf(stderr,"R isk");

```

```

    poscurs(16,31);
    fprintf(stderr,"copyright (c) 1991");
    poscurs(17,32);
    fprintf(stderr,"Johann G. Demmel");
    poscurs(23,25);
    fprintf(stderr,"< strike any key to continue >");
    while (!kbhit());
    getch();
    curson();
}

/*  FUNCTION: get_parameters                                */
/*  DESCRIPTION:                                           */
/*      Obtains analysis parameters from a LOTUS 1-2-3 input file. */

int get_parameters(int argc, char parm_file)
{
    unsigned short int i, j;
    int col, int_val, opcode, parm_code = -1, parms_found = 32767, row;
    int base2, base_row, range;
    char label[240];
    double real_val;
    char parm_names[15][17] = {
        "title",
        "project length",
        "input files",
        "monetary rate",
        "nonmonetary rate",
        "tax rate",
        "acrs",
        "samples",
        "bins",
        "strategic weight",
        "tactical weight",
        "pecuniary weight",
        "p factor",
        "q factor",
        "correlation"
    };
    char strat_attrib[6][19] = {
        "Internal Relations",
        "Market Position",
        "Mission",
        "Organization",
        "Public Relations",
        "Technology"
    };
    char tact_attrib[6][15] = {
        "Design",
        "Flexibility",

```

```

    "Integration  ",
    "Material     ",
    "Personnel    ",
    "Produceability" };

if (argc == 1) {
    poscurs(8,26);
    fprintf(stderr,"ERROR: must supply file name");
    return 1;
}
else {
    Fp = fopen(parm_file,"rb");
    if (Fp == NULL) {
        poscurs(8,26);
        fprintf(stderr,"ERROR: opening %s",parm_file);
        return 1;
    }
    Num_attrib.strategic = 0;
    Num_attrib.tactical = 0;
    poscurs(9,18);
    strupr(parm_file);
    fprintf(stderr,"Processing Parameter File %s ...",parm_file);
    do {
        opcode = lotus_read(&row, &col, &int_val, &real_val, label);
        switch (opcode) {
            case 13 : /* integer value. */
                real_val = int_val;
            case 14 : /* real value. */
            case 16 : /* real value in formula. */
                if ((col == 1) && (row != base_row))
                    range += 1;
                store_input(parm_code,real_val,range,col);
                break;
            case 15 : /* label. */
                if (col == 0) {
                    range = 0;
                    base_row = row;
                    base2 = 1;
                    parm_code = -1;
                    j = 0;
                    do {
                        if (!strnicmp(parm_names[j],label,strlen(label))) {
                            parm_code = j;
                            parms_found = parms_found ^ base2;
                        }
                        base2 = base2 * 2;
                        ++j;
                    } while ((parm_code == -1) && (j < 15));
                }
        }
    } while (1);
}

```



```

    if (parm_code == -1) {
        for (i = 0; i < 6; ++i) {
            if (strnicmp(strat_attrib[i],label,strlen(label)) == 0) {
                j = Num_attrib.strategic;
                strncpy(Str_inp[j].attribute,label,strlen(label));
                Num_attrib.strategic += 1;
                parm_code = 15;
                break;
            }
            else {
                if (strnicmp(tact_attrib[i],label,strlen(label)) == 0) {
                    j = Num_attrib.tactical;
                    strncpy(Tac_inp[j].attribute,label,strlen(label));
                    Num_attrib.tactical += 1;
                    parm_code = 16;
                    break;
                }
            }
        }
    }
}
else {
    switch (parm_code) {
        case -1 :
            break;
        case 0 :
            j = strlen(label);
            if (j > 40)
                j = 40;
            strncpy(Title,label,j);
            break;
        case 2 :
            strncpy(Input_files[Num_alts],label,strlen(label));
            Num_alts += 1;
            break;
        default :
            poscurs(20,26);
            fprintf(stderr,"ERROR: parm_code not defined");
            return 2;
    }
}
break;
default : /* ignore all other opcodes. */
    break;
}
} while (opcode != 1);
fclose(Fp);
if (parms_found) {

```

```

    base2 = 1;
    poscurs(11,25);
    fprintf(stderr,"Required parameters not found");
    poscurs(12,37);
    fprintf(stderr,"%d",parms_found);
    poscurs(13,28);
    fprintf(stderr,"Missing Parameters are:");
    j = 1;
    for (i = 1; i <= 14; ++i) {
        parm_code = parms_found & base2;
        base2 = base2 * 2;
        if (parm_code) {
            poscurs(13+j,31);
            fprintf(stderr,"%s",parm_names[i-1]);
            ++j;
        }
    }
    return 3;
}
else
    return 0;
}
}

/*  FUNCTION: store_input                                     */
/*  DESCRIPTION:                                             */
/*  Stores the analysis parameters from the input file into appropriate */
/*  variables.                                              */

void store_input(int code, double value, int range, int col)
{
    int pos;

    switch (code) {
        case -1 :
            break;
        case 1 : /* project length. */
            Proj_len[range] = value;
            break;
        case 3 : /* monetary interest rate. */
        case 4 : /* nonmonetary interest rate. */
            pos = range / 4;
            switch (range) {
                case 0 : case 4 : case 8 :
                    if (code == 3) {
                        Mon_int[pos].yr_brk[Mon_int[pos].points] = value;
                        Mon_int[pos].points += 1;
                    }
            }
    }
}

```

```

        else {
            Nonmon_int[pos].yr_brk[Nonmon_int[pos].points] = value;
            Nonmon_int[pos].points += 1;
        }
        break;
    case 9 : case 10 : case 11 :
        range -= 4;
    case 5 : case 6 : case 7 :
        range -= 4;
    case 1 : case 2 : case 3 :
        range -= 1;
        if (code == 3)
            Mon_int[pos].rate[range][col-1] = value;
        else
            Nonmon_int[pos].rate[range][col-1] = value;
        break;
    }
    break;
case 5 : /* tax rate. */
    Tax_rate = value/100.;
    break;
case 6 : /* ACRS type. */
    ACRS_type = value;
    get_ACRS();
    break;
case 7 : /* minimum NPV. */
    Sample = value;
    break;
case 8 : /* maximum NPV. */
    Bins = value;
    break;
case 9 : /* strategic weight. */
    Obj_weight[1] = value;
    break;
case 10 : /* tactical weight. */
    Obj_weight[2] = value;
    break;
case 11 : /* pecuniary weight. */
    Obj_weight[0] = value;
    break;
case 12 : /* p-factor. */
    P = value;
    break;
case 13 : /* q-factor. */
    Q = value;
    break;
case 14 : /* correlation coefficient */
    Corr_coef = value;

```

```

        break;
    case 15 : /* Strategic attribute weights. */
        Str_inp[Num_attrib.strategic-1].weight = value;
        break;
    case 16 : /* Tactical attribute weights. */
        Tac_inp[Num_attrib.tactical-1].weight = value;
        break;
    default : /* error. */
        poscurs(20,18);
        fprintf(stderr,"ERROR: Invalid parameter code (%d) in store_input",
                code);
        break;
}
}

/* FUNCTION: get_ACRS */
/* DESCRIPTION: */
/* Obtains ACRS values from an input file. */

void get_ACRS(void)
{
    unsigned short int i, skip;

    In = fopen("acrs.dat","r");
    if (In == NULL) {
        poscurs(20,28);
        fprintf(stderr,"ERROR: Opening ACRS.DAT");
        exit(1);
    }
    switch (ACRS_type) {
        case 3 :
            skip = 0;
            break;
        case 5 :
            skip = 4;
            break;
        case 7 :
            skip = 10;
            break;
        case 10 :
            skip = 18;
            break;
        case 15 :
            skip = 29;
            break;
        case 20 :
            skip = 45;
            break;
    }
}

```

```

        default :
            poscurs(20,17);
            fprintf(stderr,"ERROR: Incorrect ACRS type input %d",ACRS_type);
            exit(1);
    }
    for (i = 0; i < skip; ++i)
        fscanf(In,"%f",&ACRS[0]);
    for (i = 0; i < ACRS_type + 1; ++i)
        fscanf(In,"%f",&ACRS[i]);
    fclose(In);
}

/*  FUNCTION: norm_weights                                     */
/*  DESCRIPTION:                                              */
/*      Normalizes the weights for the nonmonetary attributes, and the */
/*      objectives.                                           */
/*

void norm_weights(void)
{
    unsigned short int i;
    float sum;

    sum = 0.;
    for (i = 0; i < 3; ++i)
        sum += Obj_weight[i];
    for (i = 0; i < 3; ++i)
        Obj_weight[i] = (Obj_weight[i] / sum) * 100.;
    sum = 0.;
    for (i = 0; i < Num_attrib.strategic; ++i)
        sum += Str_inp[i].weight;
    for (i = 0; i < Num_attrib.strategic; ++i)
        Str_inp[i].weight = (Str_inp[i].weight / sum) * 100.;
    sum = 0.;
    for (i = 0; i < Num_attrib.tactical; ++i)
        sum += Tac_inp[i].weight;
    for (i = 0; i < Num_attrib.tactical; ++i)
        Tac_inp[i].weight = (Tac_inp[i].weight / sum) * 100.;
}

/*  FUNCTION: initialize                                     */
/*  DESCRIPTION:                                              */
/*      Initializes program variables.                       */
/*

void initialize(void)
{
    unsigned short int i, j, k, l;

    NPV_max = NPV_min = 0.;

```

```

for (i = 0; i < 20; ++i) {
    Mon_inp[i].description[0] = '\0';
    for (j = 0; j < 3; ++j) {
        Mon_inp[i].data[j].points = 0;
        for (k = 0; k < 5; ++k) {
            Mon_inp[i].data[j].yr_brk[k] = 0;
            for (l = 0; l < 3; ++l)
                Mon_inp[i].data[j].rate[l][k] = 0.;
        }
    }
}

for (i = 0; i < 6; ++i) {
    for (j = 0; j < 3; ++j) {
        Str_inp[i].data[j].points = Tac_inp[i].data[j].points = 0;
        for (k = 0; k < 3; ++k) {
            Str_inp[i].data[j].yr_brk[k] = Tac_inp[i].data[j].yr_brk[k] = 0;
            for (l = 0; l < 5; ++l) {
                Str_inp[i].data[j].rate[k][l] = 0.;
                Tac_inp[i].data[j].rate[k][l] = 0.;
            }
        }
    }
}

/*  FUNCTION: read_data                                     */
/*  DESCRIPTION:                                           */
/*    Reads the cash flow and qualitative flow data from the input file */
/*    specified by the user.                               */

int read_data(unsigned short int alt)
{
    unsigned short int i, process = 0, range;
    short int pos = -1;
    int base_row, col = 0, int_val, label_len, old_row, data_row, opcode, row=0;
    double real_val;
    char label[240];

    /*  Determine the number of values to input based upon the type of
       analysis to be performed, and open the input file.  If risk, input
       required is pessimistic, most likely, and optimistic.  Otherwise, only
       one input is required.                               */

    Fp = fopen(Input_files[alt],"rb");
    if (Fp == NULL) {
        fprintf(stderr, "\nERROR: opening %s\n", Input_files[alt]);
        return 1;
    }
}

```

```

/*  Read input data from a LOTUS 1-2-3 file.  Fill arrays used in this
    program with data read from the file.                                     */

strupr(Input_files[alt]);
poscurs(9,21);
fprintf(stderr,"Processing data from %s ...",Input_files[alt]);
do {
    opcode = lotus_read(&row, &col, &int_val, &real_val, label);
    switch (opcode) {
        case 13 : /* Integer input - convert to real double. */
            real_val = int_val;
        case 14 : /* Real input - process as double. */
        case 16 : /* Formula input - contains real value. */
            if (old_row == row)
                break;
            data_row = (row - base_row) / 4;
            range = row - base_row;
            if ((row - base_row) % 4 == 0)
                fill_points(data_row,col,process,real_val,pos);
            else
                fill_real(data_row,col,range,process,real_val,pos);
            break;
        case 15 : /* Label input - contains key for processing objectives. */
            if ((col > 0) && (row == base_row))
                break;
            if (col == 0) {
                range = 0;
                base_row = row;
            }
            label_len = strlen(label);
            if (strcmp("Pecuniary",label,label_len) == 0) {
                process = 1;
                Num_attrib.pecuniary = 0;
                old_row = row;
                break;
            }
            if (strcmp("Strategic",label,label_len) == 0) {
                process = 2;
                old_row = row;
                break;
            }
            if (strcmp("Tactical",label,label_len) == 0) {
                process = 3;
                old_row = row;
                break;
            }
        }
    switch (process) {

```

```

case 0:
    strncpy(Alt_title[alt],label,label_len);
    Alt_title[alt][label_len+1] = '\0';
    break;
case 1:
    pos = Num_attrib.pecuniary;
    strncpy(Mon_inp[pos].description,label,label_len);
    Mon_inp[pos].description[label_len] = '\0';
    Num_attrib.pecuniary += 1;
    break;
case 2:
    if (strncmp("Strategic",label,label_len) != 0) {
        pos = -1;
        for (i = 0; i < Num_attrib.strategic; ++i) {
            if (strncmp(Str_inp[i].attribute,label,label_len) == 0) {
                pos = i;
            }
        }
        if (pos == -1) {
            poscurs(20,20);
            fprintf(stderr,"ERROR: Strategic attribute not defined");
            poscurs(21,10);
            fprintf(stderr,"Attrib: %s\n",label);
            for (i = 0; i < Num_attrib.strategic; ++i)
                fprintf(stderr,"%s %d\n",Str_inp[i].attribute,Str_inp[i].weight);
            exit(1);
        }
    }
    break;
case 3:
    if (strncmp("Tactical",label,label_len) != 0) {
        pos = -1;
        for (i = 0; i < Num_attrib.tactical; ++i) {
            if (strncmp(Tac_inp[i].attribute,label,label_len) == 0) {
                pos = i;
            }
        }
        if (pos == -1) {
            poscurs(20,20);
            fprintf(stderr,"ERROR: Tactical attribute not defined");
            fprintf(stderr,"Attrib: %s\n",label);
            for (i = 0; i < Num_attrib.tactical; ++i)
                fprintf(stderr,"%s %4.0d\n",Tac_inp[i].attribute,Tac_inp[i].weight);
            exit(1);
        }
    }
    break;
}

```



```

        break;
    default :
        break;
    }
} while (opcode != 1);
fclose(Fp);
}

/*  FUNCTION: fill_real                                     */
/*  DESCRIPTION:                                           */
/*    Fills the appropriate arrays with cash flows or qualitative flows. */

void fill_real(row, col, range, process, real_val, pos)
    unsigned short int process, range;
    short int pos;
    int col, row;
    double real_val;
{
    int i;

    range -= 1;
    if (range >= 8)
        range -= 8;
    if (range >= 4)
        range -= 4;
    switch (process) {
        case 1:
            Mon_inp[pos].data[row].rate[range][col-1] = real_val;
            break;
        case 2:
            Str_inp[pos].data[row].rate[range][col-1] = real_val;
            break;
        case 3:
            Tac_inp[pos].data[row].rate[range][col-1] = real_val;
            break;
        default:
            fprintf(stderr, "ERROR process %d incorrect in fill_real");
            exit(1);
            break;
    }
}

/*  FUNCTION: fill_points                                   */
/*  DESCRIPTION:                                           */
/*    Fills the appropriate arrays with year breaks for cash flows or */
/*    qualitative flows.                                     */

void fill_points(row, col, process, real_val, pos)

```

```

    unsigned short int process;
    short int pos;
    int col, row;
    double real_val;
{
    int i;

    switch (process) {
        case 1:
            Mon_inp[pos].data[row].yr_brk[col-1] = real_val;
            Mon_inp[pos].data[row].points += 1;
            break;
        case 2:
            Str_inp[pos].data[row].yr_brk[col-1] = real_val;
            Str_inp[pos].data[row].points += 1;
            break;
        case 3:
            Tac_inp[pos].data[row].yr_brk[col-1] = real_val;
            Tac_inp[pos].data[row].points += 1;
            break;
        default:
            fprintf(stderr, "ERROR process %d incorrect in fill_points");
            exit(1);
            break;
    }
}

/* FUNCTION: lotus_read */
/* DESCRIPTION: */
/* Reads input data from the LOTUS files. */

int lotus_read(row, col, int_val, real_val, label)
    int *row, *col, *int_val;
    double *real_val;
    char label[240];
{
    int end_col, end_row, format_key;
    int format_type, formula_opcode, i, label_byte, length, opcode;
    int mode, protect, size, start_row, start_col;

    opcode = getc(Fp) + (getc(Fp) * 256);
    length = getc(Fp) + (getc(Fp) * 256);
    switch (opcode) {
        case 0 : /* Beginning of file */
            if (start_processing(length) != 0)
                opcode = 1;
            break;
        case 1 : /* End of file */

```

```

    break;
case 2 : /* Calculation Method */
case 3 : /* Calculation Order */
case 4 : /* Type of Window Split */
case 5 : /* Synchronize windows to cursor movement */
    ignore_bytes(length);
    break;
case 6 : /* Range */
    start_col = getc(Fp) + (getc(Fp) * 256);
    start_row = getc(Fp) + (getc(Fp) * 256);
    end_col = getc(Fp) + (getc(Fp) * 256);
    end_row = getc(Fp) + (getc(Fp) * 256);
    break;
case 7 : /* Description of Window #1 */
case 8 : /* Defines column width */
case 9 : /* Description of Window #2 */
case 10 : /* Defines column width */
case 11 : /* Range name */
    ignore_bytes(length);
    break;
case 12 : /* Blank Cell */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    break;
case 13 : /* Integer Value */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    *int_val = getc(Fp) + (getc(Fp) * 256);
    break;
case 14 : /* Floating Point Value */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    *real_val = get_IEEE_real(*row,*col);
    break;
case 15 : /* Label */
    mode = getc(Fp);
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    i = 5;
    label_byte = getc(Fp);
    while ((i < length) && (label_byte != 0)) {
        label_byte = label[i-5] = getc(Fp);
        i += 1;
    }
    label[i-5] = '\0';

```

```

        break;
case 16 : /* Formula */
    mode = getc(Fp);
    protect = mode >> 7;
    format_type = (mode >> 4) & 7;
    format_key = mode & 15;
    *col = getc(Fp) + (getc(Fp) * 256);
    *row = getc(Fp) + (getc(Fp) * 256);
    *real_val = get_IEEE_real(*row,*col);
    size = getc(Fp) + (getc(Fp) * 256);
    formula_opcode = getc(Fp);
    for(i = 16; i < length; ++i)
        getc(Fp);
    break;
case 24 : /* Table Range */
case 25 : /* Query Range */
case 26 : /* Print Range */
case 27 : /* Sort Range */
case 28 : /* Fill Range */
case 29 : /* Primary Sort Key Range */
case 32 : /* Distribution Range */
case 35 : /* Secondary Sort Key Range */
case 36 : /* Global Protection */
case 37 : /* Footer Print */
case 38 : /* Header Print */
case 39 : /* Print Setup */
case 40 : /* Margins */
case 41 : /* Label Alignment */
case 42 : /* Borders */
case 45 : /* Graph Settings */
case 46 : /* Named Current Graph Settings */
case 47 : /* Iteration Count */
case 48 : /* Unformatted print */
case 49 : /* Cursor Location */
case 75 : /* Worksheet Password */
case 100 : /* Hidden Columns Record 1 */
case 101 : /* Hidden Columns Record 2 */
case 102 : /* Parse Ranges */
case 103 : /* Linear Regression Ranges */
case 105 : /* Matrix Mathematics Ranges */
case 150 : /* Cell Pointer Index */
    ignore_bytes(length);
    break;
default : /* Other Code is an Error */
    fprintf(stderr,"ERROR: Opcode %d not defined\n",opcode);
    ignore_bytes(length);
}
return(opcode);

```

```

}

/* FUNCTION: ignore_bytes */
/* DESCRIPTION: */
/* Reads and ignores data from the input file. */

void ignore_bytes(int length)
{
    int i;

    for (i = 0; i < length; ++i)
        getc(Fp);
}

/* FUNCTION: start_processing */
/* DESCRIPTION: */
/* Displays message to the user of the type of LOTUS file being read. */

int start_processing(int length)
{
    int i, file_format = 0;

    for (i = 0; i < length; ++i)
        file_format += (getc(Fp) * pow(256,i));
    switch (file_format) {
        case 1028 : /* File type is 1-2-3 */
            poscurs(7,28);
            fprintf(stderr,"Format type is 1-2-3.");
            return(0);
        case 1029 : /* File type is Symphony - do not process */
            poscurs(7,16);
            fprintf(stderr,"Format type is SYMPHONY and cannot be processed");
            return(1);
        case 1030 : /* File type is 1-2-3 version 2 */
            poscurs(7,24);
            fprintf(stderr,"Format type is 1-2-3 version 2.");
            return(0);
        default : /* Unknown file type */
            poscurs(7,25);
            fprintf(stderr,"Format type is unknown (%04X).",file_format);
            poscurs(9,29);
            fprintf(stderr,"processing terminated");
            return(1);
    }
}

/* FUNCTION: get_IEEE_real */
/* DESCRIPTION: */

```

```

/*      Converts the input from a 64 bit IEEE real storage into a useable      */
/*      form for the program.                                                 */

double get_IEEE_real(int row, int col)
{
    int i, j, neg_exp, sign, word;
    double exponent, mantissa, value, one_bit;
    long int temp;

    neg_exp = 52;
    value = 0.;
    for (i = 0; i < 7; ++i) {
        word = 8;
        temp = getc(Fp);
        if (temp != 0) {
            if (i == 6)
                word = 4;
            for(j = 0; j < word; ++j) {
                one_bit = temp & 1;
                value += (one_bit * (1/pow(2,neg_exp)));
                neg_exp -= 1;
                temp = temp >> 1;
            }
        }
        else
            neg_exp -= 8;
    }
    exponent = temp;
    temp = getc(Fp);
    exponent += ((temp & 15) * 16);
    temp = temp >> 4;
    exponent += ((temp & 7) * 256);
    mantissa = value;
    sign = ((temp >> 3) & 1);
    if (sign == 1)
        sign = -1;
    else
        sign = 1;
    if (exponent == 2047.) {
        if (mantissa != 0.)
            fprintf(stderr,"Value at row %d col %d is not a valid number\n",row,col);
        else
            fprintf(stderr,"Value at row %d col %d is infinity\n",row,col);
        return(NULL);
    }
    if (exponent == 0.) {
        if (mantissa != 0.) {
            exponent = pow(2,-1022.);

```

```

        return(sign * exponent * mantissa);
    }
    else
        return(0.);
}
if ((exponent > 0.) && (exponent < 2047.)) {
    exponent = pow(2,(exponent-1023.));
    mantissa += 1.;
    return(sign * exponent * mantissa);
}
fprintf(stderr,"** ERROR ** Real format not converted at row %d col %d",
        row,col);
return(NULL);
}

/*  FUNCTION: npv                                     */
/*  DESCRIPTION:                                     */
/*    Determines the NPV of the Monetary cash flows. */

void npv(unsigned short int alt)
{
    unsigned short int j, k;
    int i, years;
    double cash_flow, npv, accum_flows[21];
    char filename[14];

/*  Open file for storage of NPV to determine maximum/minimum. */

    strcpy(filename,Prefix_name);
    Out = fopen(strncat(filename,".npv",4),"w");
    if (Out == NULL) {
        poscurs(20,20);
        fprintf(stderr,"ERROR: Opening %s for output\n",filename);
        poscurs(21,20);
        perror("Error number");
        exit(1);
    }

/*  Perform calculations for the desired sample size. */

    for (k = 0; k < Sample; ++k) {

/*  Determine the length of the project. */

        years = (*Years)[k];

/*  Determine the vector of interest factors to use (Factors[]). */

        factors(years,0,'m',Mon_int);

```

```

/* Determine the cash flows to use.                                     */

    for (i = 0; i <= 21; ++i) {
        Depreciation[i] = 0.;
        accum_flows[i] = 0.;
    }
    for (i = 0; i < Num_attrib.pecuniary; ++i) {
        if ((strnicmp(Mon_inp[i].description,"salvage value",13) == 0) ||
            (strnicmp(Mon_inp[i].description,"depr investment",15) == 0) ||
            (strnicmp(Mon_inp[i].description,"investment",10) == 0)) {
            non_recurring(years,i,Mon_inp[i].data);
        }
        else {
            factors(years,i,'c',Mon_inp[i].data);
        }
        for (j = 0; j <= years; ++j)
            accum_flows[j] += Flows[j];
    }
    npv = 0.;
    for (j = 0; j <= years; ++j) {
        cash_flow = (accum_flows[j] * (1 - Tax_rate)) +
                    (Depreciation[j] * Tax_rate);
        npv += (cash_flow * Factors[j]);
    }
    if (k == 0) {
        Max[alt][12] = npv;
        Min[alt][12] = npv;
    }
    else {
        if (npv > Max[alt][12])
            Max[alt][12] = npv;
        if (npv < Min[alt][12])
            Min[alt][12] = npv;
    }
    fprintf(Out,"%d %12.2f\n",k,npv);
}
fclose(Out);
}

/* FUNCTION: det_pos                                                  */
/* DESCRIPTION:                                                       */
/*     Determines the position in the input of the values to use.    */
/*                                                                      */

void det_pos(pos1, pos2, limit, data)
short int *pos1, *pos2;
int limit;
struct Depend data[3];

```



```

{
    short int i;

    for (i = 0; i < 2; ++i) {
        *pos1 = data[i].points - 1;
        *pos2 = data[i+1].points - 1;
        if ((limit >= Proj_len[i]) && (limit <= Proj_len[i+1])) {
            if (Proj_len[i] == limit) {
                *pos1 = i;
                *pos2 = 0;
                return;
            }
            if (Proj_len[i+1] == limit) {
                *pos1 = i + 1;
                *pos2 = 0;
                return;
            }
            *pos1 = i;
            *pos2 = i + 1;
            return;
        }
    }
    poscurs(20,20);
    fprintf(stderr,"ERROR: Project Length %d not found ",limit);
    exit(1);
}

/*  FUNCTION: non_recurring                                     */
/*  DESCRIPTION:                                               */
/*      Determines the flows for non recurring attributes.     */
/*                                                                */

void non_recurring(int limit, int idx, struct Depend raw_data[3])
{
    short int loc, pos1, pos2, i, j, k;
    int ACRS_limit;
    float off_set, x1, x2;
    double mean, temp[3], var;

    det_pos(&pos1,&pos2,limit,raw_data);

    for (i = 0; i <= limit; ++i)
        Flows[i] = 0.;
    off_set = limit - Proj_len[pos1];
    off_set = off_set / (Proj_len[pos1+1] - Proj_len[pos1]);
    for (i = 0; i < raw_data[pos1].points; ++i) {
        for (j = 0; j <= limit; ++j) {
            if(raw_data[pos1].yr_brk[i] == j) {
                if (pos2 != 0) {

```



```

/*  DESCRIPTION:                                     */
/*      Determines the NPQF of the Nonmonetary cash flows.      */
/*                                                                 */

void npqf(char objective, unsigned short int alt)
{
    int i, j, k, l, years, m;
    float ni, r_ni;
    float npqf_s[6], npqf_t[6], qual_flow;
    char filename[14];

    strcpy(filename, Prefix_name);
    if (objective == 's')
        Out = fopen(strncat(filename, ".qfs", 4), "w");
    if (objective == 't')
        Out = fopen(strncat(filename, ".qft", 4), "w");
    if (Out == NULL) {
        poscurs(20, 20);
        fprintf(stderr, "ERROR: Opening %s for output", filename);
        exit(1);
    }

/*  Perform calculations for the desired sample size.          */
/*                                                                 */

    for (k = 0; k < Sample; ++k) {

/*  Get the number of years.                                    */
/*                                                                 */

        years = (*Years)[k];

/*  Determine the vector of interest factors to use (Factors[]). */
/*                                                                 */

        factors(years, 0, 'n', Nonmon_int);
        r_ni = 0.;
        for (i = 1; i <= years; ++i)
            r_ni += Factors[i];
        switch (objective) {
            case 's' :
                for (j = 0; j < Num_attrib.strategic; ++j) {
                    factors(years, j, 'q', Str_inp[j].data);
                    npqf_s[j] = 0.;
                    for (i = 1; i <= years; ++i)
                        npqf_s[j] += Flows[i] * Factors[i];
                }
                fprintf(Out, "\n%d ", k);
                for (j = 0; j < Num_attrib.strategic; ++j)
                    fprintf(Out, "%7.2f ", npqf_s[j]);
                for (j = 0; j < Num_attrib.strategic; ++j) {
                    ni = npqf_s[j] / (100. * r_ni);

```

```

        fprintf(Out,"%7.4f ",ni);
        if (k == 0) {
            Max[alt][j] = ni;
            Min[alt][j] = ni;
        }
        else {
            if (ni > Max[alt][j])
                Max[alt][j] = ni;
            if (ni < Min[alt][j])
                Min[alt][j] = ni;
        }
    }
    break;
case 't' :
    for (j = 0; j < Num_attrib.tactical; ++j) {
        factors(years,j,'q',Tac_inp[j].data);
        npqf_t[j] = 0.;
        for (i = 1; i <= years; ++i)
            npqf_t[j] += Flows[i] * Factors[i];
    }
    fprintf(Out,"\n%d ",k);
    for (j = 0; j < Num_attrib.tactical; ++j)
        fprintf(Out,"%7.2f ",npqf_t[j]);
    for (j = 0; j < Num_attrib.tactical; ++j) {
        ni = npqf_t[j] / (100. * r_ni);
        fprintf(Out,"%7.4f ",ni);
        if (k == 0) {
            Max[alt][j+Num_attrib.strategic] = ni;
            Min[alt][j+Num_attrib.strategic] = ni;
        }
        else {
            if (ni > Max[alt][j+Num_attrib.strategic])
                Max[alt][j+Num_attrib.strategic] = ni;
            if (ni < Min[alt][j+Num_attrib.strategic])
                Min[alt][j+Num_attrib.strategic] = ni;
        }
    }
    break;
}
}
fprintf(Out,"\n");
fclose(Out);
}

/*  FUNCTION: factors                                     */
/*  DESCRIPTION:                                         */
/*    Determines the interest rate and cash/qualitative flows to use in */
/*    in the analysis.                                   */

```

```

void factors(limit, attrib, fac_type, raw_data)
int limit, attrib;
char fac_type;
struct Depend raw_data[3];
{
    short int found=0, i, j, k, intervals, lim_off, pos1, pos2;
    double adjust, off_set;
    double cov[21][21], means[21], samples[22][22], values[3][21];
    float rate, x1, x2;
    char digit[4], filename[10];

/*  Generate new parameters  */

    lim_off = 1;
    det_pos(&pos1,&pos2,limit,raw_data);
    if (pos2 == 0) {
        expand(limit,raw_data[pos1],values);
    }
    else {
        expand(limit,raw_data[pos1],values);
        for (i = 0; i < 3; ++i) {
            for (j = 0; j < limit+lim_off; ++j)
                cov[i+3][j] = values[i][j];
        }
        expand(limit,raw_data[pos2],values);
        for (i = 0; i < 3; ++i) {
            for (j = 0; j < limit+lim_off; ++j)
                cov[i+6][j] = values[i][j];
        }
        off_set = limit-Proj_len[pos1];
        off_set = off_set / (Proj_len[pos2]-Proj_len[pos1]);
        for (i = 0; i < 3; ++i) {
            for (j = 0; j < Proj_len[pos1]+lim_off; ++j) {
                if (cov[i+3][j] == cov[i+6][j])
                    values[i][j] = cov[i+3][j];
                else
                    values[i][j] = cov[i+3][j] + (off_set*(cov[i+6][j]-cov[i+3][j]));
            }
        }
        for (i = 0; i < 3; ++i) {
            k = Proj_len[pos1];
            adjust = (1 - off_set) * (cov[i+6][k] - cov[i+3][k]);
            for (j = Proj_len[pos1]+1; j < limit+lim_off; ++j)
                values[i][j] = cov[i+6][j] - adjust;
        }
    }
}

```

```

/* If dependent, generate values using the multivariate normal      */
/* approximation. Otherwise, use the triangular distribution.        */

    if (Corr_coef != 0.0) {

/* Determines Means. */

        for (i = 0; i < limit+lim_off; ++i) {
            means[i] = 0.;
            for (j = 0; j < 3; ++j)
                means[i] += values[j][i];
            means[i] = means[i] / 3.;
        }

/* Determine Covariance Matrix. */

        for (i = 0; i < limit+lim_off; ++i)
            for (j = 0; j < limit+lim_off; ++j)
                cov[i][j] = 0.;

        for (i = 0; i < limit+lim_off; ++i) {
            cov[i][i] = 0.;
            for (j = 0; j < 3; ++j)
                cov[i][i] += (values[j][i] * values[j][i]);
            cov[i][i] -= (values[0][i] * values[1][i]);
            cov[i][i] -= (values[0][i] * values[2][i]);
            cov[i][i] -= (values[1][i] * values[2][i]);
            cov[i][i] = cov[i][i] / 18.;
        }
        for (i = 0; i < limit+lim_off; ++i) {
            for (j = i+1; j < limit+lim_off; ++j) {
                cov[i][j] = pow(Corr_coef,j-i) * sqrt(cov[i][i]) * sqrt(cov[j][j]);
                cov[j][i] = cov[i][j];
            }
        }

/* Determine Factors to use for this iteration. */

        for (i = 0; i < 21; ++i) {
            for (j = 0; j < 21; ++j)
                samples[i][j] = 0.;
        }
        for (i = 1; i < limit+lim_off; ++i) {
            for (j = 1; j < i; ++j) {
                adjust = chol_prod(i,j,samples);
                samples[i][j] = (cov[i][j] - adjust) / samples[j][j];
                samples[j][i] = 0.;
            }
        }

```

```

    adjust = chol_sqr(i,samples);
    samples[i][i] = sqrt(cov[i][i] - adjust);
}

for (i = 0; i < limit+lim_off; ++i) {
    if ((i%2) == 0) {
        stdnorm(&x1,&x2);
        cov[0][i] = x1;
        cov[0][i+1] = x2;
    }
    cov[1][i] = 0.;
}
for (i = 0; i < limit+lim_off; ++i) {
    for (j = 0; j <= i; ++j) {
        cov[1][i] = cov[1][i] + (samples[i][j] * cov[0][j]);
    }
}
}

switch (fac_type) {
case 'm' : /* monetary interest rates. */
case 'n' : /* nonmonetary interest rates. */
    rate = 1.;
    Factors[0] = 1.;
    for (i = 1; i < limit+lim_off; ++i) {
        if (Corr_coef != 0.0)
            rate = rate * ( 1. + ((means[i] + cov[1][i]) / 100.));
        else
            rate = rate*(1.+(tri(values[0][i],values[1][i],values[2][i])/100.));
        Factors[i] = 1. / rate;
    }
    break;
case 'c' : /* cash flows. */
case 'q' : /* qualitative flows. */
    for (i = 0; i < limit+lim_off; ++i) {
        if (Corr_coef != 0.0) {
            Flows[i] = means[i] + cov[1][i];
            if (fac_type == 'q') {
                if (Flows[i] > 100.)
                    Flows[i] = 100.;
                if (Flows[i] < -100.)
                    Flows[i] = -100.;
            }
        }
        else
            Flows[i] = tri(values[0][i],values[1][i],values[2][i]);
    }
    break;
}

```

```

    default :
        poscurs(20,20);
        fprintf(stderr,"ERROR: Incorrect fac_type in factors - %s",fac_type);
        exit(1);
    }
}

/*  FUNCTION: expand                                     */
/*  DESCRIPTION:                                         */
/*    Expands the input interest rates, cash/qualitative flows, into */
/*    values covering the entire project length.         */
/*                                                         */

void expand(limit,raw_values,values)
    int limit;
    struct Depend raw_values;
    double values[3][21];
{
    short int i, j, k, mult;
    float del_x, del_y;

    for (j = 0; j < 21; ++j) {
        for (i = 0; i < 3; ++i)
            values[i][j] = 0.;
    }
    for (i = 0; i < raw_values.points-1; ++i) {
        del_x = raw_values.yr_brk[i+1] - raw_values.yr_brk[i];
        mult = 0;
        for (k = raw_values.yr_brk[i]; k < raw_values.yr_brk[i+1]; ++k) {
            for (j = 0; j < 3; ++j) {
                del_y = raw_values.rate[j][i+1] - raw_values.rate[j][i];
                values[j][k] = ((del_y / del_x) * mult) + raw_values.rate[j][i];
            }
            mult +=1;
        }
    }
    k = raw_values.points-1;
    for (i = raw_values.yr_brk[k]; i <= limit; ++i) {
        for (j = 0; j < 3; ++j)
            values[j][i] = raw_values.rate[j][k];
    }
}

/*  FUNCTION: chol_prod                                   */
/*  DESCRIPTION:                                         */
/*    Calculates a product for the Cholesky factorization. */
/*    Used in determining random values for rates and flows. */
/*                                                         */

double chol_prod(int i, int j, double samples[22][22])

```



```

{
    int k;
    double temp;

    temp = 0.;
    for (k = 0; k < j; ++k)
        temp += (samples[i][k] * samples[j][k]);
    return temp;
}

/*  FUNCTION: chol_sqr                                     */
/*  DESCRIPTION:                                           */
/*    Calculates a square for the Cholesky factorization. */
/*    Used in determining random values for rates and flows. */

double chol_sqr(int i, double samples[22][22])
{
    int k;
    double temp;

    temp = 0.;
    for (k = 0; k < i; ++k)
        temp += (samples[i][k] * samples[i][k]);
    return temp;
}

/*  FUNCTION: stdnorm                                     */
/*  DESCRIPTION:                                           */
/*    Calculates two standard normal deviates.           */

void stdnorm(float *u1, float *u2)
{
    float v1, v2, w, y;

    w = 2.;
    while (w > 1.) {
        *u1 = drand(0);
        *u2 = drand(0);
        v1 = *u1*2 - 1.;
        v2 = *u2*2 - 1.;
        w = (v1*v1) + (v2*v2);
        if (w <= 1.) {
            y = sqrt((-2.* log(w))/w);
            *u1 = v1 * y;
            *u2 = v2 * y;
        }
    }
}

```

```

/*  FUNCTION: tri                                     */
/*  DESCRIPTION:                                     */
/*    Calculates a sample from a triangular distribution with minimum a, */
/*    mode c, and maximum b.                         */
/*                                                    */

float tri(float a, float c, float b)
{
    float u;

    u = drand(0);
    if (u <= ((c - a) / (b - a)))
        return a + sqrt((c-a)*(b-a)*u);
    else
        return b - sqrt((b-c)*(b-a)*(1.-u));
}

/*  FUNCTION: comp_prog                             */
/*  DESCRIPTION:                                     */
/*    Calculates the Composite Programming score for an alternative. */
/*                                                    */

void comp_prog(void)
{
    unsigned int alt_chk, i, j, l, m;
    int k;
    float mi, power, evaluate;
    double delta, npv, r_mi;
    char digit[4], filename[14];

    power = Q/P;

/*  Determine the overall minimum and maximum NPV.  */

    NPV_max = Max[0][12];
    NPV_min = Min[0][12];
    for (j = 1; j < Num_alts; ++j) {
        if (Max[j][12] > NPV_max)
            NPV_max = Max[j][12];
        if (Min[j][12] < NPV_min)
            NPV_min = Min[j][12];
    }
    r_mi = NPV_max;
    if (fabs(NPV_min) > NPV_max)
        r_mi = fabs(NPV_min);

/*  For each alternative, determine the Composite Programming Score.  */

    for (j = 0; j < Num_alts; ++j) {

```

```

poscurs(5,12);
fprintf(stderr,"<< PERFORMING COMPOSITE PROGRAMMING FOR ALTERNATIVE %d >>"
           ,j);
itoa(j,digit,10);
Prefix_name[6] = digit[0];
Prefix_name[7] = '\0';

/*   Begin with Pecuniary Index.   */

poscurs(7,32);
fprintf(stderr,"pecuniary index");
strcpy(filename,Prefix_name);
Compr = fopen(strncat(filename,".npv",4),"r");
if (Compr == NULL) {
    poscurs(20,26);
    fprintf(stderr,"ERROR: Opening %s",filename);
    exit(1);
}

/*   Determine the distributions of the monetary indicies and   */
/*   Pecuniary objective.                                       */

for (i = 0; i < Bins; ++i) {
    Distribution[0][i] = Distribution[1][i] = 0.0;
    Distribution[2][i] = Distribution[3][i] = 0.0;
}
delta = fabs((Max[j][12]/r_mi)-(Min[j][12]/r_mi))/Bins;
for (i = 0; i < Bins; ++i)
    Distribution[0][i] = (Min[j][12]/r_mi) + ((i+1) * delta);
delta = 100. * distance(Min[j][12]/r_mi);
delta = Obj_weight[0] * pow(delta,power);
npv = 100. * distance(Max[j][12]/r_mi);
npv = Obj_weight[0] * pow(npv,power);
delta = fabs(delta-npv) / Bins;
for (i = 0; i < Bins; ++i)
    Distribution[2][i] = npv + ((i+1) * delta);
for (i = 0; i < Sample; ++i) {
    fscanf(Compr,"%d %lf",&alt_chk,&npv);
    mi = npv / r_mi;
    for (k = 0; k < Bins; ++k) {
        if (mi <= Distribution[0][k]) {
            Distribution[1][k] += 1.;
            break;
        }
    }
    if (k == Bins-1)
        Distribution[1][k] +=1.;
}
evaluate = 100. * distance(mi);
evaluate = Obj_weight[0] * pow(evaluate,power);

```

```

    for (k = 0; k < Bins; ++k) {
        if (evaluate <= Distribution[2][k]) {
            Distribution[3][k] += 1.;
            break;
        }
        if (k == Bins-1)
            Distribution[3][k] += 1.;
    }
}
fclose(Compr);
strcpy(filename, Prefix_name);
Compr = fopen(strncat(filename, ".mi", 4), "w");
if (Compr == NULL) {
    poscurs(20, 26);
    fprintf(stderr, "ERROR: Opening %s", filename);
    exit(1);
}

/* Offset the bin number to the center of the bin. */

evaluate = (Distribution[0][1]-Distribution[0][0])/2;
mi = (Distribution[2][1]-Distribution[2][0])/2;
for (i = 0; i < Bins; ++i) {
    Distribution[0][i] -= evaluate;
    Distribution[1][i] = Distribution[1][i] / Sample;
    Distribution[2][i] -= mi;
    Distribution[3][i] = Distribution[3][i] / Sample;
}

/* Print out the results of the distribution, with mean and variance. */

mi = mean(0, 1);
for (i = 0; i < Bins; ++i)
    fprintf(Compr, "%6.4f ", Distribution[0][i]);
fprintf(Compr, "\n");
for (i = 0; i < Bins; ++i)
    fprintf(Compr, "%6.4f ", Distribution[1][i]);
fprintf(Compr, "\n");
fprintf(Compr, "MEAN      %6.4f\n", mi);
fprintf(Compr, "VARIANCE  %6.4f\n", var(0, 1, mi));
fclose(Compr);

strcpy(filename, Prefix_name);
Objout = fopen(strncat(filename, ".pec", 4), "w");
if (Objout == NULL) {
    poscurs(20, 26);
    fprintf(stderr, "ERROR: Opening %s", filename);
    exit(1);
}

```

```

    }
    mi = mean(2,3);
    for (i = 0; i < Bins; ++i)
        fprintf(Objout,"%8.2f ",Distribution[2][i]);
    fprintf(Objout,"\n");
    for (i = 0; i < Bins; ++i)
        fprintf(Objout,"%8.4f ",Distribution[3][i]);
    fprintf(Objout,"\n");
    fprintf(Compr,"MEAN      %8.4f\n",mi);
    fprintf(Compr,"VARIANCE  %8.4f\n",var(2,3,mi));
    fclose(Objout);

/*   Strategic Index.   */

    poscurs(7,32);
    fprintf(stderr,"strategic index");
    ni_index(1,j,Num_attrib.strategic,".qfs");
    ni_distn(Num_attrib.strategic,".nis",".str");

/*   Tactical Index   */

    poscurs(7,32);
    fprintf(stderr,"tactical index ");
    ni_index(2,j,Num_attrib.tactical,".qft");
    ni_distn(Num_attrib.tactical,".nit",".tac");

/*   Determine Final Score.   */

    poscurs(7,32);
    fprintf(stderr," final score ");
    get_distn(".pec",0,2);
    get_distn(".str",2,4);
    get_distn(".tac",4,6);
    evaluate = 0.;
    for (i = 0; i < 6; i += 2)
        evaluate += Distribution[i][0];
    mi = pow(evaluate,(1./Q));
    evaluate = 0.;
    for (i = 0; i < 6; i += 2)
        evaluate += Distribution[i][Bins-1];
    Distribution[6][Bins-1] = pow(evaluate,(1./Q));
    delta = fabs(Distribution[6][Bins-1] - mi) / Bins;
    for (i = 0; i < Bins; ++i) {
        Distribution[6][i] = mi + ((i+1) * delta);
        Distribution[7][i] = 0.;
    }

    strcpy(filename,Prefix_name);

```

```

Compr = fopen(strncat(filename, ".fin", 4), "w");
if (Compr == NULL) {
    poscurs(20, 26);
    fprintf(stderr, "ERROR: Opening %s", filename);
    exit(1);
}
evaluate = 0.;
for (k = 0; k < Bins; ++k) {
    for (l = 0; l < Bins; ++l) {
        for (m = 0; m < Bins; ++m) {
            evaluate = Distribution[0][k] + Distribution[2][l] + Distribution[4][m];
            evaluate = pow(evaluate, (1./Q));
            fprintf(Compr, "%6.2f\n", evaluate);
            mi = Distribution[1][k] * Distribution[3][l] * Distribution[5][m];
            for (i = 0; i < Bins; ++i) {
                if (evaluate <= Distribution[6][i]) {
                    Distribution[7][i] += mi;
                    break;
                }
                if (i == Bins-1)
                    Distribution[7][i] += mi;
            }
        }
    }
}
fclose(Compr);
strcpy(filename, Prefix_name);
Objout = fopen(strncat(filename, ".scr", 4), "w");
if (Objout == NULL) {
    poscurs(20, 26);
    fprintf(stderr, "ERROR: Opening %s", filename);
    exit(1);
}
delta = fabs(Distribution[6][1] - Distribution[6][0])/2;
for (i = 0; i < Bins; ++i)
    Distribution[6][i] -= delta;
mi = mean(6, 7);
for (i = 0; i < Bins; ++i)
    fprintf(Objout, "%6.4f ", Distribution[6][i]);
fprintf(Objout, "\n");
for (i = 0; i < Bins; ++i)
    fprintf(Objout, "%8.6f ", Distribution[7][i]);
fprintf(Objout, "\n");
fprintf(Compr, "MEAN      %6.4f\n", mi);
fprintf(Compr, "VARIANCE  %6.4f\n", var(6, 7, mi));
fclose(Objout);
}
}

```

```

/*  FUNCTION: get_distn                                     */
/*  DESCRIPTION:                                           */
/*      Input a calculated distribution from a data file.  */
/*                                                         */

void get_distn(extn,lower,upper)
char extn[5];
unsigned short lower, upper;
{
    int i, j;
    char filename[14];

    strcpy(filename,Prefix_name);
    In = fopen(strncat(filename,extn,4),"r");
    if (In == NULL) {
        poscurs(20,26);
        fprintf(stderr,"ERROR: Opening %s",filename);
        exit(1);
    }
    for (i = lower; i < upper; ++i) {
        for (j = 0; j < Bins; ++j)
            fscanf(In,"%f",&Distribution[i][j]);
    }
    fclose(In);
}

/*  FUNCTION: ni_index                                     */
/*  DESCRIPTION:                                           */
/*      Determines the Strategic and Tactical indicies.  */
/*                                                         */

void ni_index(type,alt,num_attrib,extn)
unsigned short int alt, num_attrib, type;
char extn[5];
{
    unsigned short int alt_chk, i, k, l, pos;
    float delta, evaluate, ni, power, prob, weight;
    char filename[14];

    strcpy(filename,Prefix_name);
    Compr = fopen(strncat(filename,extn,4),"r");
    if (Compr == NULL) {
        poscurs(20,26);
        fprintf(stderr,"ERROR: Opening %s",filename);
        exit(1);
    }
}

/*  Set up bins for NI distribution */

```

```

for (k = 0; k < num_attrib; ++k) {
    for (l = 0; l < Bins; ++l)
        Distribution[k*2][l] = Distribution[(k*2)+1][l] = 0.0;
    pos = k;
    if (type == 2)
        pos = k + Num_attrib.strategic;
    delta = fabs((Max[alt][pos]-Min[alt][pos])/Bins);
    for (i = 0; i < Bins; ++i)
        Distribution[k*2][i] = Min[alt][pos] + ((i+1) * delta);
}

for (k = 0; k < Sample; ++k) {
    fscanf(Compr,"%d",&alt_chk);
    for (l = 0; l < num_attrib; ++l) {
        fscanf(Compr,"%f",&evaluate);
    }
    for (l = 0; l < num_attrib; ++l) {
        fscanf(Compr,"%f",&ni);
        for (i = 0; i < Bins; ++i) {
            if (ni <= Distribution[l*2][i]) {
                Distribution[(l*2)+1][i] += 1.;
                break;
            }
            if (i == Bins-1)
                Distribution[(l*2)+1][i] += 1.;
        }
    }
}
fclose(Compr);

/* Offset the bin number to the center of the bin */

for (l = 0; l < num_attrib; ++l) {
    delta = (Distribution[l*2][l] - Distribution[l*2][0]) / 2;
    for (i = 0; i < Bins; ++i) {
        Distribution[l*2][i] = Distribution[l*2][i] - delta;
        Distribution[(l*2)+1][i] = Distribution[(l*2)+1][i] / Sample;
    }
}

/* Determine limits for Strategic and Tactical indicies. */

power = Q/P;
for (l = 0; l < 2; ++l) {
    evaluate = 0.;
    for (k = 0; k < num_attrib; ++k) {
        if (type == 1)
            weight = Str_inp[k].weight;
    }
}

```



```

        if (type == 2)
            weight = Tac_inp[k].weight;
        if (l == 1)
            l = Bins-1;
        evaluate += weight * distance(Distribution[k*2][l]);
    }
    evaluate = Obj_weight[type] * pow(evaluate,power);
    ACRS[l] = evaluate;
}
evaluate = fabs(ACRS[0] - ACRS[Bins-1]) / Bins;
for (k = 0; k < Bins; ++k) {
    Factors[k] = ACRS[Bins-1] + ((k+1) * evaluate);
}

evaluate = 0.;
for (i = 0; i < Bins; ++i)
    ACRS[i] = 0;
compromise(type,0,evaluate,1.);
}

/*  FUNCTION: ni_distn                                     */
/*  DESCRIPTION:                                           */
/*      Determine the distribtuions for the Nonmonetary Indices. */

void ni_distn(num_attrib,ni_extn,obj_extn)
unsigned short int num_attrib;
char ni_extn[5], obj_extn[5];
{
    unsigned short int i;
    short int j;
    double avg, delta;
    char filename[14];

    strcpy(filename,Prefix_name);
    Compr = fopen(strncat(filename,ni_extn,4),"w");
    if (Compr == NULL) {
        poscurs(20,26);
        fprintf(stderr,"ERROR: Opening %s",filename);
        exit(1);
    }
    for (j = 0; j < num_attrib; ++j) {
        avg = mean((j*2),((j*2)+1));
        for (i = 0; i < Bins; ++i)
            fprintf(Compr,"%6.4f ",Distribution[j*2][i]);
        fprintf(Compr,"\n");
        for (i = 0; i < Bins; ++i)
            fprintf(Compr,"%6.4f ",(Distribution[(j*2)+1][i]));
        fprintf(Compr,"\n");
    }
}

```

```

        fprintf(Compr,"MEAN      %6.4f\n",avg);
        fprintf(Compr,"VARIANCE  %6.4f\n",var((j*2),((j*2)+1),avg));
    }
    fclose(Compr);
    strcpy(filename,Prefix_name);
    Objout = fopen(strncat(filename,obj_extn,4),"w");
    if (Objout == NULL) {
        poscurs(20,26);
        fprintf(stderr,"ERROR: Opening %s",filename);
        exit(1);
    }
    avg = 0.;
    delta = fabs(Factors[1] - Factors[0])/2;
    for (j = 0; j < Bins; ++j) {
        fprintf(Objout,"%8.2f ",(Factors[j]-delta));
        avg += ((Factors[j]-delta) * ACRS[j]);
    }
    fprintf(Objout,"\n");
    delta = 0.;
    for (j = 0; j < Bins; ++j) {
        fprintf(Objout,"%8.6f ",ACRS[j]);
        delta += ((Factors[j]-delta) * (Factors[j]-delta) * ACRS[j]);
    }
    fprintf(Objout,"\n");
    delta -= (avg * avg);
    fprintf(Compr,"MEAN      %12.4f\n",avg);
    fprintf(Compr,"VARIANCE  %12.4f\n",delta);
    fclose(Objout);
}

/*  FUNCTION: compromise                                     */
/*  DESCRIPTION:                                           */
/*      Calculates the compromise programming portion for each objective. */

void compromise(type,inc,evaluate,prob)
unsigned int inc, type;
float evaluate, prob;
{
    unsigned short int i, j, inc_lim;
    float joint_prob, power, result, weight;

    power = Q/P;
    if (type == 1) {
        weight = Str_inp[inc].weight;
        inc_lim = Num_attrib.strategic - 1;
    }
    else {
        weight = Tac_inp[inc].weight;

```

```

    inc_lim = Num_attrib.tactical - 1;
}
for (i = 0; i < Bins; ++i) {
    if (inc < inc_lim) {
        result = evaluate + (weight * distance(Distribution[inc*2][i]));
        joint_prob = prob * Distribution[(inc*2)+1][i];
        compromise(type,inc+1,result,joint_prob);
    }
    else {
        result = evaluate + (weight * distance(Distribution[inc*2][i]));
        result = Obj_weight[type] * pow(result,power);
        joint_prob = prob * Distribution[(inc*2)+1][i];
        for (j = 0; j < Bins; ++j) {
            if (result <= Factors[j]) {
                ACRS[j] += joint_prob;
                break;
            }
            if (j == Bins-1)
                ACRS[j] += joint_prob;
        }
    }
}
}
}

/*  FUNCTION: distance                                     */
/*  DESCRIPTION:                                           */
/*  Calculates the distance an attribute is from the ideal. */
/*

float distance(float term)
{
    float results;

    results = ((1. - term) / 2.);
    return pow(results,P);
}

/*  FUNCTION: mean                                         */
/*  DESCRIPTION:                                           */
/*  Determines the mean of a distribution.                 */
/*

float mean(int value, int prob)
{
    unsigned short int i;
    float temp;

    temp = 0.;
    for (i = 0; i < Bins; ++i)
        temp += Distribution[value][i] * Distribution[prob][i];
}

```

```

    return temp;
}

/*  FUNCTION: var                                     */
/*  DESCRIPTION:                                     */
/*    Determines the variance of a distribution.      */
/*                                                    */

double var(int value, int prob, double mean)
{
    unsigned short int i;
    double temp;

    temp = 0.;
    for (i = 0; i < Bins; ++i)
        temp += (pow(Distribution[value][i],2.0) * Distribution[prob][i]);
    return (temp - pow(mean,2.0));
}

/*  FUNCTION: print_parms                             */
/*  DESCRIPTION:                                     */
/*    Prints the input parameters specified by the user. */
/*                                                    */

void print_parms()
{
    unsigned short int i, j, k, limit;

    limit = 3;
    Out = fopen("amstep-r.prm","w");
    if (Out == NULL) {
        poscurs(20,26);
        fprintf(stderr,"ERROR: opening AMSTEP-R.PRM");
        exit(1);
    }
    fprintf(Out,"%s\n",Title);
    fprintf(Out,"Tax rate %5.2f\n",Tax_rate*100.);
    fprintf(Out,"Depreciation ACRS %d years\n",ACRS_type);
    fprintf(Out,"Project Length ");
    for (j = 0; j < limit; ++j)
        fprintf(Out,"%d ",Proj_len[j]);
    fprintf(Out,"\nMonetary Rate ");
    for (i = 0; i < limit; ++i) {
        for (j = 0; j < Mon_int[i].points; ++j)
            fprintf(Out,"%3d ",Mon_int[i].yr_brk[j]);
        fprintf(Out,"\n");
        for (j = 0; j < limit; ++j) {
            for (k = 0; k < Mon_int[i].points; ++k)

```

```

        fprintf(Out,"%5.2f ",Mon_int[i].rate[j][k]);
        fprintf(Out,"\n");
    }
}
fprintf(Out,"Nonmonetary Rate ");
for (i = 0; i < limit; ++i) {
    for (j = 0; j < Nonmon_int[i].points; ++j)
        fprintf(Out,"%3d ",Nonmon_int[i].yr_brk[j]);
    fprintf(Out,"\n");
    for (j = 0; j < limit; ++j) {
        for (k = 0; k < Nonmon_int[i].points; ++k)
            fprintf(Out,"%5.2f ",Nonmon_int[i].rate[j][k]);
        fprintf(Out,"\n");
    }
}
for (j = 0; j < Num_attrib.strategic; ++j)
    fprintf(Out,"%s \t %4.1f\n",Str_inp[j].attribute,Str_inp[j].weight);
for (j = 0; j < Num_attrib.tactical; ++j)
    fprintf(Out,"%s \t %4.1f\n",Tac_inp[j].attribute,Tac_inp[j].weight);
fprintf(Out,"Pecuniary Weight %4.1f\n",Obj_weight[0]);
fprintf(Out,"Strategic Weight %4.1f\n",Obj_weight[1]);
fprintf(Out,"Tactical Weight %4.1f\n",Obj_weight[2]);
fprintf(Out,"NPV min %12.2f   NPV max %12.2f\n",NPV_min,NPV_max);
fprintf(Out,"Sample size %d      ",Sample);
fprintf(Out,"Number of bins %d\n",Bins);
fprintf(Out,"Correlation coefficient %4.2f ",Corr_coef);
fclose(Out);
}

/*  FUNCTION: print_input                                     */
/*  DESCRIPTION:                                             */
/*  Prints the input data specified by the user.             */
/*  */

void print_input(unsigned short int alt)
{
    unsigned short int i, j, k, l, limit;
    char filename[14];

    limit = 3;

    strcpy(filename,Prefix_name);
    Out = fopen(strncat(filename,".inp",4),"w");
    if (Out == NULL) {
        poscurs(20,20);
        fprintf(stderr,"ERROR: Opening %s for output",filename);
        exit(1);
    }
    fprintf(Out,"%s\n",Alt_title[alt]);

```

```

fprintf(Out,"PECUNIARY");
for (i = 0; i < Num_attrib.pecuniary; ++i) {
    for (j = 0; j < limit; ++j) {
        fprintf(Out,"\n%s",Mon_inp[i].description);
        for (k = 0; k < Mon_inp[i].data[j].points; ++k)
            fprintf(Out,"\t%d",Mon_inp[i].data[j].yr_brk[k]);
        fprintf(Out,"\n");
        for (k = 0; k < limit; ++k) {
            for (l = 0; l < Mon_inp[i].data[j].points; ++l)
                fprintf(Out,"\t%15.2f",Mon_inp[i].data[j].rate[k][l]);
            fprintf(Out,"\n");
        }
    }
}
fprintf(Out,"\n\nSTRATEGIC");
for (i = 0; i < Num_attrib.strategic; ++i) {
    for (j = 0; j < limit; ++j) {
        fprintf(Out,"\n%s ",Str_inp[i].attribute);
        fprintf(Out,"%4.0f ",Str_inp[i].weight);
        for (k = 0; k < Str_inp[i].data[j].points; ++k)
            fprintf(Out,"\t%d",Str_inp[i].data[j].yr_brk[k]);
        fprintf(Out,"\n");
        for (k = 0; k < limit; ++k) {
            for (l = 0; l < Str_inp[i].data[j].points; ++l)
                fprintf(Out,"\t%6.0f",Str_inp[i].data[j].rate[k][l]);
            fprintf(Out,"\n");
        }
    }
}
fprintf(Out,"\n\nTACTICAL");
for (i = 0; i < Num_attrib.tactical; ++i) {
    for (j = 0; j < limit; ++j) {
        fprintf(Out,"\n%s ",Tac_inp[i].attribute);
        fprintf(Out,"%4.0f ",Tac_inp[i].weight);
        for (k = 0; k < Tac_inp[i].data[j].points; ++k)
            fprintf(Out,"\t%d",Tac_inp[i].data[j].yr_brk[k]);
        fprintf(Out,"\n");
        for (k = 0; k < limit; ++k) {
            for (l = 0; l < Tac_inp[i].data[j].points; ++l)
                fprintf(Out,"\t%6.0f",Tac_inp[i].data[j].rate[k][l]);
            fprintf(Out,"\n");
        }
    }
}
fclose(Out);
}

```

Appendix J

Frequency Distributions for Independent Risk

Figure J.1: Frequency Distribution of Pecuniary Objective - Manual Alternative

Figure J.2: Frequency Distribution of Strategic Objective - Manual Alternative

Figure J.3: Frequency Distribution of Tactical Objective - Manual Alternative

Figure J.4: Frequency Distribution of Pecuniary Objective - Semi-Automatic Alternative

Figure J.5: Frequency Distribution of Strategic Objective - Semi-Automatic Alternative

Figure J.6: Frequency Distribution of Tactical Objective - Semi-Automatic Alternative

Figure J.7: Frequency Distribution of Pecuniary Objective - Automatic Alternative

Figure J.8: Frequency Distribution of Strategic Objective - Automatic Alternative

Figure J.9: Frequency Distribution of Tactical Objective - Automatic Alternative

Appendix K

Data for Dependent Risk

The interest rates used for the dependent case are shown in Table K.1. Cash flows are provided in Tables K.2 thru K.4, and qualitative flows in Tables K.5 thru K.7.

Table K.1: Interest Rates in Percent

PARAMETER	YEAR/RATE		
monetary rate	1	3	8
	13.00	13.00	14.60
	13.40	13.40	15.40
	13.60	13.60	16.20
	1	3	10
	13.00	13.00	15.00
	13.40	13.40	15.60
	13.60	13.60	16.20
	1	3	12
	13.00	13.00	15.40
	13.40	13.40	16.00
	13.60	13.60	16.60
nonmonetary rate	1	3	8
	7.80	7.80	8.50
	7.90	7.90	9.00
	8.00	8.00	9.50
	1	3	10
	7.90	7.90	8.70
	8.00	8.00	9.20
	8.10	8.10	9.70
	1	3	12
	8.00	8.00	9.00
	8.10	8.10	9.50
	8.20	8.20	10.00

Table K.2: Manual Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW				
Labor	1	3	6	8	
	(\$114,660)	(\$136,500)	(\$169,260)	(\$136,500)	
	(\$109,200)	(\$130,000)	(\$161,200)	(\$130,000)	
	(\$103,740)	(\$123,500)	(\$153,140)	(\$123,500)	
	1	3	7	10	
	(\$114,660)	(\$136,500)	(\$169,260)	(\$136,500)	
	(\$109,200)	(\$130,000)	(\$161,200)	(\$130,000)	
	(\$103,740)	(\$123,500)	(\$153,140)	(\$123,500)	
	1	3	9	12	
	(\$114,660)	(\$147,420)	(\$169,260)	(\$136,500)	
	(\$109,200)	(\$140,400)	(\$161,200)	(\$130,000)	
	(\$103,740)	(\$133,380)	(\$153,140)	(\$123,500)	
Maintenance	1	3	5	8	
	(\$2,100)	(\$2,310)	(\$2,541)	(\$2,795)	
	(\$2,000)	(\$2,200)	(\$2,420)	(\$2,662)	
	(\$1,900)	(\$2,090)	(\$2,299)	(\$2,529)	
	1	3	5	7	10
	(\$2,100)	(\$2,310)	(\$2,541)	(\$2,795)	(\$3,075)
	(\$2,000)	(\$2,200)	(\$2,420)	(\$2,662)	(\$2,928)
	(\$1,900)	(\$2,090)	(\$2,299)	(\$2,529)	(\$2,782)
	1	4	7	10	12
	(\$2,100)	(\$2,310)	(\$2,795)	(\$3,075)	(\$3,075)
	(\$2,000)	(\$2,200)	(\$2,662)	(\$2,928)	(\$2,928)
	(\$1,900)	(\$2,090)	(\$2,529)	(\$2,782)	(\$2,782)
Training	1	3	6	8	
	(\$1,500)	(\$1,984)	(\$3,017)	(\$2,624)	
	(\$1,000)	(\$1,323)	(\$2,011)	(\$1,749)	
	(\$500)	(\$661)	(\$1,066)	(\$875)	
	1	3	5	7	10
	(\$1,500)	(\$1,984)	(\$2,624)	(\$3,470)	(\$3,019)
	(\$1,000)	(\$1,323)	(\$1,749)	(\$2,313)	(\$2,012)
	(\$500)	(\$661)	(\$875)	(\$1,157)	(\$1,007)
	1	4	7	9	12
	(\$1,500)	(\$2,281)	(\$3,470)	(\$4,589)	(\$3,992)
	(\$1,000)	(\$1,521)	(\$2,313)	(\$3,059)	(\$2,661)
	(\$500)	(\$760)	(\$1,157)	(\$1,530)	(\$1,331)
Documentation	1				
	(\$5,500)				
	(\$5,000)				
	(\$4,500)				
	1				
	(\$5,500)				
	(\$5,000)				
	(\$4,500)				
	1				
	(\$5,500)				
	(\$5,000)				
	(\$4,500)				
Space	1	3	4	7	
	(\$5,350)	(\$5,350)	(\$10,700)	(\$16,050)	
	(\$5,000)	(\$5,000)	(\$10,000)	(\$15,000)	
	(\$4,650)	(\$4,650)	(\$9,300)	(\$13,950)	
	1	3	4	7	
	(\$5,350)	(\$5,350)	(\$10,700)	(\$16,050)	
	(\$5,000)	(\$5,000)	(\$10,000)	(\$15,000)	
	(\$4,650)	(\$4,650)	(\$9,300)	(\$13,950)	
	1	3	4	7	
	(\$5,350)	(\$5,350)	(\$10,700)	(\$16,050)	
	(\$5,000)	(\$5,000)	(\$10,000)	(\$15,000)	
	(\$4,650)	(\$4,650)	(\$9,300)	(\$13,950)	
Rework	1	3	6	8	
	(\$86,940)	(\$106,260)	(\$140,070)	(\$128,864)	
	(\$75,600)	(\$92,400)	(\$121,800)	(\$112,056)	
	(\$64,260)	(\$78,540)	(\$103,530)	(\$95,248)	
	1	4	7	10	
	(\$86,940)	(\$115,920)	(\$154,560)	(\$142,195)	
	(\$75,600)	(\$100,800)	(\$134,400)	(\$123,648)	
	(\$64,260)	(\$85,680)	(\$114,240)	(\$105,101)	
	1	4	9	12	
	(\$86,940)	(\$115,920)	(\$188,370)	(\$173,300)	
	(\$75,600)	(\$100,800)	(\$163,800)	(\$150,696)	
	(\$64,260)	(\$85,680)	(\$139,230)	(\$128,092)	

Table K.2: Manual Operations Cash Flows - cont'd.

ATTRIBUTE	YEAR/CASH FLOW				
Transportation	1	4	5	8	
	(\$10,700)	(\$10,700)	(\$16,050)	(\$16,050)	
	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)	
	(\$9,300)	(\$9,300)	(\$13,950)	(\$13,950)	
	1	4	5	8	9
	(\$10,700)	(\$10,700)	(\$16,050)	(\$16,050)	(\$21,400)
	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)	(\$20,000)
	(\$9,300)	(\$9,300)	(\$13,950)	(\$13,950)	(\$18,600)
	1	4	5	8	9
	(\$10,700)	(\$10,700)	(\$16,050)	(\$16,050)	(\$21,400)
	(\$10,000)	(\$10,000)	(\$15,000)	(\$15,000)	(\$20,000)
	(\$9,300)	(\$9,300)	(\$13,950)	(\$13,950)	(\$18,600)
Cash Inflow	1	6	8		
	\$652,800	\$1,052,160	\$867,987		
	\$816,000	\$1,315,200	\$1,209,984		
	\$979,200	\$1,578,240	\$1,451,981		
	1	7	10		
	\$652,800	\$1,167,360	\$1,073,971		
	\$816,000	\$1,459,200	\$1,342,464		
	\$979,200	\$1,751,040	\$1,610,957		
	1	9	12		
	\$652,800	\$1,420,800	\$1,307,136		
	\$816,000	\$1,776,000	\$1,633,920		
	\$979,200	\$2,131,200	\$1,960,704		

Table K.3: Semi-Automatic Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW			
Investment	0			
	(\$38,000)			
	(\$30,000)			
	(\$24,000)			
	0			
	(\$38,000)			
	(\$30,000)			
	(\$24,000)			
	0			
	(\$38,000)			
	(\$30,000)			
	(\$24,000)			
Depr Investment	0			
	(\$144,000)			
	(\$120,000)			
	(\$96,000)			
	0			
	(\$144,000)			
	(\$120,000)			
	(\$96,000)			
	0			
	(\$144,000)			
	(\$120,000)			
	(\$96,000)			
Salvage value	8			
	\$9,825			
	\$7,500			
	\$6,375			
	10			
	\$8,325			
	\$5,500			
	\$4,675			
	12			
	\$4,025			
	\$3,500			
	\$2,975			
Labor	1	3	6	8
	(\$297,440)	(\$320,320)	(\$388,960)	(\$320,320)
	(\$270,400)	(\$291,200)	(\$353,600)	(\$291,200)
	(\$243,360)	(\$262,080)	(\$318,240)	(\$262,080)
	1	3	7	10
	(\$297,440)	(\$320,320)	(\$388,960)	(\$320,320)
	(\$270,400)	(\$291,200)	(\$353,600)	(\$291,200)
	(\$243,360)	(\$262,080)	(\$318,240)	(\$262,080)
	1	3	9	12
	(\$297,440)	(\$320,320)	(\$388,960)	(\$320,320)
	(\$270,400)	(\$291,200)	(\$353,600)	(\$291,200)
	(\$243,360)	(\$262,080)	(\$318,240)	(\$262,080)
Maintenance	1			
	(\$7,659)			
	(\$6,660)			
	(\$5,661)			
	1			
	(\$7,659)			
	(\$6,660)			
	(\$5,661)			
	1			
	(\$7,659)			
	(\$6,660)			
	(\$5,661)			
Training	1	3	8	
	(\$30,000)	(\$22,500)	(\$15,000)	
	(\$20,000)	(\$15,000)	(\$10,000)	
	(\$10,000)	(\$7,500)	(\$5,000)	
	1	3	10	
	(\$30,000)	(\$22,500)	(\$15,000)	
	(\$20,000)	(\$15,000)	(\$10,000)	
	(\$10,000)	(\$7,500)	(\$5,000)	
	1	3	12	
	(\$30,000)	(\$22,500)	(\$15,000)	
	(\$20,000)	(\$15,000)	(\$10,000)	
	(\$10,000)	(\$7,500)	(\$5,000)	

Table K,3: Semi-Automatic Operations Cash Flows - cont'd

ATTRIBUTE	YEAR/CASH FLOW		
Documentation	1		
	(\$3,000)		
	(\$2,500)		
	(\$2,000)		
	1		
	(\$3,000)		
	(\$2,500)		
	(\$2,000)		
	1		
	(\$3,000)		
	(\$2,500)		
	(\$2,000)		
Space	1		
	(\$6,688)		
	(\$6,250)		
	(\$5,813)		
	1		
	(\$6,688)		
	(\$6,250)		
	(\$5,813)		
	1		
	(\$6,688)		
	(\$6,250)		
	(\$5,813)		
Rework	1	2	8
	(\$86,940)	(\$85,008)	(\$87,620)
	(\$75,600)	(\$73,920)	(\$58,800)
	(\$64,260)	(\$62,832)	(\$49,980)
	1	8	10
	(\$86,940)	(\$78,246)	(\$87,620)
	(\$75,600)	(\$68,040)	(\$58,800)
	(\$64,260)	(\$57,834)	(\$49,980)
	1	8	12
	(\$86,940)	(\$78,246)	(\$87,620)
	(\$75,600)	(\$68,040)	(\$58,800)
	(\$64,260)	(\$57,834)	(\$49,980)
Programming	1	3	4
	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$15,000)	(\$10,000)
Cash Inflow	1	6	8
	\$645,120	\$1,098,240	\$1,010,381
	\$808,400	\$1,372,800	\$1,262,976
	\$967,680	\$1,647,360	\$1,515,571
	1	7	10
	\$645,120	\$1,221,120	\$1,123,430
	\$808,400	\$1,528,400	\$1,404,288
	\$967,680	\$1,831,680	\$1,685,146
	1	9	12
	\$645,120	\$1,489,920	\$1,370,726
	\$808,400	\$1,862,400	\$1,713,408
	\$967,680	\$2,234,880	\$2,056,090

Table K.4: Automatic Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW		
Investment	0		
	(\$80,000)		
	(\$50,000)		
	(\$40,000)		
	0		
	(\$60,000)		
	(\$50,000)		
	(\$40,000)		
	0		
	(\$60,000)		
	(\$50,000)		
	(\$40,000)		
Depr Investment	0		
	(\$720,000)		
	(\$600,000)		
	(\$480,000)		
	0		
	(\$720,000)		
	(\$600,000)		
	(\$480,000)		
	0		
	(\$720,000)		
	(\$600,000)		
	(\$480,000)		
Salvage value	8		
	\$40,000		
	\$40,000		
	\$34,000		
	10		
	\$34,500		
	\$30,000		
	\$25,500		
	12		
	\$23,000		
	\$20,000		
	\$17,000		
Labor	1	3	6
	(\$400,400)	(\$331,760)	(\$331,760)
	(\$364,000)	(\$301,600)	(\$301,600)
	(\$327,600)	(\$271,440)	(\$271,440)
	1	3	6
	(\$400,400)	(\$331,760)	(\$331,760)
	(\$364,000)	(\$301,600)	(\$301,600)
	(\$327,600)	(\$271,440)	(\$271,440)
	1	3	6
	(\$400,400)	(\$331,760)	(\$331,760)
	(\$364,000)	(\$301,600)	(\$301,600)
	(\$327,600)	(\$271,440)	(\$271,440)
Maintenance	1		
	(\$18,400)		
	(\$16,000)		
	(\$13,600)		
	1		
	(\$18,400)		
	(\$16,000)		
	(\$13,600)		
	1		
	(\$18,400)		
	(\$16,000)		
	(\$13,600)		
Training	1	3	4
	(\$60,000)	(\$45,000)	(\$30,000)
	(\$40,000)	(\$30,000)	(\$20,000)
	(\$20,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$60,000)	(\$45,000)	(\$30,000)
	(\$40,000)	(\$30,000)	(\$20,000)
	(\$20,000)	(\$15,000)	(\$10,000)
	1	3	4
	(\$60,000)	(\$45,000)	(\$30,000)
	(\$40,000)	(\$30,000)	(\$20,000)
	(\$20,000)	(\$15,000)	(\$10,000)

Table K.4: Automatic Operations Cash Flows - cont'd

ATTRIBUTE	YEAR/CASH FLOW			
Documentation	1	2		
	(\$6,000)	(\$3,600)		
	(\$5,000)	(\$3,000)		
	(\$4,000)	(\$2,400)		
	1	2		
	(\$6,000)	(\$3,600)		
	(\$5,000)	(\$3,000)		
	(\$4,000)	(\$2,400)		
	1	2		
	(\$6,000)	(\$3,600)		
	(\$5,000)	(\$3,000)		
	(\$4,000)	(\$2,400)		
Space	1			
	(\$6,888)			
	(\$6,250)			
	(\$5,813)			
	1			
	(\$6,888)			
	(\$6,250)			
	(\$5,813)			
	1			
	(\$6,888)			
	(\$6,250)			
	(\$5,813)			
Rework	1	5	6	8
	(\$86,940)	(\$65,205)	(\$35,018)	(\$33,810)
	(\$75,600)	(\$56,700)	(\$30,450)	(\$29,400)
	(\$64,260)	(\$48,195)	(\$25,883)	(\$24,990)
	1	5	6	10
	(\$86,940)	(\$65,205)	(\$35,018)	(\$31,153)
	(\$75,600)	(\$56,700)	(\$30,450)	(\$27,090)
	(\$64,260)	(\$48,195)	(\$25,883)	(\$23,027)
	1	5	6	12
	(\$86,940)	(\$65,205)	(\$35,018)	(\$31,153)
	(\$75,600)	(\$56,700)	(\$30,450)	(\$27,090)
	(\$64,260)	(\$48,195)	(\$25,883)	(\$23,027)
Programming	1	2	3	4
	(\$75,000)	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$25,000)	(\$15,000)	(\$10,000)
	1	2	3	4
	(\$75,000)	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$25,000)	(\$15,000)	(\$10,000)
	1	2	3	4
	(\$75,000)	(\$75,000)	(\$45,000)	(\$30,000)
	(\$50,000)	(\$50,000)	(\$30,000)	(\$20,000)
	(\$25,000)	(\$25,000)	(\$15,000)	(\$10,000)
Cash Inflow	1	6	8	
	\$622,080	\$1,105,920	\$1,017,446	
	\$777,600	\$1,382,400	\$1,271,808	
	\$933,120	\$1,658,880	\$1,526,170	
	1	7	10	
	\$622,080	\$1,221,120	\$1,123,430	
	\$777,600	\$1,526,400	\$1,404,288	
	\$933,120	\$1,831,680	\$1,685,146	
	1	9	12	
	\$622,080	\$1,480,920	\$1,370,726	
	\$777,600	\$1,862,400	\$1,713,408	
	\$933,120	\$2,234,880	\$2,056,090	

Table K.5: Manual Operations Qualitative Flows

ATTRIBUTE	STRATEGIC YEAR/QUAL. FLOW					ATTRIBUTE	TACTICAL YEAR/QUAL. FLOW			
	1	3	6	7	8		1	4	5	8
Internal Relations	10	-35	-35	-55	-55	Design	-5			
	15	-30	-30	-80	-50		0			
	20	-25	-25	-45	-45		5			
	1	3	6	7	9		1			
	10	-35	-35	-55	-85		-5			
	15	-30	-30	-50	-80		0			
	20	-25	-25	-45	-75		5			
	1	3	6	8	9		1			
	10	-35	-35	-55	-85		-5			
	15	-30	-30	-50	-80		0			
Market Position	20	-25	-25	-45	-75	Flexibility	5			
	1	4	8				1	4	5	8
	0	-20	-95				-55	-55	-95	-95
	20	0	-75				-40	-40	-80	-80
	40	20	-55				-25	-25	-65	-65
	1	4	8	10			1	4	5	10
	0	-20	-95	-100			-55	-55	-95	-95
	20	0	-75	-85			-40	-40	-80	-80
	40	20	-55	-65			-25	-25	-65	-65
	1	4	8	12			1	4	5	12
Mission	0	-20	-95	-100		Integration	-55	-55	-95	-95
	20	0	-75	-90			-40	-40	-80	-80
	40	20	-55	-70			-25	-25	-65	-65
	1	2	8				1	8		
	10	-40	-55				-27	-72		
	15	-30	-45				-15	-60		
	20	-20	-35				-3	-48		
	1	2	10				1	10		
	10	-40	-95				-27	-92		
	15	-30	-85				-15	-80		
Organization	20	-20	-75			Material	-3	-68		
	1	2	10				1	12		
	10	-40	-95				-27	-100		
	15	-30	-85				-15	-90		
	20	-20	-75				-3	-78		
	1						1	3	4	8
	-55						19	-6	-26	-46
	-50						25	0	-20	-40
	-45						31	6	-14	-34
	1						1	3	4	10
Public Relations	-55					Personnel	19	-6	-26	-56
	-50						25	0	-20	-50
	-45						31	6	-14	-44
	1						1	3	4	12
	-55						19	-6	-26	-56
	-50						25	0	-20	-50
	-45						31	6	-14	-44
	1						1	3	4	12
	-55						19	-6	-26	-56
	-50						25	0	-20	-50
Technology	-45					Producibility	31	6	-14	-44
	1	2	8				1	8		
	13	-7	-67				27	-3	-23	
	20	0	-80				35	5	-15	
	27	7	-53				43	13	-7	
	1	2	10				1	7	10	
	13	-7	-87				27	-18	-43	
	20	0	-80				35	-10	-35	
	27	7	-73				43	-2	-27	
	1	2	11	12			1	9	12	

Table K.6: Semi-Automatic Operations Qualitative Flows

ATTRIBUTE	STRATEGIC YEAR/QUAL. FLOW				ATTRIBUTE	TACTICAL YEAR/QUAL. FLOW			
	1	3	7			1			
Internal Relations	-40	0	35		Design	-5			
	-35	5	40			0			
	-30	10	45			5			
	1	3	7	10		1			
	-40	0	35	55		-5			
	-35	5	40	60		0			
	-30	10	45	65		5			
	1	3	7	12		1			
	-40	0	35	65		-5			
	-35	5	40	70		0			
Market Position	-30	10	45	75	Flexibility	5			
	1	2	3	8		1	5	8	
	-10	-40	-20	15		-35	0	15	
	10	-20	0	35		-20	15	30	
	30	0	20	55		-15	30	45	
	1	2	3	7	10	1	3	10	
	-10	-40	-20	15	35	-35	-15	25	
	10	-20	0	35	55	-20	0	40	
	30	0	20	55	75	-15	15	55	
	1	2	3	7	12	1	4	12	
Mission	-10	-40	-20	15	40	-35	-10	35	
	10	-20	0	35	60	-20	5	50	
	30	0	20	55	80	-15	20	65	
	1	3	4	6	7	1	3	8	
	20	20	25	25	30	-27	-7	18	
	30	30	35	35	40	-15	5	30	
	40	40	45	45	50	-3	17	42	
	1	3	4	6	10	1	2	10	
	20	20	25	25	40	-27	-12	28	
	30	30	35	35	50	-15	0	40	
Organization	40	40	45	45	60	-3	12	52	
	1	3	4	6	12	1	3	12	
	20	20	25	25	60	-27	-7	33	
	30	30	35	35	70	-15	5	45	
	40	40	45	45	80	-3	17	57	
	1	3	8		Material	1	3	8	
	-40	5	35			-16	9	44	
	-35	10	40			-10	15	50	
	-30	15	45			-4	21	56	
	1	3	8			1	3	8	
	-40	5	35			-16	9	44	
	-35	10	40			-10	15	50	
	-30	15	45			-4	21	56	
	1	3	8			1	2	8	
	-40	5	35			-16	9	44	
Public Relations	-35	10	40		Personnel	-10	15	50	
	-30	15	45			-4	21	56	
	1	7				1	6	8	
	18	48				27	37	35	
	25	55				35	45	43	
	32	62				43	53	51	
	1	7				1	7	10	
	18	48				27	37	35	
	25	55				35	45	43	
	32	62				43	53	51	
Technology	1	7			Producibility	1	9	12	
	18	48				27	37	35	
	25	55				35	45	43	
	32	62				43	53	51	
	1	4	5			1	4	8	
	0	20	30			-36	4	34	
	10	30	40			-25	15	45	
	20	40	50			-14	26	58	
	1	4	5			1	4	10	
	0	20	30			-36	4	44	
	10	30	40			-25	15	55	
	20	40	50			-14	26	66	
	1	4	5	11	12	1	4	12	
	0	20	30	45	55	-36	4	54	
	10	30	40	50	60	-25	15	65	
	20	40	50	55	65	-14	26	76	

Table K.7: Automatic Operations Qualitative Flows

STRATEGIC				TACTICAL			
ATTRIBUTE	YEAR/QUAL. FLOW			ATTRIBUTE	YEAR/QUAL. FLOW		
Strategic Internal Relations	1	3	7	Tactical Design	1		
	-40	0	35		15		
	-35	5	40		20		
	-30	10	45		25		
	1	3	7		1		
	-40	0	35		15		
	-35	5	40		20		
	-30	10	45		25		
	1	3	7		1		
	-40	0	35		15		
Market Position	-35	5	40	Flexibility	20		
	-30	10	45		25		
	1	3	7		1		
	-40	0	35		15		
	-35	5	40		20		
	-30	10	45		25		
	1	3	7		1		
	-40	0	35		15		
	-35	5	40		20		
	-30	10	45		25		
Mission	1	2	3	Integration	1	3	6
	-10	-40	-10		-35	-5	35
	10	-20	10		-20	10	50
	30	0	30		-5	25	65
	1	2	3		1	3	6
	-10	-40	-10		-35	-5	35
	10	-20	10		-20	10	50
	30	0	30		-5	25	65
	1	2	3		1	3	6
	-10	-40	-10		-35	-5	35
Organization	10	-20	10	Material	-20	10	50
	30	0	30		-5	25	65
	1	4	6		1	3	5
	30	50	70		-27	-7	18
	40	60	80		-15	5	30
	50	70	90		-3	17	42
	1	4	6		1	3	5
	30	50	70		-27	-7	18
	40	60	80		-15	5	30
	50	70	90		-3	17	42
Public Relations	1	4	6	Personnel	1	3	5
	30	50	70		-27	-7	18
	40	60	80		-15	5	30
	50	70	90		-3	17	42
	1	3	5		1	2	3
	-40	5	20		-16	4	9
	-35	10	25		-10	10	15
	-30	15	30		-4	16	21
	1	3	5		1	2	3
	-40	5	20		-16	4	9
Technology	-35	10	25	Producibility	-10	10	15
	-30	15	30		-4	16	21
	1	3	5		1	6	8
	-40	5	20		-28	47	45
	-35	10	25		-20	55	53
	-30	15	30		-12	63	61
	1	4	7		1	7	10
	38	48	68		-28	62	60
	45	55	75		-20	70	68
	52	62	82		-12	78	76

Appendix L

Frequency Distributions for Dependent Risk

Figure L.1: Frequency Distribution of Pecuniary Objective - Manual Alternative, $\theta = 1.0$

Figure L.2: Frequency Distribution of Strategic Objective - Manual Alternative, $\theta = 1.0$

Figure L.3: Frequency Distribution of Tactical Objective - Manual Alternative, $\theta = 1.0$

Figure L.4: Frequency Distribution of Pecuniary Objective - Semi-Automatic Alternative, $\theta = 1.0$

Figure L.5: Frequency Distribution of Strategic Objective - Semi-Automatic Alternative, $\theta = 1.0$

Figure L.6: Frequency Distribution of Tactical Objective - Semi-Automatic Alternative, $\theta = 1.0$

Figure L.7: Frequency Distribution of Pecuniary Objective - Automatic Alternative, $\theta = 1.0$

Figure L.8: Frequency Distribution of Strategic Objective - Automatic Alternative, $\theta = 1.0$

Figure L.9: Frequency Distribution of Tactical Objective - Automatic Alternative, $\theta = 1.0$

Figure L.10: Frequency Distribution of Pecuniary Objective - Manual Alternative, $\theta = 0.5$

Figure L.11: Frequency Distribution of Strategic Objective - Manual Alternative, $\theta = 0.5$

Figure L.12: Frequency Distribution of Tactical Objective - Manual Alternative, $\theta = 0.5$

Figure L.13: Frequency Distribution of Pecuniary Objective - Semi-Automatic Alternative, $\theta = 0.5$

Figure L.14: Frequency Distribution of Strategic Objective - Semi-Automatic Alternative, $\theta = 0.5$

Figure L.15: Frequency Distribution of Tactical Objective - Semi-Automatic Alternative, $\theta = 0.5$

Figure L.16: Frequency Distribution of Pecuniary Objective - Automatic Alternative, $\theta = 0.5$

Figure L.17: Frequency Distribution of Strategic Objective - Automatic Alternative, $\theta = 0.5$

Figure L.18: Frequency Distribution of Tactical Objective - Automatic Alternative, $\theta = 0.5$

Appendix M

Case Study Data

M.1 Fitted Simplex-Centroid Model for Six and Four Components

Recall that α_{nk} is the weighting factor for the importance of the attributes/elements of a Strategic or Tactical objective in the model. The fitted simplex-centroid model for six components for the Strategic objective ($n = 2$) of the current operations is:

$$\begin{aligned}
 \hat{y}_{current} = & 68.2\alpha_{21} + 67.7\alpha_{22} + 69.1\alpha_{23} + 68.9\alpha_{24} + 67.6\alpha_{25} + 69.5\alpha_{26} - \\
 & 0.2\alpha_{21}\alpha_{22} + 0.2\alpha_{21}\alpha_{23} - 0.2\alpha_{21}\alpha_{24} + 0\alpha_{21}\alpha_{25} + 0.2\alpha_{21}\alpha_{26} + \\
 & 0\alpha_{22}\alpha_{23} + 0\alpha_{22}\alpha_{24} - 0.2\alpha_{22}\alpha_{25} + 0\alpha_{22}\alpha_{26} + 0\alpha_{23}\alpha_{24} + \\
 & 0.2\alpha_{23}\alpha_{25} + 0\alpha_{23}\alpha_{26} + 0.2\alpha_{24}\alpha_{25} + 0\alpha_{24}\alpha_{26} + 0.2\alpha_{25}\alpha_{26} - \\
 & 2.1\alpha_{21}\alpha_{22}\alpha_{23} - 1.5\alpha_{21}\alpha_{22}\alpha_{24} + 0.3\alpha_{21}\alpha_{22}\alpha_{25} + 0.9\alpha_{21}\alpha_{22}\alpha_{26} - \\
 & 0.9\alpha_{21}\alpha_{23}\alpha_{24} - 1.2\alpha_{21}\alpha_{23}\alpha_{25} - 2.1\alpha_{21}\alpha_{23}\alpha_{26} - 0.9\alpha_{21}\alpha_{24}\alpha_{25} + \\
 & 0.9\alpha_{21}\alpha_{24}\alpha_{26} + 0.6\alpha_{21}\alpha_{25}\alpha_{26} - 1.8\alpha_{22}\alpha_{23}\alpha_{24} - 0.9\alpha_{22}\alpha_{23}\alpha_{25} + \\
 & 0.9\alpha_{22}\alpha_{23}\alpha_{26} + 0.9\alpha_{22}\alpha_{24}\alpha_{25} + 0\alpha_{22}\alpha_{24}\alpha_{26} + 0.9\alpha_{22}\alpha_{25}\alpha_{26} - \\
 & 2.1\alpha_{23}\alpha_{24}\alpha_{25} + 0.9\alpha_{23}\alpha_{24}\alpha_{26} + 0.6\alpha_{23}\alpha_{25}\alpha_{26} - 0.3\alpha_{24}\alpha_{25}\alpha_{26} + \\
 & 15.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24} + 23.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25} - 7.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{26} - \\
 & 3.2\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25} - 6.0\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{26} + 2.0\alpha_{21}\alpha_{22}\alpha_{25}\alpha_{26} + \\
 & 26.8\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25} - 4.8\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{26} - 4.4\alpha_{21}\alpha_{23}\alpha_{25}\alpha_{26} + \\
 & 5.2\alpha_{21}\alpha_{24}\alpha_{25}\alpha_{26} + 6.0\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} + 0\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} - \\
 & 2.8\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} - 15.6\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + 0.4\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} -
 \end{aligned}$$

$$\begin{aligned}
& 209.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} + 62.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} - \\
& 158.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 15.5\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + \\
& 21.5\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + 157.5\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 772.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26}
\end{aligned}$$

The fitted simplex-centroid model for six components for the Strategic objective ($n = 2$) of the development system is:

$$\begin{aligned}
\hat{y}_{development} = & 63.2\alpha_{21} + 62.4\alpha_{22} + 61.2\alpha_{23} + 62.4\alpha_{24} + 61.8\alpha_{25} + 59.7\alpha_{26} + \\
& 0\alpha_{21}\alpha_{22} + 0\alpha_{21}\alpha_{23} + 0\alpha_{21}\alpha_{24} + 0\alpha_{21}\alpha_{25} + 0.2\alpha_{21}\alpha_{26} + \\
& 0.4\alpha_{22}\alpha_{23} + 0\alpha_{22}\alpha_{24} + 0\alpha_{22}\alpha_{25} + 0.2\alpha_{22}\alpha_{26} + 0\alpha_{23}\alpha_{24} + \\
& 0\alpha_{23}\alpha_{25} + 0.2\alpha_{23}\alpha_{26} + 0\alpha_{24}\alpha_{25} + 0.2\alpha_{24}\alpha_{26} + 0.2\alpha_{25}\alpha_{26} - \\
& 11.1\alpha_{21}\alpha_{22}\alpha_{23} + 14.1\alpha_{21}\alpha_{22}\alpha_{24} + 0.9\alpha_{21}\alpha_{22}\alpha_{25} - 0.3\alpha_{21}\alpha_{22}\alpha_{26} + \\
& 0.9\alpha_{21}\alpha_{23}\alpha_{24} + 0.9\alpha_{21}\alpha_{23}\alpha_{25} - 0.3\alpha_{21}\alpha_{23}\alpha_{26} + 0.9\alpha_{21}\alpha_{24}\alpha_{25} - \\
& 0.3\alpha_{21}\alpha_{24}\alpha_{26} - 0.3\alpha_{21}\alpha_{25}\alpha_{26} - 1.2\alpha_{22}\alpha_{23}\alpha_{24} + 1.5\alpha_{22}\alpha_{23}\alpha_{25} + \\
& 0.3\alpha_{22}\alpha_{23}\alpha_{26} + 0\alpha_{22}\alpha_{24}\alpha_{25} + 1.5\alpha_{22}\alpha_{24}\alpha_{26} + 1.5\alpha_{22}\alpha_{25}\alpha_{26} - \\
& 0\alpha_{23}\alpha_{24}\alpha_{25} + 1.5\alpha_{23}\alpha_{24}\alpha_{26} + 1.5\alpha_{23}\alpha_{25}\alpha_{26} + 1.5\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 7.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24} - 5.6\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25} + 8.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{26} - \\
& 2.0\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25} + 2.4\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{26} - 10.4\alpha_{21}\alpha_{22}\alpha_{25}\alpha_{26} + \\
& 2.0\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25} + 2.4\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{26} - 10.4\alpha_{21}\alpha_{23}\alpha_{25}\alpha_{26} - \\
& 10.4\alpha_{21}\alpha_{24}\alpha_{25}\alpha_{26} + 5.2\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} - 5.2\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} - \\
& 28.8\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} - 21.2\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} - 21.2\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\
& 142.5\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} - 143.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} + \\
& 88.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 243.0\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + \\
& 55.5\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + 316.0\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} -
\end{aligned}$$

$$2293.2\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26}$$

The fitted simplex-centroid model for six components for the Strategic objective ($n = 2$) of the full system is:

$$\begin{aligned}\hat{y}_{full} = & 65.3\alpha_{21} + 63.5\alpha_{22} + 61.2\alpha_{23} + 64.9\alpha_{24} + 62.7\alpha_{25} + 60.8\alpha_{26} + \\ & 0\alpha_{21}\alpha_{22} + 0.6\alpha_{21}\alpha_{23} + 0\alpha_{21}\alpha_{24} + 0.4\alpha_{21}\alpha_{25} + 0.6\alpha_{21}\alpha_{26} + \\ & 0.2\alpha_{22}\alpha_{23} + 0\alpha_{22}\alpha_{24} + 0\alpha_{22}\alpha_{25} + 0.2\alpha_{22}\alpha_{26} + 0.6\alpha_{23}\alpha_{24} + \\ & 0.2\alpha_{23}\alpha_{25} + 0\alpha_{23}\alpha_{26} + 0\alpha_{24}\alpha_{25} + 0.6\alpha_{24}\alpha_{26} + 0.2\alpha_{25}\alpha_{26} - \\ & 33.0\alpha_{21}\alpha_{22}\alpha_{23} + 42.9\alpha_{21}\alpha_{22}\alpha_{24} + 0.6\alpha_{21}\alpha_{22}\alpha_{25} + 0.3\alpha_{21}\alpha_{22}\alpha_{26} - \\ & 0.9\alpha_{21}\alpha_{23}\alpha_{24} + 0\alpha_{21}\alpha_{23}\alpha_{25} + 0.9\alpha_{21}\alpha_{23}\alpha_{26} - 1.2\alpha_{21}\alpha_{24}\alpha_{25} + \\ & 0\alpha_{21}\alpha_{24}\alpha_{26} + 0.9\alpha_{21}\alpha_{25}\alpha_{26} + 0.3\alpha_{22}\alpha_{23}\alpha_{24} - 0.3\alpha_{22}\alpha_{23}\alpha_{25} + \\ & 0.6\alpha_{22}\alpha_{23}\alpha_{26} + 0\alpha_{22}\alpha_{24}\alpha_{25} + 1.2\alpha_{22}\alpha_{24}\alpha_{26} + 0.6\alpha_{22}\alpha_{25}\alpha_{26} - \\ & 0.6\alpha_{23}\alpha_{24}\alpha_{25} - 0.9\alpha_{23}\alpha_{24}\alpha_{26} - 0.3\alpha_{23}\alpha_{25}\alpha_{26} - 0.3\alpha_{24}\alpha_{25}\alpha_{26} - \\ & 2.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24} - 14.8\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25} - 3.2\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{26} - \\ & 7.6\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25} - 12.8\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{26} + 0\alpha_{21}\alpha_{22}\alpha_{25}\alpha_{26} + \\ & 1.2\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25} + 3.6\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{26} - 12.4\alpha_{21}\alpha_{23}\alpha_{25}\alpha_{26} - \\ & 9.6\alpha_{21}\alpha_{24}\alpha_{25}\alpha_{26} - 7.2\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} - 4.8\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} - \\ & 2.4\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} - 18.0\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + 6.0\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + \\ & 197.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25} + 209.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{26} + \\ & 117.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{25}\alpha_{26} + 87.5\alpha_{21}\alpha_{22}\alpha_{24}\alpha_{25}\alpha_{26} + \\ & 76.0\alpha_{21}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} + 109.5\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26} - \\ & 528.0\alpha_{21}\alpha_{22}\alpha_{23}\alpha_{24}\alpha_{25}\alpha_{26}\end{aligned}$$

The fitted simplex-centroid model for four components for the Tactical objec-

tive ($n = 3$) of the current operations is:

$$\begin{aligned}\hat{y}_{current} = & 67.5\alpha_{31} + 67.3\alpha_{32} + 67.1\alpha_{33} + 67.4\alpha_{34} + \\ & 0\alpha_{31}\alpha_{32} + 0\alpha_{31}\alpha_{33} + 0.2\alpha_{31}\alpha_{34} + \\ & 0\alpha_{32}\alpha_{33} + 0.2\alpha_{32}\alpha_{34} + 0.2\alpha_{33}\alpha_{34} + \\ & 0\alpha_{31}\alpha_{32}\alpha_{33} - 1.2\alpha_{31}\alpha_{32}\alpha_{34} + \\ & 0.6\alpha_{31}\alpha_{33}\alpha_{34} - 0.3\alpha_{32}\alpha_{33}\alpha_{34} + \\ & 13.2\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\end{aligned}$$

The fitted simplex-centroid model for four components for the Tactical objective ($n = 3$) of the development system is:

$$\begin{aligned}\hat{y}_{development} = & 60.6\alpha_{31} + 60.5\alpha_{32} + 59.0\alpha_{33} + 61.7\alpha_{34} + \\ & 0.2\alpha_{31}\alpha_{32} + 0\alpha_{31}\alpha_{33} + 0.2\alpha_{31}\alpha_{34} + \\ & 0.2\alpha_{32}\alpha_{33} + 0\alpha_{32}\alpha_{34} + 0.2\alpha_{33}\alpha_{34} + \\ & 1.8\alpha_{31}\alpha_{32}\alpha_{33} + 0.6\alpha_{31}\alpha_{32}\alpha_{34} + \\ & 0.6\alpha_{31}\alpha_{33}\alpha_{34} + 0\alpha_{32}\alpha_{33}\alpha_{34} - \\ & 5.6\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}\end{aligned}$$

The fitted simplex-centroid model for four components for the Tactical objective ($n = 3$) of the full system is:

$$\begin{aligned}\hat{y}_{full} = & 62.1\alpha_{31} + 61.8\alpha_{32} + 60.4\alpha_{33} + 62.7\alpha_{34} + \\ & 0.2\alpha_{31}\alpha_{32} + 0.2\alpha_{31}\alpha_{33} + 0\alpha_{31}\alpha_{34} + \\ & 0\alpha_{32}\alpha_{33} - 0.2\alpha_{32}\alpha_{34} + 0.2\alpha_{33}\alpha_{34} + \\ & 0.6\alpha_{31}\alpha_{32}\alpha_{33} + 0\alpha_{31}\alpha_{32}\alpha_{34} + \\ & 0.6\alpha_{31}\alpha_{33}\alpha_{34} + 1.8\alpha_{32}\alpha_{33}\alpha_{34} -\end{aligned}$$

$$5.6\alpha_{31}\alpha_{32}\alpha_{33}\alpha_{34}$$

M.2 Data for Risk Analysis

The parameters used in the risk analysis are the same as for the deterministic analysis, except for the interest rates. The interest rates used are shown in Table M.1. Cash flows are provided in Tables M.2 thru M.4, and qualitative flows in Tables M.5 thru M.7.

Table M.1: Interest Rates in Percent

PARAMETER	YEAR/RATE		
Monetary	1	2	
	5.90	5.90	
	6.10	6.10	
	6.30	6.30	
	1	3	5
	5.90	6.1	6.2
	6.10	6.3	6.4
	6.30	6.5	6.6
	1	5	8
	5.90	6.2	6.4
	6.10	6.4	6.6
	6.30	6.6	6.8
Nonmonetary	1	2	
	5.90	5.90	
	6.10	6.10	
	6.30	6.30	
	1	3	5
	5.90	6.1	6.2
	6.10	6.3	6.4
	6.30	6.5	6.6
	1	5	8
	5.90	6.2	6.4
	6.10	6.4	6.6
	6.30	6.6	6.8

Table M.2: Current Operations Cash Flows

ATTRIBUTE	YEAR/CASH FLOW		
Labor	1	2	
	(\$1,485,000)	(\$1,485,000)	
	(\$1,350,000)	(\$1,350,000)	
	(\$1,215,000)	(\$1,215,000)	
	1	3	5
	(\$1,485,000)	(\$1,485,000)	(\$1,552,500)
	(\$1,350,000)	(\$1,350,000)	(\$1,350,000)
	(\$1,215,000)	(\$1,215,000)	(\$1,147,500)
	1	5	8
	(\$1,485,000)	(\$1,552,500)	(\$1,620,000)
	(\$1,350,000)	(\$1,350,000)	(\$1,350,000)
	(\$1,215,000)	(\$1,147,500)	(\$1,080,000)

Table M.3: Development System Cash Flows

ATTRIBUTE	YEAR/CASH FLOW			
Labor	1	2		
	(\$1,188,000)	(\$756,000)		
	(\$1,080,000)	(\$675,000)		
	(\$972,000)	(\$594,000)		
	1	2	3	
	(\$1,188,000)	(\$756,000)	(\$310,500)	
	(\$1,080,000)	(\$675,000)	(\$270,000)	
	(\$972,000)	(\$594,000)	(\$229,500)	
	1	2	3	
	(\$1,188,000)	(\$756,000)	(\$310,500)	
	(\$1,080,000)	(\$675,000)	(\$270,000)	
	(\$972,000)	(\$594,000)	(\$229,500)	
Depr Investment	0	1		
	(\$735,000)	(\$1,176,000)		
	(\$700,000)	(\$1,120,000)		
	(\$665,000)	(\$1,064,000)		
	0	1		
	(\$735,000)	(\$1,176,000)		
	(\$700,000)	(\$1,120,000)		
	(\$665,000)	(\$1,064,000)		
	0	1		
	(\$735,000)	(\$1,176,000)		
	(\$700,000)	(\$1,120,000)		
	(\$665,000)	(\$1,064,000)		
Maintenance	1			
	(\$21,400)			
	(\$20,000)			
	(\$18,600)			
	1			
	(\$21,400)			
	(\$20,000)			
	(\$18,600)			
	1			
	(\$21,400)			
	(\$20,000)			
	(\$18,600)			
Operating Cost	1			
	(\$275)			
	(\$250)			
	(\$225)			
	1			
	(\$275)			
	(\$250)			
	(\$225)			
	1			
	(\$275)			
	(\$250)			
	(\$225)			
Nondepr Invest	0	1		
	(\$147,000)	(\$77,000)		
	(\$140,000)	(\$70,000)		
	(\$133,000)	(\$63,000)		
	0	1		
	(\$147,000)	(\$77,000)		
	(\$140,000)	(\$70,000)		
	(\$133,000)	(\$63,000)		
	0	1		
	(\$147,000)	(\$77,000)		
	(\$140,000)	(\$70,000)		
	(\$133,000)	(\$63,000)		
Setup	1			
	(\$352,000)			
	(\$320,000)			
	(\$288,000)			
	1	3	4	5
	(\$352,000)	(\$352,000)	(\$55,000)	\$0
	(\$320,000)	(\$320,000)	(\$50,000)	\$0
	(\$288,000)	(\$288,000)	(\$45,000)	\$0
	1	3	4	5
	(\$352,000)	(\$352,000)	(\$55,000)	\$0
	(\$320,000)	(\$320,000)	(\$50,000)	\$0
	(\$288,000)	(\$288,000)	(\$45,000)	\$0

Table M.4: Full System Cash Flows

ATTRIBUTE	YEAR/CASH FLOW			
	1	2		
Labor	1	2		
	(\$891,000)	(\$310,500)		
	(\$810,000)	(\$270,000)		
	1	2		
	(\$891,000)	(\$310,500)		
	(\$810,000)	(\$270,000)		
	1	2		
	(\$891,000)	(\$310,500)		
	(\$810,000)	(\$270,000)		
Depr Investment	0	1		
	(\$735,000)	(\$1,176,000)		
	(\$700,000)	(\$1,120,000)		
	0	1		
	(\$735,000)	(\$1,176,000)		
	(\$700,000)	(\$1,120,000)		
	0	1		
	(\$735,000)	(\$1,176,000)		
	(\$700,000)	(\$1,120,000)		
Maintenance	1			
	(\$214,000)			
	(\$200,000)			
	1			
	(\$214,000)			
	(\$200,000)			
	1			
	(\$214,000)			
	(\$200,000)			
Operating Cost	1			
	(\$275)			
	(\$250)			
	1			
	(\$275)			
	(\$250)			
	1			
	(\$275)			
	(\$250)			
Nondepr Invest	0	1		
	(\$147,000)	(\$77,000)		
	(\$140,000)	(\$70,000)		
	0	1		
	(\$147,000)	(\$77,000)		
	(\$140,000)	(\$70,000)		
	0	1		
	(\$147,000)	(\$77,000)		
	(\$140,000)	(\$70,000)		
Setup	1			
	(\$352,000)			
	(\$320,000)			
	1	3	4	5
	(\$352,000)	(\$352,000)	(\$55,000)	\$0
	(\$320,000)	(\$320,000)	(\$50,000)	\$0
	1	3	4	5
	(\$352,000)	(\$352,000)	(\$55,000)	\$0
	(\$320,000)	(\$320,000)	(\$50,000)	\$0
	1	3	4	5
	(\$352,000)	(\$352,000)	(\$55,000)	\$0
	(\$320,000)	(\$320,000)	(\$50,000)	\$0

Table M.5: Current Operations Qualitative Flows

STRATEGIC					TACTICAL				
ATTRIBUTE	YEAR/QUAL. FLOW				ATTRIBUTE	YEAR/QUAL. FLOW			
Internal Relations	1	2			Flexibility	1			
	-5	-7				5			
	0	-2				10			
	5	3				15			
	1	3	5			1			
	-5	-9	-13			5			
	0	-4	-8			10			
	5	1	-3			15			
	1	5	8			1	6	8	
	-5	-13	-21			5	5	-5	
	0	-8	-16			10	10	0	
	5	-3	-11			15	15	5	
Market Position	1				Integration	1	2		
	-7					11	6		
	0					15	12		
	7					19	16		
	1	2	3	5		1	3	5	
	-7	-7	-12	-30		11	5	5	
	0	0	-5	-20		15	9	9	
	7	7	2	-10		19	13	13	
	1	2	3	8		1	3	6	8
	-7	-7	-12	-40		11	5	5	2
	0	0	-5	-30		15	9	9	6
	7	7	2	-20		19	13	13	10
Mission	1	2			Material	1			
	-5	-7				12			
	0	-2				15			
	5	3				18			
	1	5				1	2	3	5
	-5	-27				12	12	7	7
	0	-20				15	15	10	10
	5	-13				18	18	13	13
	1	8				1	2	3	6
	-5	-45				12	12	7	7
	0	-35				15	15	10	10
	5	-25				18	18	13	13
Organization	1	2			Personnel	1	2		
	-6	-12				12	7		
	0	-6				15	10		
	6	0				18	13		
	1	5				1	2	4	5
	-6	-21				12	7	7	2
	0	-15				15	10	10	5
	6	-9				18	13	13	8
	1	8				1	2	4	8
	-6	-30				12	7	7	0
	0	-24				15	10	10	3
	6	-18				18	13	13	6
Public Relations	1								
	.5								
	0								
	5								
	1								
	.5								
	0								
	5								
	1	6	8						
	.5	-5	-13						
	0	0	-8						
	5	5	-3						
Technology	1								
	-18								
	-10								
	-2								
	1	2	5						
	-18	-18	-24						
	-10	-10	-16						
	-2	-2	-8						
	1	2	8						
	-18	-18	-30						
	-10	-10	-22						
	-2	-2	-14						

Table M.6: Development System Qualitative Flows

ATTRIBUTE	STRATEGIC YEAR/QUAL. FLOW				ATTRIBUTE	TACTICAL YEAR/QUAL. FLOW			
	1	2	3	5		1	2	3	5
Internal Relations	-9	-12			Flexibility	5	10		
	-4	-2				10	15		
	1	8				15	20		
	1	2	3	5		1	2	3	
	-9	-12	0	13		5	10	25	
	-4	-2	5	18		10	15	30	
	1	8	10	23		15	20	35	
	1	2	3	8		1	2	3	6
	-9	-12	0	25		5	10	25	25
	-4	-2	5	30		10	15	30	30
Market Position	1	8	10	35		15	20	35	35
	1	2			Integration	1	2		
	-2	3				6	8		
	5	10				10	12		
	12	17				14	16		
	1	5				1	2	5	
	-2	8				6	8	36	
	5	15				10	12	40	
	12	22				14	16	44	
	1	5	8			1	2	8	
Mission	-2	8	13			6	8	46	
	5	15	20		Material	10	12	50	
	12	22	27			14	16	54	
	1	2				1	2		
	0	3				12	17		
	5	8				15	20		
	10	13				18	23		
	1	2	4	5		1	3	5	
	0	3	20	35		12	37	47	
	5	8	25	40		15	40	50	
	10	13	30	45		18	43	53	
Organization	1	2	4	8		1	3	5	8
	0	3	20	50	Personnel	12	37	47	57
	5	8	25	55		15	40	50	60
	10	13	30	60		18	43	53	63
	1	2				1			
	-11	-6				7			
	-5	0				10			
	1	6				13			
	1	3	5			1	5		
	-11	4	24			7	22		
	-5	10	30			10	25		
Public Relations	1	16	38			13	28		
	1	3	5	8		1	5	8	
	5	10	15	25		7	22	32	
	10	15	20	30		10	25	35	
	15	20	25	35		13	28	38	
	1	3	6						
	5	10	15						
	10	15	20						
	15	20	25						
	1	2							
Technology	7	10							
	15	18							
	23	26							
	1	2	3	5					
	7	10	22	37					
	15	18	30	45					
	23	26	38	53					
	1	2	3	8					
	7	10	22	52					
	15	18	30	60					
	23	26	38	68					

Table M.7: Full System Qualitative Flows

ATTRIBUTE	STRATEGIC YEAR/QUAL. FLOW				ATTRIBUTE	TACTICAL YEAR/QUAL. FLOW			
	1	2				1	2		
Internal Relations	-17	-13			Flexibility	0	5		
	-12	-8				5	10		
	-7	-3				10	15		
	1	5				1	3	4	
	-17	0				0	10	25	
	-12	5				5	15	30	
	-7	10				10	20	35	
	1	5	8			1	3	4	5
	-17	0	10			0	10	25	25
	-12	5	15			5	15	30	30
	-7	10	20			10	20	35	35
									40
Market Position	1	2			Integration	1	2		
	8	6				1	4		
	15	13				5	8		
	22	20				9	12		
	1	5				1	2	5	
	8	-2				1	4	36	
	15	5				5	8	40	
	22	12				9	12	44	
	1	5	8			1	2	8	
	8	-2	-12			1	4	40	
	15	5	-5			5	8	50	
	22	12	2			9	12	54	
Mission	1	2			Material	1	2		
	5	10				7	12		
	10	15				10	15		
	15	20				13	18		
	1	4				1	3	5	
	5	35				7	27	47	
	10	40				10	30	50	
	15	45				13	33	53	
	1	4	5	8		1	3	5	8
	5	35	35	50		7	27	47	57
	10	40	40	55		10	30	50	60
	15	45	45	60		13	33	53	63
Organization	1	2			Personnel	1	2		
	-20	-13				12	7		
	-14	-7				15	10		
	-8	-1				18	13		
	1	5				1	3	5	
	-20	14				12	7	17	
	-14	20				15	10	20	
	-8	26				18	13	23	
	1	6	8			1	3	8	
	-20	14	29			12	7	27	
	-14	20	35			15	10	30	
	-8	26	41			18	13	33	
Public Relations	1								
	15								
	20								
	25								
	1	5							
	15	5							
	20	10							
	25	15							
	1	5	6	8					
	15	5	5	15					
	20	10	10	20					
	25	15	15	25					
Technology	1	2							
	7	10							
	15	18							
	23	26							
	1	2	3	5					
	7	10	22	37					
	15	18	30	45					
	23	26	38	53					
	1	2	3	8					
	7	10	22	47					
	15	18	30	55					
	23	26	38	63					

M.3 Frequency Distributions for Risk Analysis

Figure M.1: Frequency Distribution of Pecuniary Objective - Current System

Figure M.2: Frequency Distribution of Strategic Objective - Current System

Figure M.3: Frequency Distribution of Tactical Objective - Current System

Figure M.4: Frequency Distribution of Pecuniary Objective - Development System

Figure M.5: Frequency Distribution of Strategic Objective - Development System

Figure M.6: Frequency Distribution of Tactical Objective - Development System

Figure M.7: Frequency Distribution of Pecuniary Objective - Full System

Figure M.8: Frequency Distribution of Strategic Objective - Full System

Figure M.9: Frequency Distribution of Tactical Objective - Full System

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