ASSESSMENT OF THE EFFECTIVENESS OF THE ADVANCED PROGRAMMATIC RISK ANALYSIS AND MANAGEMENT MODEL (APRAM) AS A DECISION SUPPPORT TOOL FOR CONSTRUCTION PROJECTS

A Thesis

by

WILLIAM KWEKU ANSAH IMBEAH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2007

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Seth Guikema
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	Daren Cline
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ABSTRACT

Assessment of the Effectiveness of the Advanced Programmatic Risk Analysis and Management Model (APRAM) as a Decision Support Tool for Construction Projects. (May 2007)

William Kweku Ansah Imbeah, B.Sc., Kwame Nkrumah University of Science and Technology, Ghana

Chair of Advisory Committee: Dr. Seth Guikema

Construction projects are complicated and fraught with so many risks that many projects are unable to meet pre-defined project objectives. Managers of construction projects require decision support tools that can be used to identify, analyze and implement measures that can mitigate the effects of project risks. Several risk analysis techniques have been developed over the years to enable construction project managers to make useful decisions that can improve the chances of project success. These risk analysis techniques however fail to simultaneously address risks relating to cost, schedule and quality. Also, construction projects may have scarce resources and construction managers still bear the responsibility of ensuring that project goals are met. Certain projects require trade-offs between technical and managerial risks and managers need tools that can help them do this.

This thesis evaluates the usefulness of the Advanced Programmatic Risk Analysis and Management Model (APRAM) as a decision support tool for managing construction projects. The development of a visitor center in Midland, Texas was used as a case study for this research. The case study involved the implementation of APRAM

during the concept phase of project development to determine the best construction system that can minimize the expected cost of failure. A risk analysis performed using a more standard approach yielded an expected cost of failure that is almost eight times the expected cost of failure yielded by APRAM.

This study concludes that APRAM is a risk analysis technique that can minimize the expected costs of failure by integrating project risks of time, budget and quality through the allocation of resources. APRAM can also be useful for making construction management decisions. All identified component or material configurations for each alternative system however, should be analyzed instead of analyzing only the lowest cost alternative for each system as proposed by the original APRAM model. In addition, it is not possible to use decision trees to determine the optimal allocation of management reserves that would mitigate managerial problems during construction projects. Furthermore, APRAM does not address the issue of safety during construction and assumes all identifiable risks can be handled with money.

DEDICATION

This thesis is dedicated to my friend Evans Opoku-Barimah (Bounty Killa). Even though he has been gone for some time now, I still have him in my heart and believe the Lord will continue taking care of him. May he rest in peace.

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May God bless you all.

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CHAPTER I

INTRODUCTION

Success for an owner in the construction industry is measured by the ability to complete a project on time and within budget in conformance to performance requirements without injuries or loss of life. Construction, like many other industries, has substantial risk built into its profit structure (Mustafa and Al-Bahar 1991; Akintoye and Macleod 1997). Due to the nature of the different activities involved, construction projects can be complicated and are often fraught with a number of uncertainties. Uncertainties about the adequacy of labor force, delivery of critical equipment and supplies, communication/coordination between design and construction teams, worker and site safety and weather conditions are examples of uncertainties typical for most construction projects. It must be emphasized however that uncertainty as used in this context does not necessarily mean something negative or bad. Uncertainty as used in this study simply refers to an unknown likelihood. These uncertainties can be referred to as project risks and can be the cause of a construction project's failure to achieve pre-defined objectives of cost, schedule and quality (Mustafa and Al-Bahar 1991). Managers of construction projects therefore need to be able to identify, assess and analyze project risks in order to achieve project goals. Risk can be defined as the chance or possibility of a loss or harmful consequences or the probability and consequence of

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This thesis follows the style of *ASCE Journal of Construction Engineering and Management*.

not achieving pre-defined project goals.

Various fields have different definitions for risk and in the construction industry risk is defined as the potential failure to safely achieve overall project objectives within pre-defined costs and schedule in conformance to performance requirements. It is therefore necessary to develop appropriate methods for identifying and managing project risks in order to improve the chances of project success.

Managers of construction projects are faced with the challenge of ensuring the appropriate allocation of all project resources including financial, material and human resources during the lifetimes of projects in order to minimize the risks of project failures. Project resources may, however, be scarce for projects, and project managers still bear the responsibility of deciding how to allocate these sometimes scarce resources. In their attempts to appropriately allocate scarce project resources, project managers are again faced with the challenge of balancing technical and managerial failure risks, where technical risks refer to failure to provide a product that conforms to specifications or perform as required, and managerial risks refer to the inability to complete a project within a specified funding plan or budget and within a specified duration. Such situations call for trade-offs between technical and managerial failure risks and it is essential that managers are furnished with some decision-support systems or tools that would help them make valuable decisions. The Advanced Programmatic Risk Analysis and Management Model (APRAM) is an example of a decision-support framework that can be useful for the management of the risk of project failures (Dillon and Paté-Cornell 2001; Dillon et al. 2003).

The APRAM model can be used to optimize the allocation of budget reserves through trade-offs between technical and managerial failure risks based on the preferences of the decision maker(s), and it allows for checking whether technical and managerial risks meet the thresholds of acceptability (Dillon et al. 2003).

Such a decision-support framework, if used in the construction industry, could add value by helping project managers better address issues relating to almost all types of identifiable failure risks, and, at the same time, provide owners with facilities that are in conformance to their requirements.

APRAM was developed for the aerospace industry, particularly the management of NASA's "Faster, Better-Cheaper" unmanned space missions (Dillon and Paté-Cornell 2001; Dillon et al. 2003). These projects had limited scope (i.e. smaller projects) and tight resource constraints, and project managers needed a tool that could help them decide what resources were needed in order to satisfy certain thresholds of safety. Project managers also needed a way of figuring out how to determine management reserves using unambiguous information regarding risk instead of adopting the conventional rule of thumb in which about 10 to 30% of total project budgets are set aside as management reserves.

The APRAM model involves first identifying alternatives for design and then determining the residual budget. The residual budget refers to the difference between the total project budget and the cost of the minimum design alternative. With the alternatives identified, the next step is to perform an optimization for the reinforcement budget for the design alternatives. The reinforcement budget describes the portion of the residual budget available for reinforcement of the technical system. The difference between the residual budget and the reinforcement budget is referred to as the budget reserve. The optimal response of each reserve budget to development problems is then determined. With the allocation of reinforcement budget and reserve budget optimized for each design alternative, the next step integrates the two optimizations in order to make a decision on the appropriate design and budget allocation that would minimize the overall failure risk.

With a choice of design and budget allocation made, project managers have to determine whether the level of risk for the selected alternative and budget is acceptable. APRAM provides a framework that can be used to determine how many additional resources are needed to reduce the failure risk to a tolerable level (Dillon et al. 2003). Figure 1.1 shows the steps involved in the APRAM process.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

The collapse of the Tacoma Narrows Bridge in the 1940s and the collapse of the Hyatt Regency walkway in the 1980s are only two examples of cases where constructed facilities have either failed to serve the purposes for which they were constructed or failed because of improper design. The collapse of the Hyatt Regency walkway left 114 people dead and nearly 200 injured (Pfatteicher 2000) while no human life was lost in the collapse of the Tacoma Narrows Bridge. In the aftermath of these and failures of other constructed facilities, there has been a rising need for a thorough and effective risk analysis for all constructed projects. Successful construction projects can be defined as

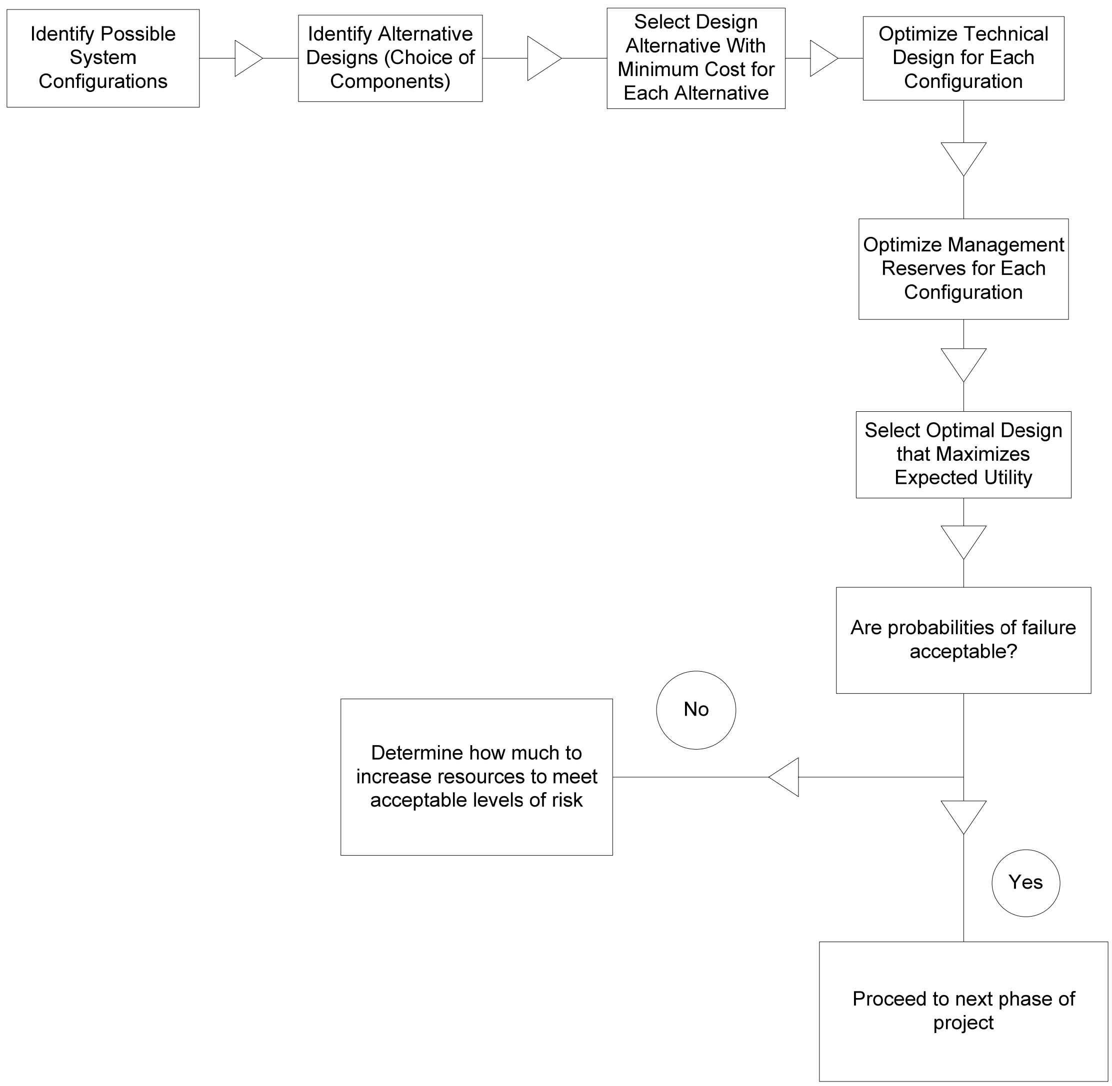


Figure 1.1 The APRAM Process

projects whose overall objectives are safely achieved within pre-defined costs and schedule and at the same time meet performance requirements. Successful projects provide value to owners, improve the reputations of contractors, enhance owner confidence in architects and/or engineers and provide users with constructed facilities that are safe and perform as required.

Owners and developers of construction projects are increasingly becoming interested in simultaneously reducing the total costs of construction projects as well as delivering quality constructed facilities. For some construction projects, early time to market provides competitive advantage to the owner. In order for projects to meet pre-defined goals of cost, duration and quality, project managers need to be furnished with decision-support tools to enhance valuable allocations of scarce project resources. Various techniques have been developed for use in the management of risks in construction but most of these techniques either address risks relating to only cost or schedule or structural reliability or a combination of cost and schedule risks. A careful analysis of construction risks can show that these risks are all interrelated. For instance, a schedule slippage can impact the total cost of construction in the event of inflation or escalation of material costs. There is a need therefore for techniques that will address the integration of the different risks of failure involved in construction. In other words, in addition to ensuring that projects are completed on time and under budget, project managers need to simultaneously address issues relating to the technical aspects of their facilities and then make some trade-offs between these by optimizing the use of budget reserves. That is, in some cases, projects may slightly slip budget if there is an urgent need to improve some technical aspects of the project in order to provide a quality facility that can fully serve the purposes for which it was constructed. This sort of trade off however, should be made only when it adds value to project participants.

The main purpose of this study is to evaluate the effectiveness of the APRAM model for construction projects. That is, this study will determine whether APRAM is useful and practical to the extent that it can be used in making useful decisions (i.e. decisions that add value) in construction. This will be done by implementing the model in the design and development of a construction project. An actual construction project will be used as the basis for the implementation of the model and the only inputs for the project being utilized in this endeavor are the construction drawings and specifications. It is important to emphasize here, however, that this study does not claim to be a comprehensive application of the APRAM model in construction because different owners and project managers may have different perspectives of risks and no single risk source can be identified as universal for all construction projects. Again, the purpose of this study is to determine whether or not APRAM can be used for construction projects.

Certain modifications were made to the APRAM model in order to obtain a practical decision support tool that managers of construction projects can use to allocate project resources to improve the chances of project success. Among these is the use of all identified configurations for each construction system in the analysis rather than the lowest cost configuration for each construction system. Also, decision trees were not used to determine the optimal allocation of management reserves because of differences between project development in construction and the development of space missions (APRAM was developed for space missions).

SCOPE OF STUDY

This research study involves the evaluation of a decision-support tool that can be used by project managers in managing risks related to their projects. The study is thus limited to risks related to construction. The risks here involve the risk of cost overrun, schedule overrun and technical failure. An attempt will be made to include a discussion on unanticipated events or natural disasters such as flooding since these events can impact constructed facilities.

The study addresses issues that can be taken into account during the design and construction of facilities. Some assumptions are made regarding inputs to the pre-project planning phase of this project in order to generate illustrative numbers as probabilities.

To add to the above, this study does not address the selection or putting together of a risk management team. It is assumed that in order to implement APRAM, the owner and/or contractor should have a risk management team in place as early as the feasibility phase.

FINDINGS OF THE STUDY

This study concludes that APRAM can actually be used as a decision support tool during the management of construction projects. The model however, requires some modifications in order to be effective as a decision support tool in a construction setting. These modifications include the use of all possible component configurations for each system in the analysis rather than the use of the lowest cost component configuration as suggested by the original APRAM model. Also, the use of decision trees to determine the optimal allocation of management reserves that would mitigate managerial problems can not be possible in construction. Finally, the assumption in the original APRAM model that the cost of both total managerial failure and total technical failure is the total budget can not be a valid assumption for construction projects.

Even though APRAM can be effective for the management of construction projects, it has certain limitations. These limitations include the fact that APRAM assumes that all identifiable project risks can be handled using money. Also, APRAM can not effectively address risks referred to in construction as “acts of God”.

RESEARCH CONTRIBUTION

This research has demonstrated that managers of construction projects can use APRAM to make useful decisions that can improve the chances of project success. Some of the important features of APRAM are:

i. Simultaneously addresses cost, schedule and budget risks

ii. Provides a sound basis for the allocation of project resources

iii. Can aid selection of a construction system that minimizes the overall costs of failure

Also, this research highlights the fact that good risk analysis alone is not enough to reduce the chances of project failure. Good management practices must be adhered to. In addition, appropriate health and safety regulations must be strictly enforced and the integration of all project participants early in project development is critical.

Finally this research shows that the construction industry can utilize certain decision support tools developed in other fields to address risks that can lead to project failure.

THESIS LAYOUT

This thesis is organized in six chapters. Chapter I provides an introduction to risks in construction and also provides a background on APRAM. The chapter also outlines the problem statement and objective of the research. In addition, the scope of the study is stated as well as the layout of the thesis. The main findings as well as the contribution of this research to the practice of construction are also summarized in this chapter.

In Chapter II, a comprehensive literature review on risk analysis in construction is provided. The chapter begins with an introduction followed by various application dependent definitions of risk. A review of the risks of failure in construction is also provided in this chapter. An overview of construction risk analysis is given and this includes different methods that have been used to address construction risks. A summary of the chapter is provided at the end.

Chapter III focuses on the research methodology. The construction project used for this study is presented and the preparation of detailed cost estimates described. The implementation of the APRAM model for the project is described in detail by carefully outlining all the steps involved. The chapter clearly states all assumptions used for this study and concludes with a summary.

Chapter IV documents the results obtained from the implementation of APRAM. This chapter also begins with an introduction. In this chapter, results obtained from the application of APRAM are presented. In addition, the results of an alternative approach used to determine the overall expected cost of failure are presented in this chapter.

The results presented in Chapter IV are discussed in Chapter V. Chapter V evaluates the process of applying APRAM to a construction project. The chapter mentions certain differences between the aerospace industry and the construction industry. Modifications to APRAM required to obtain an appropriate decision support tool that managers of construction projects can use to appropriately allocate scarce project resources to minimize the risks of project failure are described in this chapter. In addition, a discussion is included on how to get actual information or data on construction projects in practice. The chapter concludes with a summary.

Chapter VI provides a summary of the salient points of this thesis. The chapter also includes conclusions and recommendations from the study. The contribution of this research is also summarized in this chapter.

CHAPTER II

LITERATURE REVIEW

INTRODUCTION

Construction is a very complicated, expensive and challenging process that involves a lot of uncertainties. As a result of this, risk forms an inherent and expected part of almost all construction projects. It is therefore the responsibility of all stakeholders of construction projects to ensure appropriate measures are put in place to identify all recognizable risks. Kerzner (2003) however points out that a risk management process should be able to do more than just identify the risk. In other words, once risk is identified, there should be an effort to determine measures that could be implemented to minimize the impacts of risk on project success. It is important to note that project risks cannot be totally eliminated. Appropriate measures can only reduce the likelihood of risky events occurring or mitigate the impacts of risk events on projects.

This literature review comprises four sections. The first section provides definitions of risk based on different applications. This is followed by a discussion of risks in the construction industry. The third section focuses on construction risk analysis. In this section, various techniques that have been used in the past to assess construction risks as well as techniques currently in use are discussed. The chapter concludes with a summary of the salient points of the literature review.

DEFINITIONS OF RISK

Risk can be defined differently depending on specific applications. In everyday parlance, risk is usually referred to as something bad or undesirable. In finance/investment, risk can be defined as the possibility of loss or the uncertainty of future returns while risk can be defined as the possibility of loss of trading capital in commerce/trading. These definitions of risk neither address the probability of occurrence of a risky event/outcome nor provide an indication of a measure of the severity of the outcome. In the field of engineering, the definition of risk combines the probability of occurrence as well as the consequence of a specified risky event and this is often simply expressed as the product of the probability of occurrence of the risk and the consequence of the risk (Kerzner 2003). In construction, risk refers to the potential failure to achieve pre-defined project goals which are usually related to project budget, schedule and performance of the constructed facility.

CONSTRUCTION RISKS

Three types of risks can generally be identified in the construction industry. The first type of risk is related to cost and can simply be described in terms of a project exceeding its budget. According to Abdou (1996) budget overrun is not always a result of poor construction supervision. He attributes budget overrun to poor planning and wishful pricing or the lack of coordination/communication between design professionals and construction trades. Rydeen (2006) also mentions overlooked budget items, poor management, unforeseen site conditions and inaccurate cost estimates as some of the factors that contribute to budget overruns for construction projects.

The second type of risk deals with time; that is, the inability to complete the construction of a facility within a specified duration. For projects in which the time to market is critical, delays could mean failure to reach the market ahead of competitors. In addition, delays in the completion of certain construction projects could mean lost revenue because every day that the completion of a facility extends beyond the planned completion date represents a day that the facility cannot be used. Mulholland and Christian (1999) in their study on risk assessment in construction schedules mentioned excessive change orders, poor communication between disciplines, poor planning, incompetent management and poor management controls as some of the causes of schedule overrun. It can be concluded from the causes of cost and schedule overrun listed above that some of the causes of budget overruns can also cause schedule overruns. Thus cost and schedule risks can be interrelated and this is unsuspectingly expressed in the popular phrase "time is money."

The third risk is design related, that is, risk related to the technical characteristics of the constructed facility. This type of risk could simply be described as a constructed facility failing to meet performance requirements. Quality control and safety should be the priority of all construction managers because defects or failures in constructed facilities can result in very large costs of re-construction and even severe injuries and deaths in the worst case.

It should be noted that the order in which the different types of construction risks are mentioned above does not necessarily depict order of importance even though for some projects one type of risk may be more critical than the others. Each construction project has its own technical characteristics and these differ from project to project. The technical characteristics of any construction project will depend on the construction type, execution time as well as the construction environment (Öztas and Ökmen 2005). This leads to a different risk management atmosphere for each project. Risk management can be described in this context as a systematic procedure of controlling all risks that are predicted to be faced on a project rather than as a kind of insurance system.

The development of construction projects involves considerable risk due to the uniqueness of different projects, the uncertainties introduced by project stakeholders and intrinsic and extrinsic constraints (Mbachu and Vinasithamby 2005). Risks can adversely impact the achievement of key project objectives of time, cost and quality. The failure to reach pre-defined project objectives could mean extra costs over the planned costs and less returns on investment to the owner. To the engineers and/or architects, it could mean loss of the confidence their clients have in them. To the contractors, it could mean loss of profit through penalties for non-completion and declined client satisfaction that could affect their chances of future jobs (Mbachu and Vinasithamby 2005). To the end user in the case of reinforced concrete structures such as bridges, failure to provide quality facilities could mean disruptions of traffic due to frequent and often lengthy repairs and renovations (Trejo and Reinschmidt 2005). There is therefore the need to determine which risks are likely to affect all projects and document the characteristics of each in order to devise means of addressing these risks.

CONSTRUCTION RISK ANALYSIS

There are several risk analysis methods available for assessing risks during construction projects. Some of these risk analysis methods only address either budget overrun alone or schedule overrun alone or in some cases a combination of the two. There are also risk assessment techniques which only address the structural reliability of constructed facilities. Since the issue of quality (i.e. conformance to performance requirements) is of significant importance in construction, there is the need to develop risk analysis methods that can simultaneously address project failures due to costs, time and quality. This section describes some risk analysis methods that have been used for evaluating risks in construction. Comparisons will be made between APRAM and some of these risk assessment techniques in this study.

Judgmental Risk Analysis Process

The Judgmental Risk Analysis Process (JRAP) is a schedule risk analysis method that can be utilized during the configuration of a project's risk management system. This technique was proposed by Öztaş and Ökmen (2005). JRAP can be used in cases where there is little or no historical data on similar or related projects. JRAP has the ability to convert uncertainty to risk judgmentally in construction projects and it employs a pessimistic risk analysis in which the effect of an engineer making inaccurate data estimation during risk modeling is decreased.

The first step in JRAP is determining the critical risks that may have an effect on activity durations. This can be done by examining the critical activities of the schedule network and then selecting the risks that influence theses critical activities from a predetermined risk list. The second step involves the assignment of probability distributions to the identified risks, and this can be achieved by using experience and engineering judgment in cases where there is not sufficient historical data. In the next step, maximum and minimum durations of activities are determined. JRAP assumes it is less probable to have a situation in which the actual duration of a construction activity is below the appraised most likely duration. That is, JRAP assumes the actual duration of a construction activity is greater than the most likely duration more than 50% of the time. According to Öztaş and Ökmen (2005) this characteristic makes JRAP a pessimistic approach.

The next step of the process involves the establishment of an activity-risk factor matrix. The activity-risk factor matrix quantifies the varying effect of each risk over each activity with the constraint that the total influence of all risk factors should be 100% on a given activity. JRAP then performs spreadsheet modeling and Monte Carlo Simulations (MCS) on the schedule network for the project. MCS utilizes the established activity-risk factor matrix to calculate the variations in activity durations. From the simulations, a list of the critical activities and their probabilities as well as the total project duration can be obtained. JRAP is a schedule risk analysis methodology and therefore cannot be used to assess risks relating to costs and quality.

Estimating Project and Activity Duration Using Network Analysis

Dawood (1998) proposed a methodology to accurately model activity dependence and realistically predict project duration using a risk management approach. The first task in this process is to identify risk factors that can cause variations in predicted activity durations. The identification of risk factors is dependent on historical data. A representative distribution having a minimum value (0) and a maximum value (1) can then be used to model the identified risk factors through the generation of random numbers. The influence of each risk factor on activity durations is then assessed judgmentally through elicitation. As in the case of activity-risk factors for JRAP, the total influence of all factors should be 100% for any given activity. The last task in this process is to calculate the duration of all activities. The duration of an activity using this methodology can be calculated with the equation (Dawood 1998):

$$D_A \quad MinTime \quad [MaxTime \quad MinTime] \quad [(RF_1 \quad Random_1) \quad (RF_2 \quad Random_2) \quad (RF_3 \quad Random_3) \quad ... \quad (RF_n \quad Random_n)] \quad \ldots\ldots\ldots\ldots 2.1$$

where D_A - duration of activity A

MinTime - minimum duration that can be assigned to activity A

MaxTime - maximum duration that can be assigned to activity A

RF_i, (i=1…n) - influence of a risk factor on activity A

$Random_i$,(i=1…n) - generated independent random number with a uniform distribution

Once the methodology has been used to determine the outcome of the project duration, managers need to determine measures that can be adopted to reduce variations and reduce the pessimistic part of the project duration. The results obtained from using this methodology are only beneficial for forecasting project durations and estimating the effects of risk factors on schedule.

Computer Aided Simulation for Project Appraisal and Review

Computer Aided Simulation for Project Appraisal and Review (CASPAR) is a project management tool designed by the Project Management Group at the University of Manchester Institute of Science and Technology. CASPAR was designed to model the interaction of time, resources, cost and revenue throughout the duration of a project (Willmer 1991). This tool can be used for the analysis of the financial and construction risks associated with the engineering, operation and management of a project. CASPAR involves two programs, the CASPAR Cost Program and the CASPAR Time Program. To analyze a project using the CASPAR Cost Program, the project is represented by a precedence network which defines work activities and their relationships. Costs and resources are added to the model in order to generate realistic cash flows. CASPAR provides a single figure estimate of the outcome of the project based on deterministic estimates of time, cost, and revenue and resource usage. The CASPAR Cost Program evaluates projects in terms of economic parameters such as net present value, internal rate of return and payback period. The CASPAR Time Program can use the same data as the one developed for the cost program but ignores all data related to costs, revenues or resources because the program only analyzes the project network. CASPAR provides a timing report for the project being analyzed which includes the early or late start and finish dates as well as the total float for activities. Total float is defined as the number of days an activity can be delayed without delaying the entire project (Halpin and Woodhead 1998).

CASPAR can further be used to perform a sensitivity analysis to determine the sensitivity of economic parameters in the case of the cost program and project duration in the case of the time program to changes in risk variables. In addition, CASPAR can be used to perform probability analysis. The CAPSAR Cost Program uses MCS to sample values for each risk variable and the results can be presented in the form of cumulative frequency diagrams. The CASPAR Time Program uses MCS to determine the effect uncertainty has on schedule by substituting different values for the duration of each activity in the network. This analysis provides the earliest, latest and most likely project finish dates as well as the standard deviation and skewness of the distribution. Analysis of projects using CASPAR can only evaluate risks associated with project costs and schedule.

Schedule Risk System

The schedule risk system is a system used to consider and quantify uncertainty in construction schedules. The system involves two phases: risk identification and risk measurement (Mulholland and Christian 1999). Risk identification describes the process of identifying the variables likely to affect the project schedule and this can be done with a computer application program called HyperCard. The HyperCard system provides a database of previously experienced schedule risks. Once the risks in the database are provided, the project team needs to follow-up with a brainstorming session to obtain a list of potential schedule risks for the project at hand. The new list can then be reordered into relevant risks for each dimension of schedule uncertainty (HyperCard allows the addition of additional information).

Risk measurement describes the process of evaluating and quantifying the chances of the occurrence of a risk and its effects on schedule. The variance of the performance time distribution of a project can be used to measure schedule risk. The larger the variance, the greater the risk associated with project schedule. Alternatively, a spreadsheet can be used for modeling the effects of the risks on the project schedule in order to obtain the project's schedule risk profile. The spreadsheet can also be used to vary one uncertain element at a time in order to examine the effect on the total project schedule. An advantage of this risk assessment approach is that the HyperCard database can be used as a communication structure for the transfer of learning experiences between projects. This risk assessment technique is a time based model and can only be used to assess schedule risk.

Data-Driven Analysis of Corporate Risk Using Historical Cost-Control Data

This risk analysis technique addresses risks in a company's group of projects by classifying risks into those that occur simultaneously and those that occur routinely rather than analyzing unique characteristics associated with individual projects (Minato and Ashley 1998). This methodology starts with the identification of corporate risks, that is, the different cost elements that are associated with inherent risk factors across all of a company's ongoing projects. These risks, according to Minato and Ashley (1998), are results of combinations of political, economic, industrial and company conditions that are common to multiple projects as well as conditions specific to individual projects. The methodology requires the determination of the total risk of a project. The total risk of a project is the sum of dependent risk and independent risk. Dependent risk describes uncertainty that arises due to the interactions of common factors that affect multiple cost elements simultaneously. Independent risks refer to uncertainty that results from unique risk factors within the cost element independently. Since most construction companies engage in multiple projects at the same time, when a number of dependent risks are identified for almost all of a company's projects, they may be classified as corporate risk. The uncertainty due to dependent risk is then quantified by using the company's cost-control data from past projects to estimate the uncertainty for future projects. The performance of a project can be defined at project completion with the equation (Minato and Ashley 1998):

$$\textit{Performance}\ (\%) = \frac{\textit{Actual Cost} - \textit{Expected Cost}}{\textit{Expected Cost}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

Expected cost refers to the budgeted cost of the work and actual cost is the total cost of construction at completion.

A positive performance represents cost overrun while a negative performance represents cost underrun. This method further determines the covariance among the performances of a project's cost elements using a variance/covariance matrix. A value, beta, is determined by the ratio of the covariance between the performance of the cost element to overall project performance. Beta serves as a measure of corporate risk. Attention should therefore be directed to all cost elements with a beta value greater than the beta value computed for the overall project performance. This methodology can only be used to assess the performance of a project on a cost basis.

Estimating Using Risks Analysis

An essential feature of all projects is the setting aside of some money to be used for dealing with uncertainties related to construction projects. This amount of money is referred to as a contingency allowance. Typically, the contingency allowance is a percentage of the base cost for the development of the facility and follows a rule of thumb such as 10 to 30% of the project budget. Estimating using risk analysis (ERA) is a methodology developed by the government of Hong Kong. ERA can be used to substantiate a project's contingency by identifying uncertainties and estimating their financial implications (Mak and Picken 2000). In order to use the ERA process, a risk free base estimate first has to be prepared. Risks are identified by the project team and these are classified as either fixed or variable. Fixed risk events are those that either fully occur or do not occur at all while variable risk events are events that will definitely occur but whose extent of occurrence is uncertain. An average risk allowance and a maximum risk allowance are then calculated for each risk event. With all risk events identified and the average and maximum risk allowances calculated, the average risk allowances for all events are summed and this becomes the contingency of the project. One advantage of the ERA is that it can be performed as a project progresses hence certain events that were initially identified as uncertain become more certain and can be included in the base estimate.

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed in the 1970s by Thomas Saaty, then a professor at the Wharton Business School (Mustafa and Al-Bahar 1991). The AHP is a multi-criteria decision analysis tool that permits objective as well as subjective factors to be considered in the risk analysis process. Mustafa and Al-Bahar (1991) applied AHP to assess the risks involved in the construction of the Jamuna Multipurpose Bridge in Bangladesh. AHP involves first formulating the decision problem in a hierarchical structure. This is done in such a way that the top level reflects the focus of the decision problem and the lowest level shows the decision options. With the hierarchy constructed, the decision maker prioritizes risk elements in order to determine the relative importance of the elements in each level of the hierarchy as well as the likelihood of the levels of risk. A number of square matrices are formed starting from the top of the hierarchy and working down. This is done by making pairwise comparisons of elements in each level with respect to their importance in making the decision under consideration. In other words, elements in each level are paired and compared to an element in the level immediately above. Once the comparison matrices are formed, relative weights are derived for the various elements and the composite weights of the decision alternatives determined by aggregating the weights through the hierarchy to get a normalized vector of the overall weights of the options. The aggregated weight can then be characterized as high, medium or low total risk based on priorities of factors, sub factors and levels of risk.

Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) is an analytical tool that has been proven to be useful in the analysis of reliability, maintainability and safety in identifying system failures of significant consequence (Onodera 1997). FMEA requires the use of an FMEA worksheet at each life-cycle stage.

To successfully execute FMEA, potential sources of failure for the system to be assessed should be identifiable. Once the failure sources have been identified, the potential modes in which they can occur, the potential causes of failure and the potential effects of the potential failure modes are determined. The severity of the failure effects are assigned a number based usually on a scale of 1 to 10 where 10 is catastrophic to the viability of the entire project and 1 is negligible. The assigned number is dependent on the owner's perception of risk or the risk management team's assessment of the project. The likelihood of occurrence of each potential cause of failure as well as the chances of using management controls to detect each cause of failure are also assigned a number on similar scales of 1 to 10. For the likelihood of occurrence, 1 represents no known failures with almost identical projects and 10 represents inevitable failure. In the case of management controls detecting the causes of failure, 1 means indicators will almost certainly detect the failure mode in time while 10 means there are no known indicators to provide advance warning of the failure mode.

The product of the severity, likelihood and detection of each identified source of failure gives the Risk Priority Number (RPN). The RPNs obtained can be used as a guide to address the identified sources of failure. An advantage of the FMEA identified by Onodera (1997) is that FMEAs can still be used to add value even after the completion of construction activities.

Utility-Functions in Engineering Performance Assessment (Multiple Attribute Utility Functions/Eigenvector Prioritization Method)

Multiple attribute utility theory refers to a decision-making tool that managers of engineering projects can use to make a selection from a set of alternatives (Georgy et al. 2005). The term utility basically provides a measure of the decision maker's preference for a particular outcome. Georgy et al. (2005) further define utility-function as a mathematical function developed between all possible outcomes of each individual measure for a set of predefined engineering performance measures and their corresponding relative preference or attractiveness to the evaluator. A multiple attribute utility function therefore integrates all utility functions into a single platform and thus provides a collective assessment of engineering performance on a project.

Once the various measures of engineering performance are integrated, a preference structure that shows the relative importance of each measure to the others needs to be identified. The process of using the multiple attribute utility theory involves breaking down the multiple attribute utility function into a number of single-attribute functions such that each single-attribute utility function can identify the decision maker's preference for all the possible values that can be associated with a particular attribute. Two values are most important in this process. These values are U_L and U_H and they respectively represent the lowest and highest values that the decision maker's preference can have. U_L represents the value where the utility is zero and U_H represents the value where the utility is 1.0. The expected utility (EU) defined as the degree of preference for each alternative is calculated and used in the selection process. In the selection process, the alternatives are ranked and the alternative with the highest EU value is selected.

Alternatively, the eigenvector prioritization method can be used to derive the preference structure. This method forms the core of AHP and is based on three principles: decomposition, comparative judgment and synthesis of priorities (Georgy et al. 2005). The decomposition principle requires the problem at hand to be broken down into a hierarchy. Comparative judgment calls for the pairwise comparison of elements in a given level with respect to their parent in the level immediately above. Comparison matrices are formed from the pairwise comparisons and the matrix entries used to generate a ratio scale that is a reflection of the local priorities of the elements in that level. The synthesis of priorities step takes each of the ratio scale local priorities and constructs a composite set of priorities for the elements at the lowest level of the hierarchy. This methodology provides a platform for integrating several measures of engineering performance into a single indicator of engineering performance.

Program Evaluation and Review Technique

The Program Evaluation and Review Technique (PERT) was developed for the U.S. Navy in 1958 to address significant uncertainties involved in non-routine or risky projects (Kerzner 2003; Nasir et al. 2003). According to Kerzner (2003) all the various tasks required to complete a project must be clear enough to be put in a network comprising of events and activities to be able to use PERT. In addition, the events and activities should be logically sequenced on the network. A PERT chart is constructed to determine how much time is required to complete a project and hence uses time as a common denominator to analyze project success. The PERT evaluator must define a statistical distribution for each activity that will represent possible durations as a result of project uncertainties. A beta distribution is normally used and this requires three values for each activity: the optimistic (L), most likely (ML) and pessimistic durations (U). These values are usually estimated based on expert opinion or by the person most familiar with the project. From the three duration estimates, the mean and variance of each activity can be calculated from the equations (Nasir et al. 2003):

$$Mean = \frac{L + 4ML + U}{6} \quad \ldots\ldots 2.3$$

$$Variance = \left(\frac{U - L}{6}\right)^2 \quad \ldots\ldots 2.4$$

The mean duration for each path is the sum of the mean duration for each activity along that path. The critical path can then be computed and this refers to the sequence of activities and events with the maximum duration.

Monte Carlo Process

The Monte Carlo process creates a series of probability distributions for potential risk items and randomly samples the distributions and the numbers into useful information that reflects the quantification of a project's potential risks (Kerzner 2003). This process can be used to assess a project by using either project cost or schedule as the parameter to analyze project success or both. The steps involved in the process involve first identifying the activity level for which probability distributions are required. A reference point is then estimated for each activity within the model. This reference point can either be cost or duration.

The next step involves the identification of activities containing uncertainty and the development of appropriate probability distributions for each activity with uncertainty. MCS can then be performed to combine the activity probability distributions. If the variable used for this process is cost, the results of the simulation will be a cost estimate at the end of the project and a cumulative distribution function of probability versus cost. The outputs from the simulation can be analyzed to determine the level of cost risk and to identify specific cost drivers.

If schedule is the variable used, the simulation will provide a project schedule at the desired level and a cumulative distribution function of probability versus schedule. The outputs can then be analyzed to determine the level of schedule risk and also to identify schedule drivers. Nasir et al. (2003), in their study to develop a method to assist in the determination of the lower and upper activity duration values for schedule risks by PERT or MCS, concluded that MCS has two advantages over PERT. The first is that the criticality index which is the frequency with which an activity falls on the critical path can be calculated when MCS is used. The second is, with MCS, cost and duration can be determined for each run of the simulation. There is therefore more comprehensive information about the possible events and the relationship between the two performance measures.

Other Ways of Analyzing Construction Risks

There are several other ways of addressing construction risks. These range from the use of complicated mathematical models to the use of rules of thumb based mainly on experience and intuition. Akintoye and MacLeod (1997) mentioned risk premium, risk adjusted discount rate, decision analysis, stochastic dominance and subjective probability as some of the techniques of risk analysis for construction projects. To add to the above, the owner starts out in all construction projects with all the risks but by contracting with parties such as an Architect/ Engineer or a contractor, the owner spreads out the risks and shares them with other project participants. Another way some construction companies have addressed risks especially on very large projects has been to form partnerships with other companies in order to share these risks. Finally, Abdou (1996) identified a number of steps that can be used to analyze and manage construction risks. The steps he identified are as follows:

i. Understanding the types and phases of risk
ii. Assessing the risks of a particular construction project
iii. Matching risks with in-house capabilities and building a team

iv. Defining a building strategy

v. Understanding the bidding process

vi. Selecting the right kind of construction contract

vii. Selecting the contractor

viii. Monitoring construction

In view of the several techniques that managers of construction projects can use to minimize the chances of failure for their projects, it is also important to ensure that sufficient information is provided regarding details of predictable risks to the health and safety of all personnel on site and the general public. One way of doing this is strictly enforcing regulations such as the Occupational Health and Safety Act (OSHA) regulations and the Construction Health, Safety, and Welfare (CHSW) regulations. CHSW is used in the United Kingdom and it outlines steps to be taken for work over approximately 2 meters high. Even though all parties involved in a project should be concerned with health and safety, the construction manager assumes a contractual duty to ensure worker safety. According to Baylis (2003), a Health and Safety file prepared on completion of a construction project could inform the end user of the risks that must be managed in the future, that is, the need for maintenance, repairs or renovations.

SUMMARY

This chapter provided a literature review related to this research. Definitions for risk based on different applications have been provided. Risks in the construction industry have been identified as well as some possible causes of risks. The chapter finally discusses various techniques that have been used to analyze risk in the construction industry. Table 2.1 summarizes the risk analysis techniques discussed in this chapter in terms of the construction risks they address. As can be seen from the table, only FMEA addresses all the types of risks. Construction risks relating to time, cost and quality may be interrelated and managers of construction projects need to be furnished with risk analysis tools that can address all construction failure types since this would enhance the chances of project success.

Table 2.1 Summary of Risk Analysis Techniques and Risks Addressed

Risk Analysis Technique	Addresses Schedule Risk	Addresses Budget Risk	Addresses Technical Risks (Quality)
CASPAR	Yes	Yes	No
Schedule Risk System	Yes	No	No
JRAP	Yes	No	No
Estimating Project and Activity Duration Using Network Analysis	Yes	No	No
Data-Driven Analysis of Corporate Risk Using Historical Cost-Control Data	No	Yes	No
ERA	No	Yes	No
AHP	Yes	Yes	No
FMEA	Yes	Yes	Yes
Utility-Functions in Engineering Performance Assessment	No	No	Yes
PERT	Yes	No	No
Monte Carlo Process	Yes	Yes	No

CHAPTER III

RESEARCH METHODOLOGY

INTRODUCTION

The principles of the APRAM model were applied to the development of the Historic Old Rankin Highway Visitor Center in Midland, Texas to evaluate the effectiveness of APRAM in a construction setting. The plans and specifications for this project were obtained from the Texas Department of Transportation (TXDOT) website. Appendix A shows the exterior elevations as well as the roof plan for the visitor center. The plans and specifications were mainly used to determine the scope of work. This project involved the construction of the main visitor center building, rest stop and picnic areas as well as roads tying in to existing roads. This chapter shows the methods used to obtain inputs to APRAM. The chapter further provides a list of all the assumptions used for the study and concludes with a summary.

TOTAL PROJECT BUDGET

Before committing to undertaking any project, the owner or owner organization has to be willing to invest a certain amount of money. This amount of money reflects the total amount the owner organization intends to spend on the development of the proposed facility even though spending less than this amount would be desirable. A cost estimate for the project used for this study suggested that TXDOT intended to spend a total of $1,600,000. This total budget includes approximately $1,200,000, the initial cost of development (determined from the cost estimates). This figure has been adjusted for location, that is, the initial cost of development was adjusted using the construction cost index for Midland, Texas (Means 2005). The total budget includes additional money the owner intends to set aside for the project.

DEVELOPING BASIS FOR CONTROLLING THE PROJECT

Work Breakdown Structure

To effectively manage any project, it is important to divide the project into identifiable parts that will unambiguously define the work to be performed to achieve pre-defined project objectives. It is essential for each identifiable part of a project to be sufficiently defined in order for work to be measured, budgeted, scheduled and managed. The various identifiable parts are referred to as work packages. According to Halpin (2006) the summation of work packages in a hierarchical format is called a Work Breakdown Structure (WBS). The U.S. Department of Energy Project Management Practices (2003) defines a WBS as the cornerstone of effective project planning, execution, controlling and reporting. The WBS thus establishes a base for project scheduling and control. Figure 3.1 shows the WBS (a graphic representation of the division of work in a multi-level system) developed for this project. The division of a project into identifiable parts is normally done such that the divisions are in conformance to the Construction Specifications Institute's (CSI) format of 16 divisions.

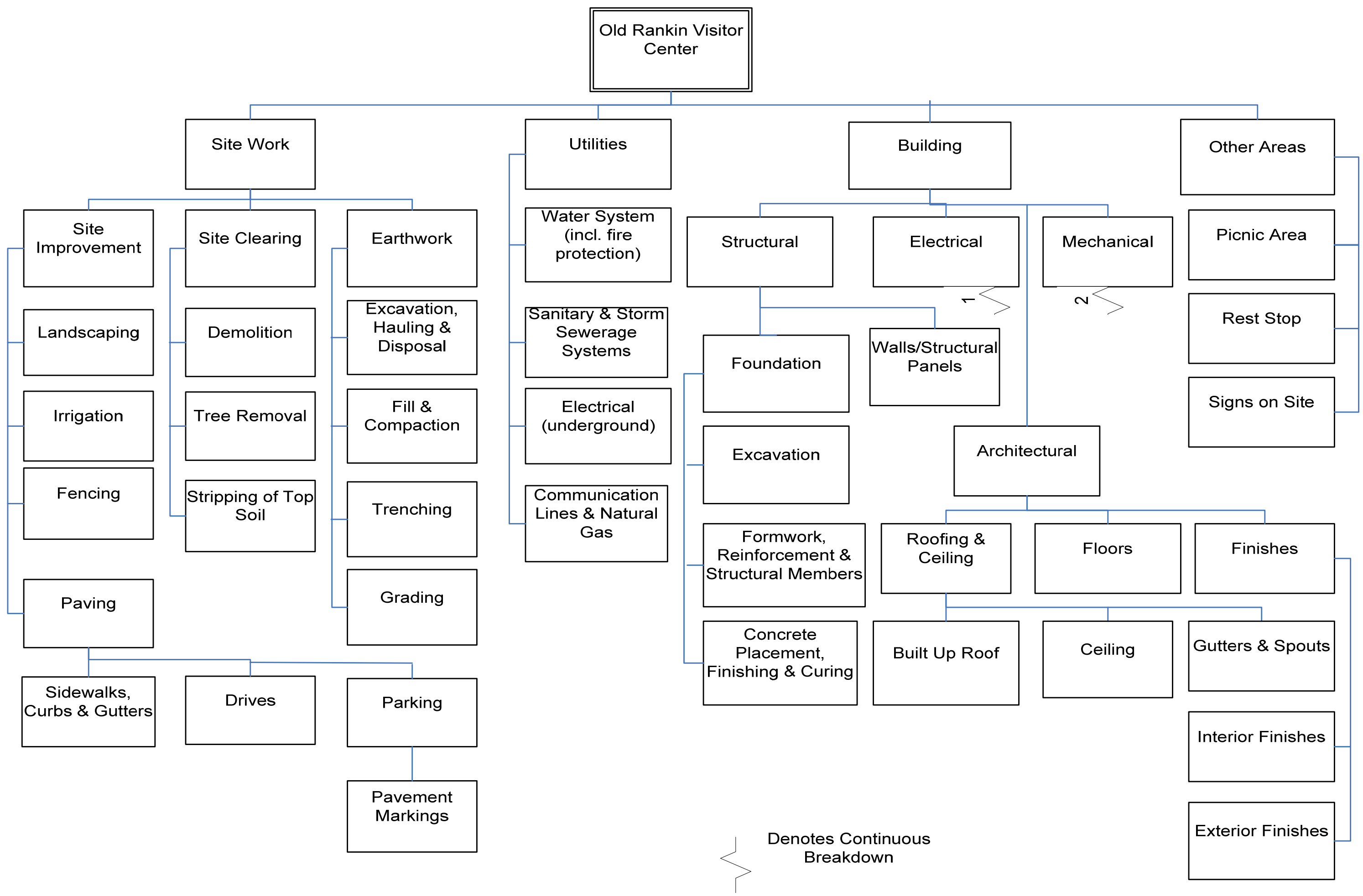


Figure 3.1 Work Breakdown Structure

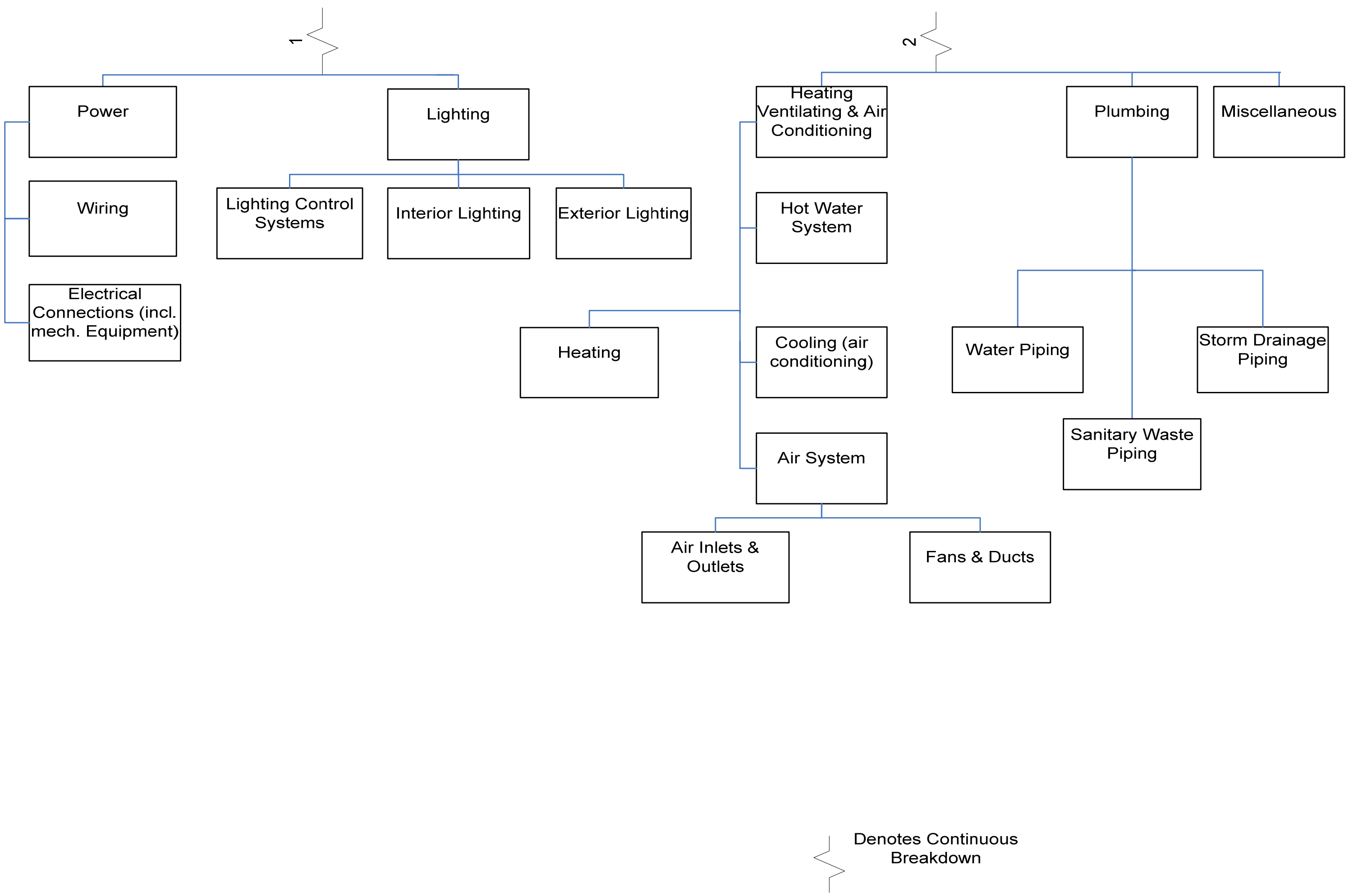


Figure 3.1 (Continued)

Detailed Cost Estimates

A detailed cost estimate was prepared in order to determine the total cost of developing the facility. This was done using the plans as well as the WBS as a guide. The required materials as well as their quantities were determined from the construction drawings and unit costs of materials were obtained from the Building Construction Cost Data (Means 2005). Appendix B shows detailed cost estimates for the different divisions of the project (i.e. site work, concrete, masonry, metals, wood and plastics, thermal and moisture protection, doors and windows, finishes, specialties, mechanical and electrical). Equipment, furnishings, special construction and conveying systems are the other divisions in building projects. Table 3.1 provides a summary of the estimates while Table 3.2 shows location adjustment to the total cost of construction.

Table 3.1 Summary of Estimates

Project Component	Amount	Comment
Direct Field Costs	$ 1,000,000	
Contractors Overhead and Profit	$ 193,000	20% of Direct field costs
Other Project Costs	$ 7,000	Includes protective equipment and field office expenses
Permits	$ 97,000	10% of Direct field costs
Insurance	$ 242,000	25% of Direct field costs
Office Trailer	$ 1,400.00	
Cost of Implementing APRAM	$80,000	
Total Costs	$ 1,600,000	

Table 3.2 Location Adjustment

Total Cost Based on National Average	$ 1,600,000
Midland Construction Cost Index	77.4%
Adjusted Cost of Work	$ 1,200,000

Project Planning and Scheduling

The next step involved the identification of all the activities necessary to complete the project. This was done by referring to the various work packages on the WBS and determining what activities were to be carried out in order to complete the work packages. Once the planned activities had been identified, the relationships between activities were determined to obtain the sequence of activities. The duration of each activity was determined from the Building Construction Cost Data (Means 2005). The Critical Path Method (CPM) was then used to determine the total project duration using the activity durations and their relationships. The activities, activity durations and activity relationships were then entered into the Primavera scheduling software. Figure 3.2 shows the project schedule generated by Primavera. The total duration determined for the project was 221 days.

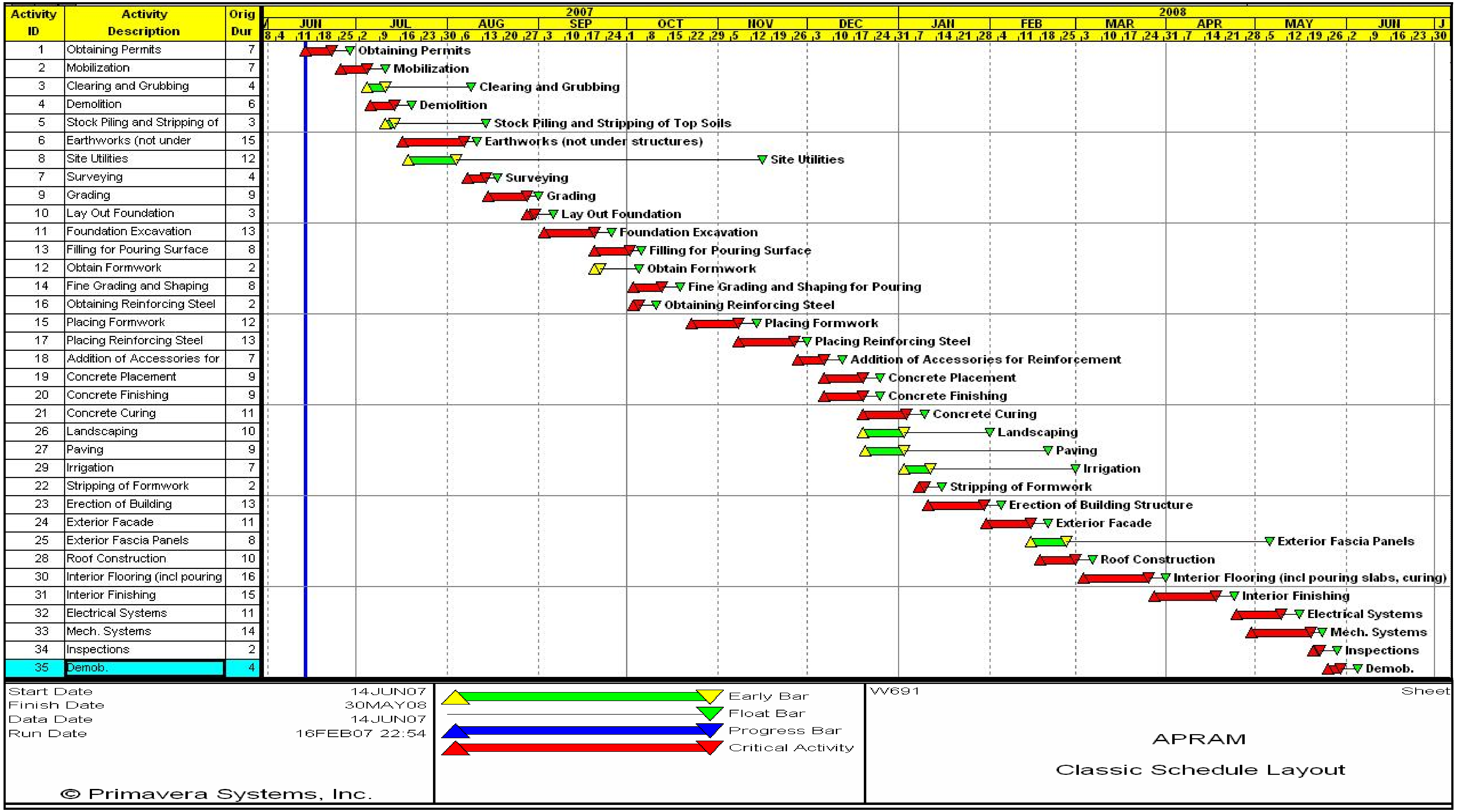


Figure 3.2 Project Schedule

IMPLEMENTATION OF APRAM

Identification of Possible System Configurations

Among the inputs necessary for implementing APRAM is the owner/decision maker's acceptable risk threshold. This risk threshold is a probability representing the maximum risk the owner is prepared to accept on the project. An owner can either have the same risk threshold for both technical and managerial failures or different risk thresholds. This methodology shows how the total project budget may be increased in order for risks to meet the level of acceptability in the event the resultant probabilities of technical and managerial failures of the optimal allocation of the residual budget are greater than acceptable risk levels.

APRAM also requires the identification of all alternatives that can be used in the development of the facility. In other words, all financially and technically feasible configurations of the completed facility need to be identified to be able to apply APRAM. For this study, different options for constructing the facility were selected based on the combination of materials that can be used for building the main elements of the facility. A Conventional Construction System (CCS) and a Lightweight Construction System (LCS) were thus selected. CCS as used in this study refers to the use of masonry, mainly brick and concrete, for the main structural support system. LCS has lightweight steel framing or timber framing as the main structural support system. Once the alternatives have been identified, APRAM further requires the choices of materials and/or components that can be used for CCS and LCS. Two different sets of materials and/or components were identified for each construction system and these are referred to as CCS 1, CCS 2, LCS 1 and LCS 2. These will be referred to as configurations from this point of the thesis. Table 3.3 provides a summary of some of the materials and/or components for each construction system.

Table 3.3 Construction System Configurations

Component	CCS 1	CCS 2	LCS 1	LCS 2
Structural frame	Precast concrete	Cast-in-place concrete	Steel Framing (galvanized steel)	Timber Framing
Reinforcement steel	Modified steel	Black steel	N/A	N/A
HVAC	Single HVAC zone	Multiple HVAC zones	Single HVAC zone	Multiple HVAC zones
Roofing	Tile roofing	Built up roofing (modified bitumen)	Metal roofing	Slate roofing
Façade	Tiled wall	Concrete wall	Metal cladding	Glass curtain wall
Moisture protection	Damp-proofing	Damp-proofing and waterproofing	Waterproofing	Damp-proofing and waterproofing

Determination of Residual Budget

The prepared cost estimate was slightly adjusted to obtain the cost of developing the facility with each of the configurations shown in Table 3.3. Once the development costs were obtained, the residual budget (r) for each configuration was determined by finding the difference between the project budget (T_B) and the total cost of development of the facility (Dev_{cost}). The residual budget refers to the amount of money available for improving the technical elements of the facility and for management reserves. Table 3.4

shows the total cost of developing the facility as well as the residual budget for each identified configuration.

Table 3.4 Development Costs and Residual Budgets for Different Configurations

Configuration	Development Cost	Residual Budget
CCS 1	$ 1,250,000	$ 350,000
CCS 2	$ 1,300,000	$ 300,000
LCS 1	$ 1,255,000	$ 345,000
LCS 2	$ 1,350,000	$ 250,000

Identification of Technical Failures and Managerial Problems (total and partial)

Dillon et al. (2003) selected the lowest cost configuration for each alternative system in their application of APRAM for an aerospace project. This study however used all identified configurations as inputs for APRAM since a low development cost does not necessarily imply low expected cost of failure. For each configuration, possible technical failures as well as managerial problems that may arise were identified. This was done by considering factors that can result in completing the project behind schedule and over budget. Also, factors that can result in the completed facility performing at a degraded level were considered in identifying technical failures. The identified technical failures and managerial problems were assigned illustrative probabilities for the purpose of this study. Appendix C shows identified failures and their assigned probabilities.

The probabilities of technical and managerial project failures (both partial and managerial) were computed for each configuration using fault tree analysis. Fault tree analysis refers to a top-down method of analyzing system performance. This analysis involves the identification of a top event (failure in this case) and sequentially identifying unions and intersections of events that can lead to the occurrence of the top event (Paté-Cornell 1984). Figures 3.3 through 3.10 show the fault trees for managerial failure and technical failure for each configuration.

Equations 3.1 through 3.4 provide the formulae used to compute the probabilities of technical and managerial failures (partial and total). The fault tree computations are based on the number of events (failures) that lead to each high level event. Assuming n is the number of events (failures) at a lower level,

If n = 2, then;

$$p(T) \quad p(F_1) \quad p(F_2) \quad p(F_1F_2) \qquad \text{…3.1}$$

If n = 3, then;

$$p(T) \quad p(F_1) \quad p(F_2) \quad p(F_3) \quad p(F_1F_2) \quad p(F_1F_3) \quad p(F_2F_3) \quad p(F_1F_2F_3) \qquad \text{…..3.2}$$

If n = 4, then;

$$p(T) \quad p(F_1) \quad p(F_2) \quad p(F_3) \quad p(F_4) \quad p(F_1F_2) \quad p(F_1F_3) \quad p(F_1F_4) \quad p(F_2F_3) \quad p(F_2F_4) \quad p(F_3F_4) \quad p(F_1F_2F_3) \quad p(F_1F_2F_4) \quad p(F_2F_3F_4) \quad p(F_2F_3F_4) \quad p(F_1F_2F_3F_4) \qquad \text{…..3.3}$$

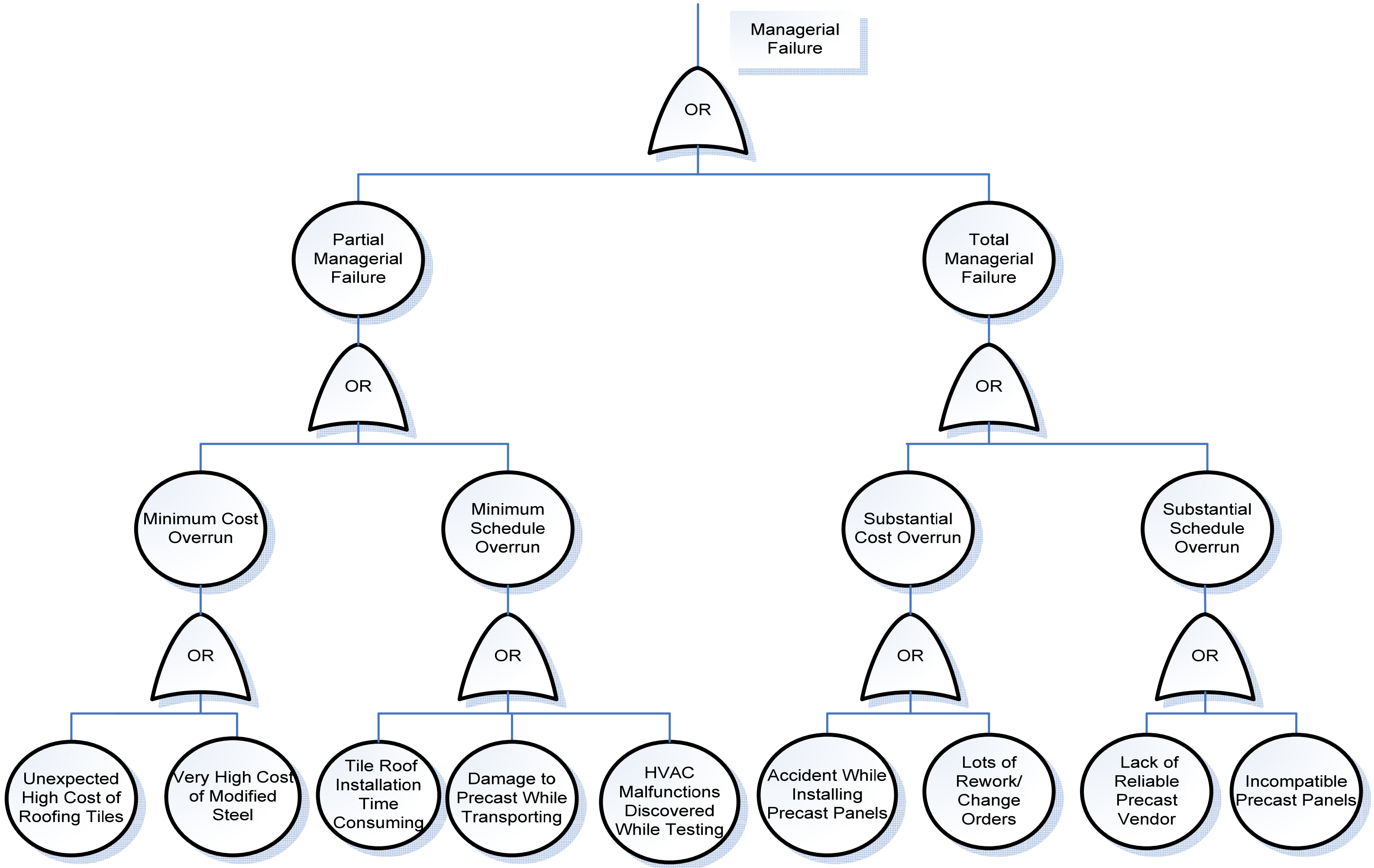


Figure 3.3 Managerial Failure States for Conventional Construction System 1

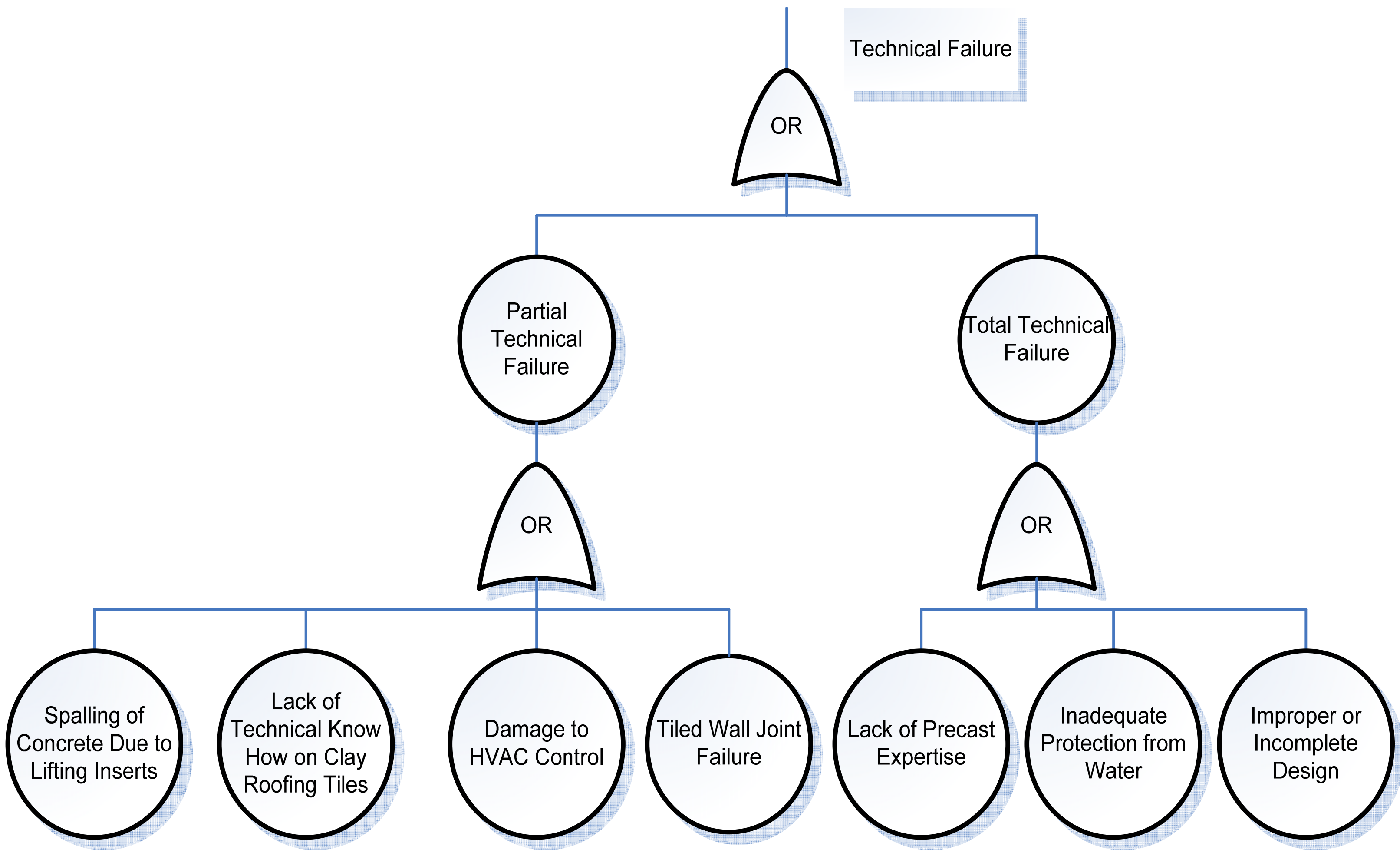


Figure 3.4 Technical Failure States for Conventional Construction System 1

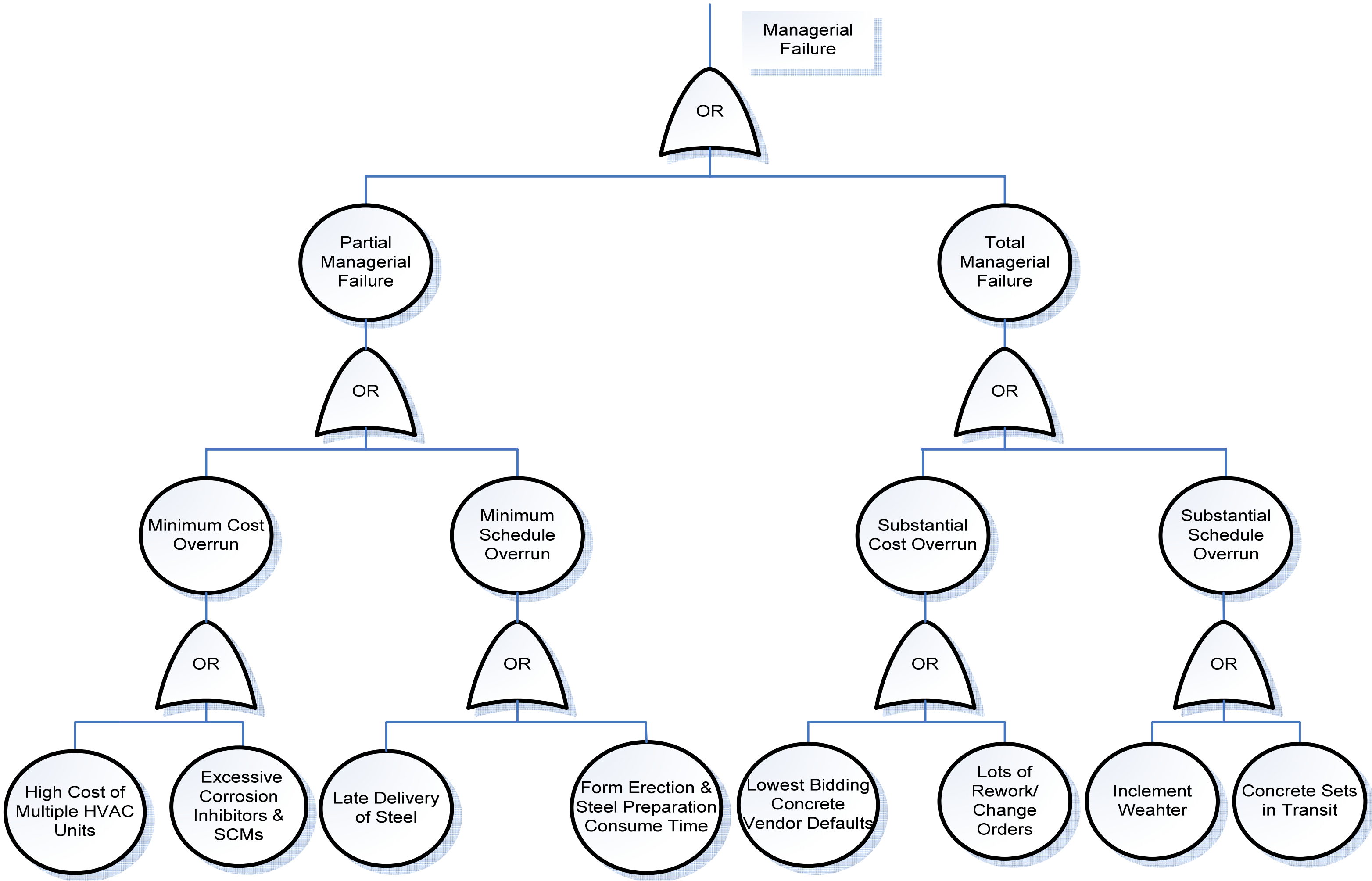


Figure 3.5 Managerial Failure States for Conventional Construction System 2

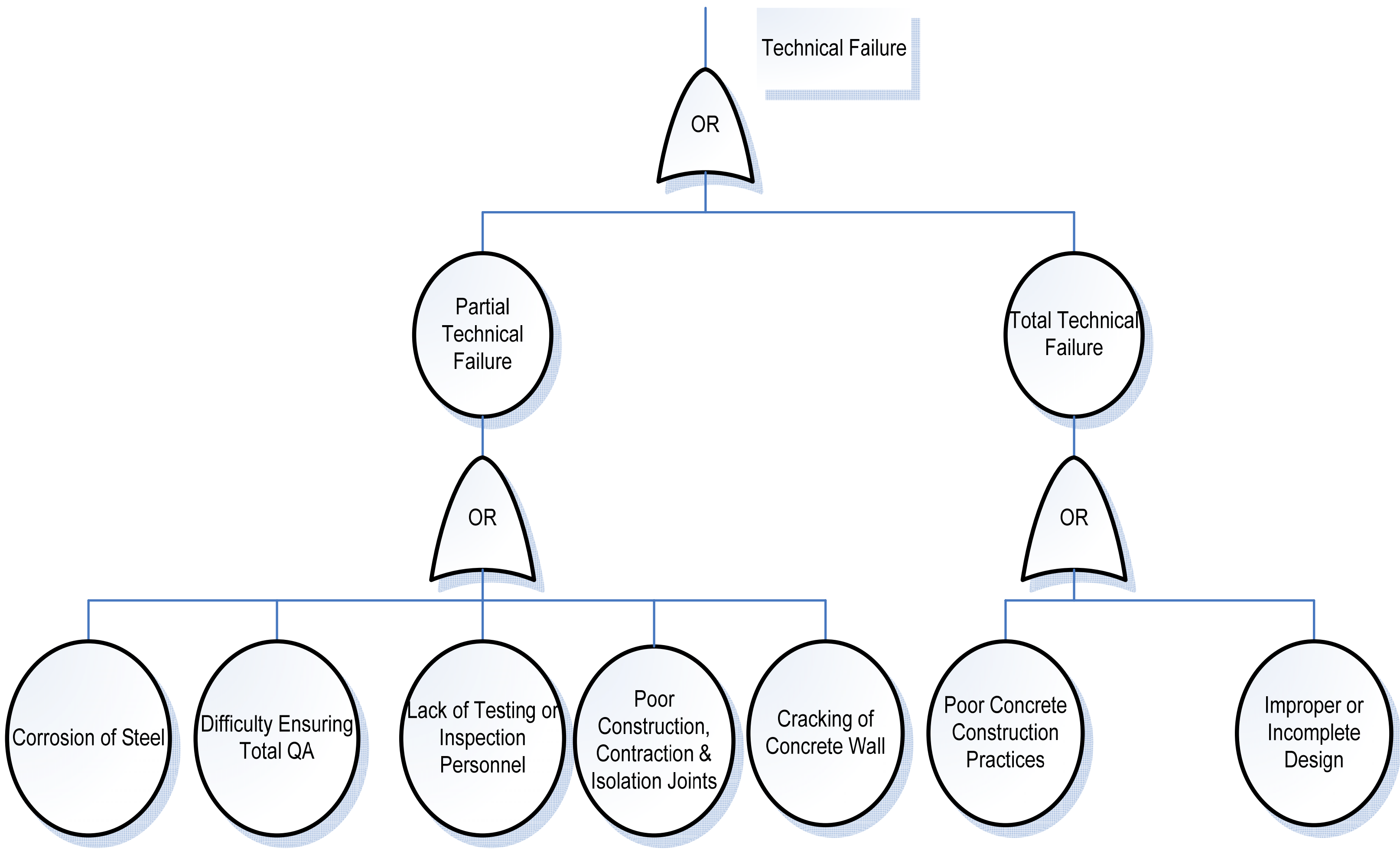


Figure 3.6 Technical Failure States for Conventional Construction System 2

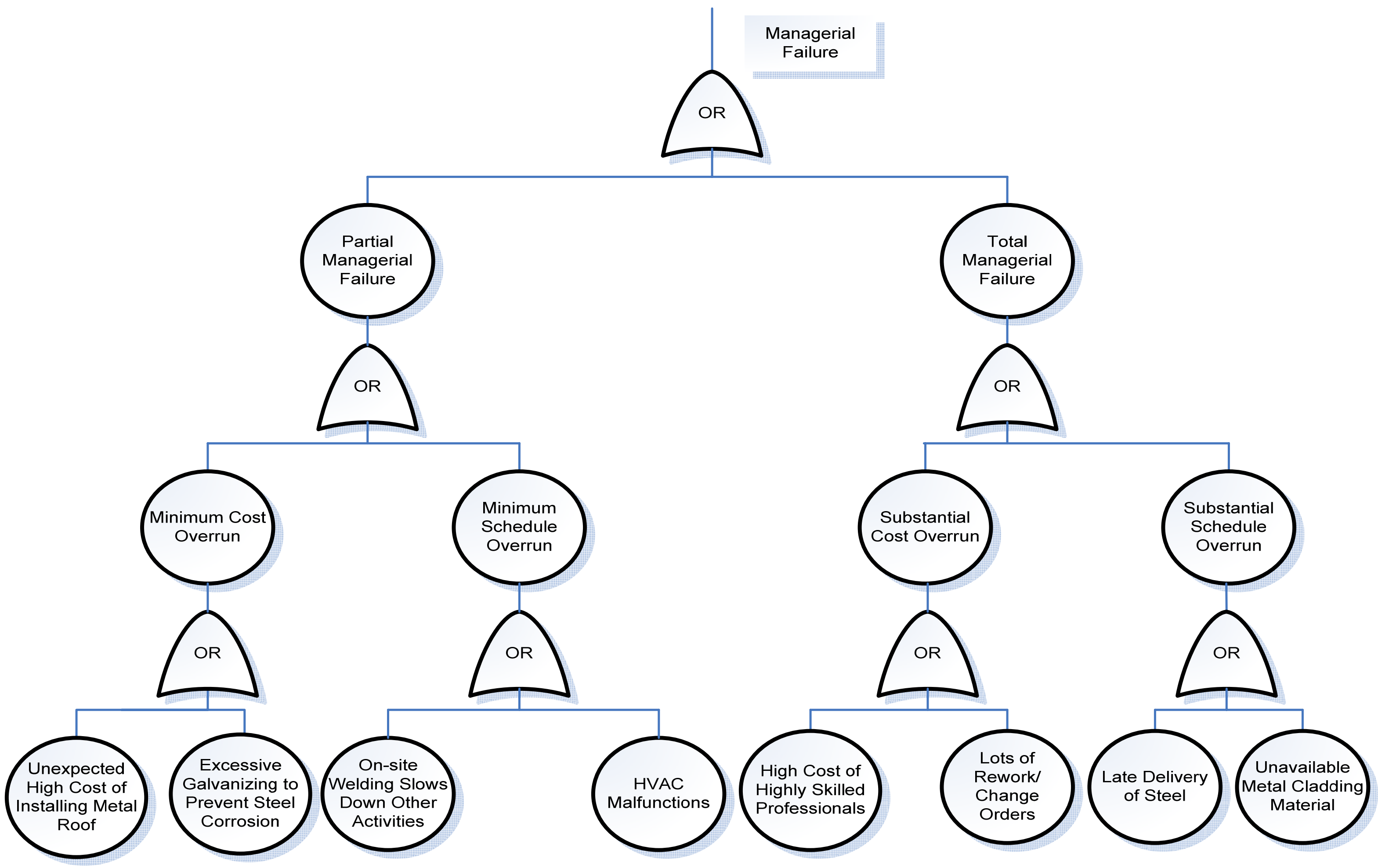


Figure 3.7 Managerial Failure States for Lightweight Construction System 1

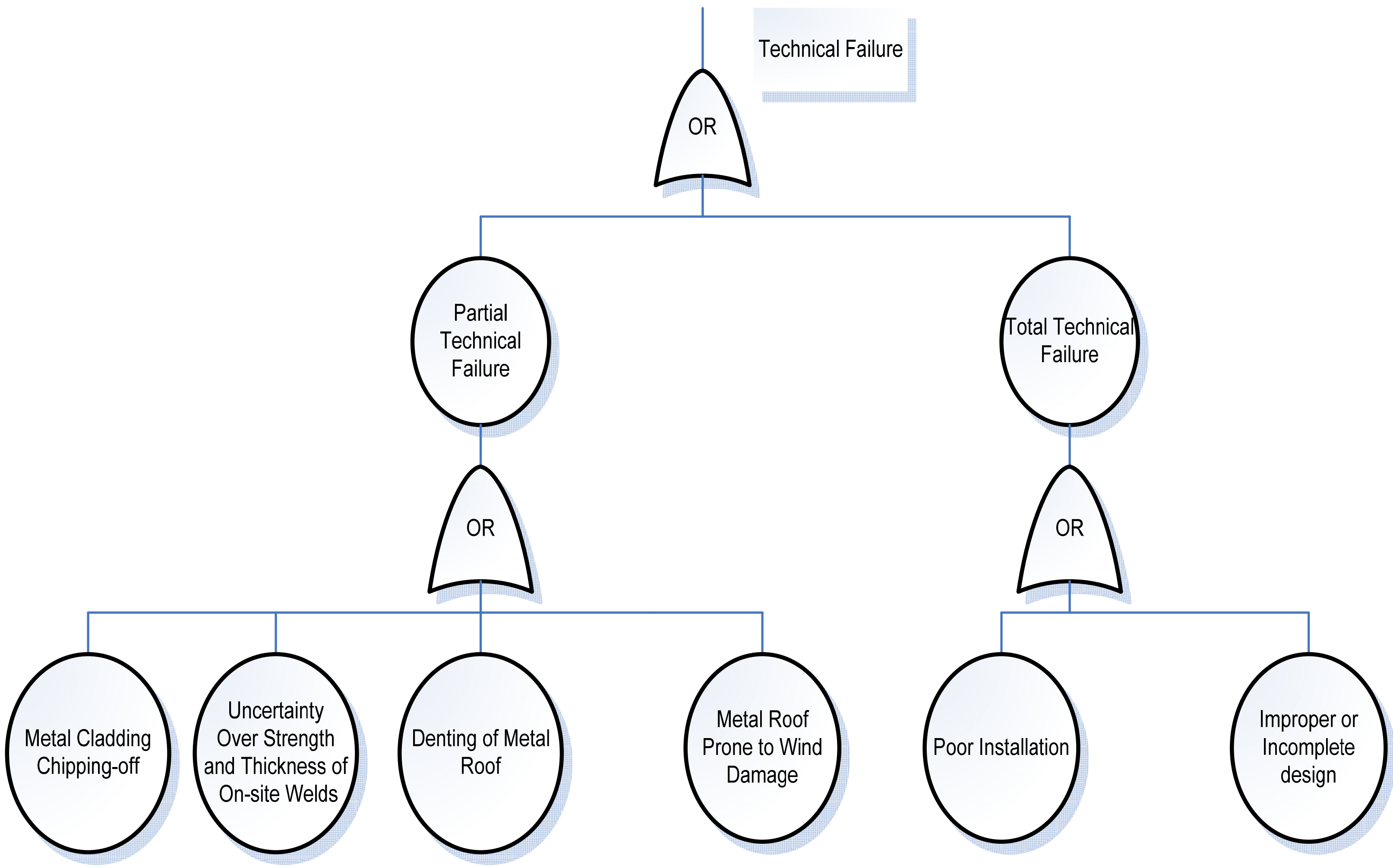


Figure 3.8 Technical Failure States for Lightweight Construction System 1

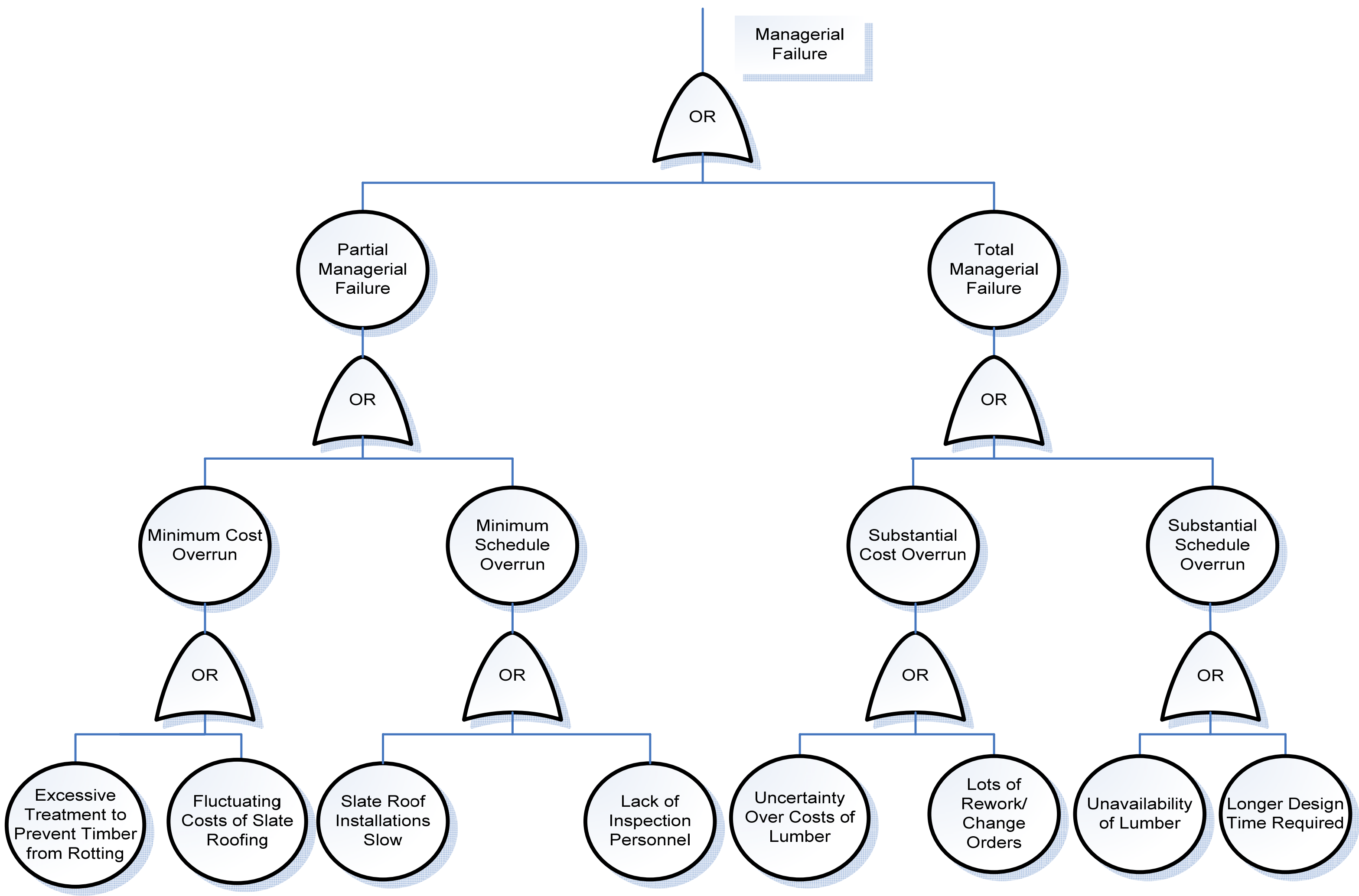


Figure 3.9 Managerial Failure States for Lightweight Construction System 2

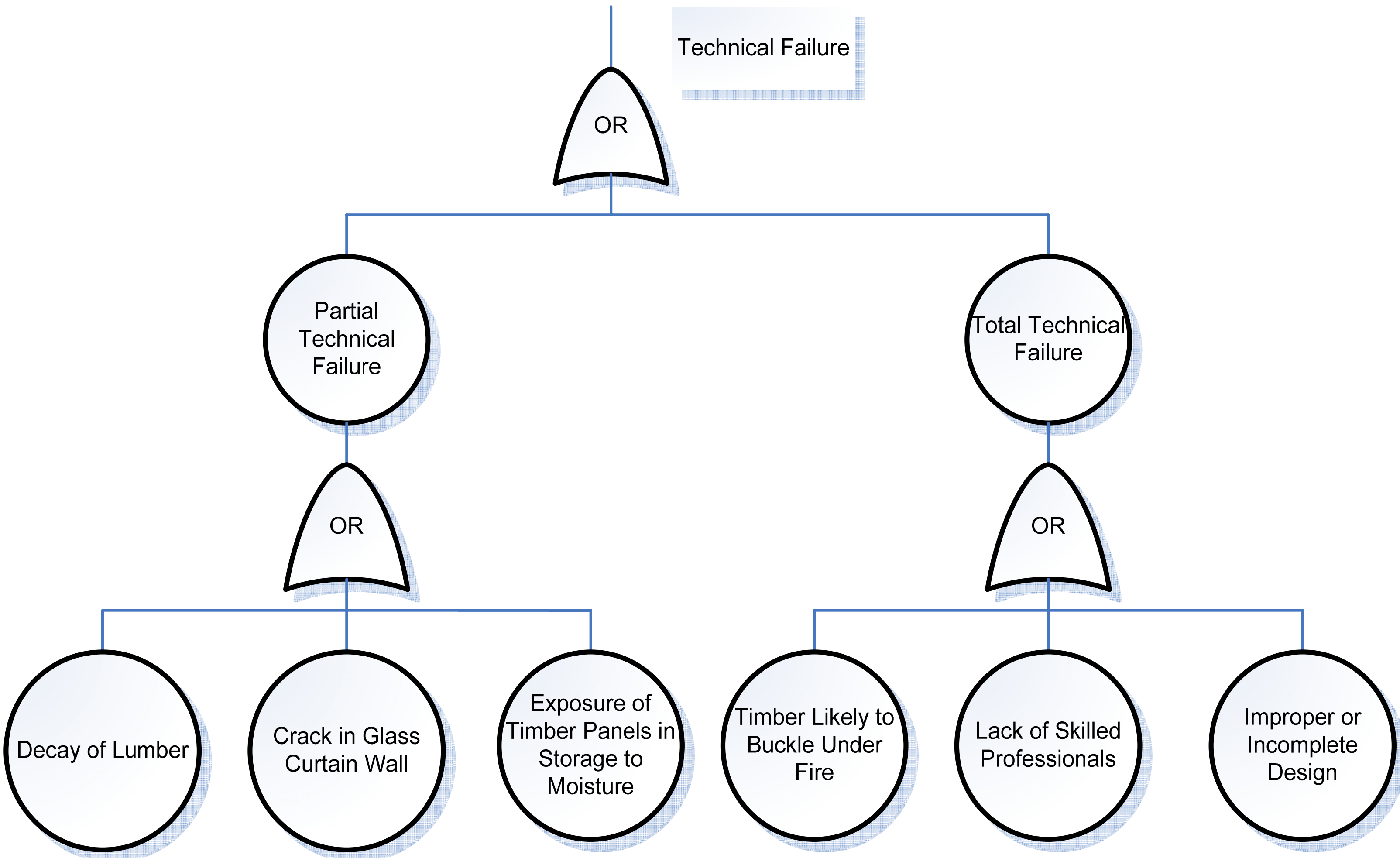


Figure 3.10 Technical Failure States for Lightweight Construction System 2

If n = 5, then;

$$p(T) \quad p(F_1) \quad p(F_2) \quad p(F_3) \quad p(F_4) \quad p(F_5) \quad p(F_1F_2)$$
$$p(F_1F_3) \quad p(F_1F_4) \quad p(F_1F_5) \quad p(F_2F_3) \quad p(F_2F_4) \quad p(F_2F_5)$$
$$p(F_3F_4) \quad p(F_3F_5) \quad p(F_4F_5) \quad p(F_1F_2F_3) \quad p(F_1F_2F_4)$$
$$p(F_1F_2F_5) \quad p(F_1F_3F_4) \quad p(F_1F_3F_5) \quad p(F_1F_4F_5) \quad p(F_2F_3F_4) \qquad \text{.......3.4}$$
$$p(F_2F_3F_5) \quad p(F_2F_4F_5) \quad p(F_3F_4F_5) \quad p(F_1F_2F_3F_4) \quad p(F_1F_2F_3F_5)$$
$$p(F_1F_2F_4F_5) \quad p(F_1F_3F_4F_5) \quad p(F_2F_3F_4F_5) \quad p(F_1F_2F_3F_4F_5)$$

where $F_1 ... F_n$ - Events

$p(T)$ - probability of an upper level event

Guikema and Paté-Cornell (2002) defined a risk/cost function for modeling systems in which the probabilities of failure of a system decrease exponentially as money is invested to make the system more robust and improve system performance. These exponential curves are only approximations but they work well in many situations. A decreasing exponential curve was thus used for each identified failure state to reflect the expected reduction of the probability of each failure with the allocation of a portion of the residual budget. Figures 3.11 through 3.14 show plots of the probabilities of different failure states (technical and managerial failures) versus the fraction of residual budget allocated to improving the technical system for each configuration.

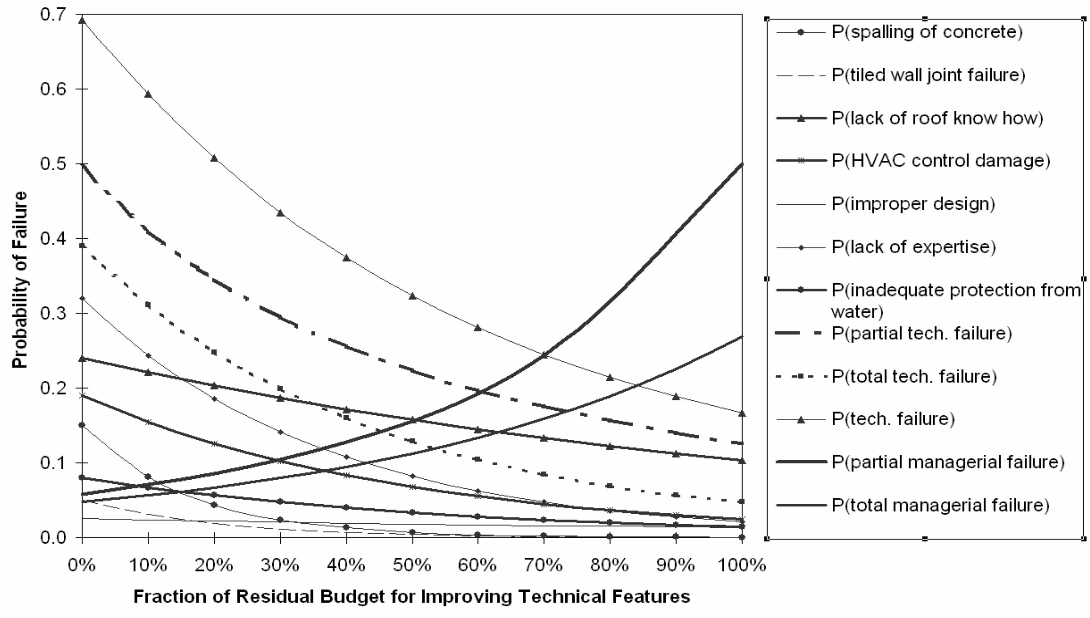


Figure 3.11 Probabilities of Different Failure States versus Fractions of Residual Budget (CCS 1)

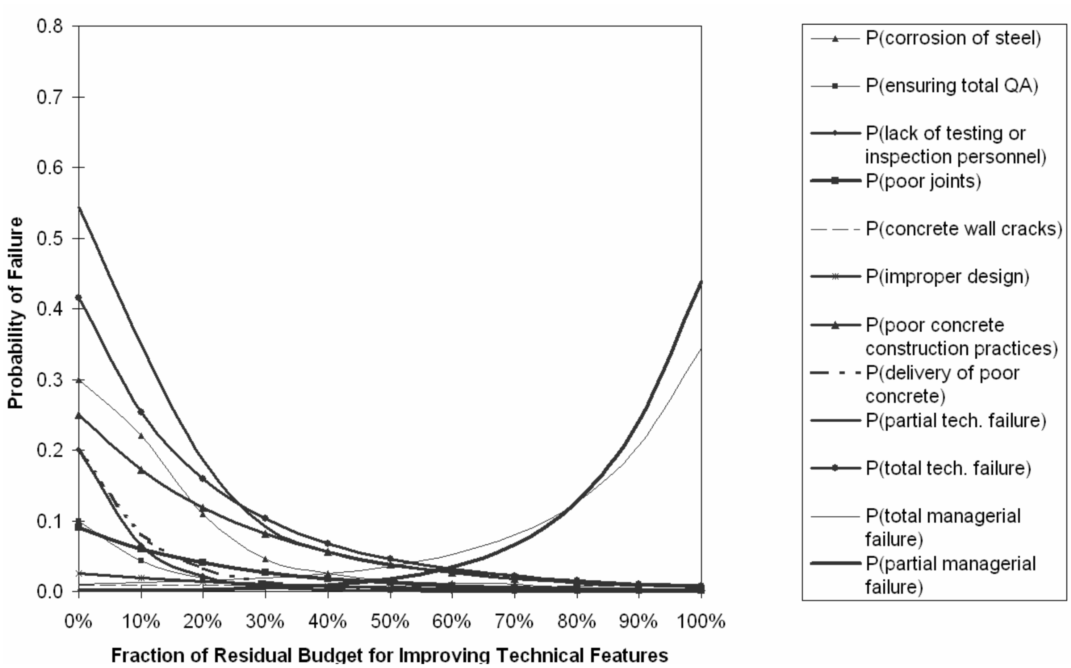


Figure 3.12 Probabilities of Different Failure States versus Fractions of Residual Budget (CCS 2)

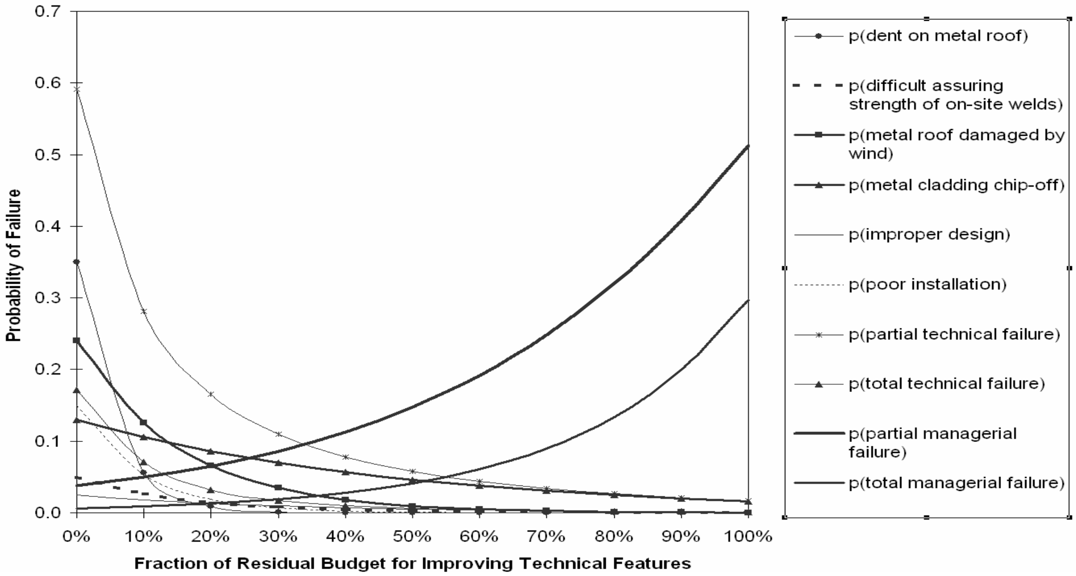


Figure 3.13 Probabilities of Different Failure States versus Fractions of Residual Budget (LCS 1)

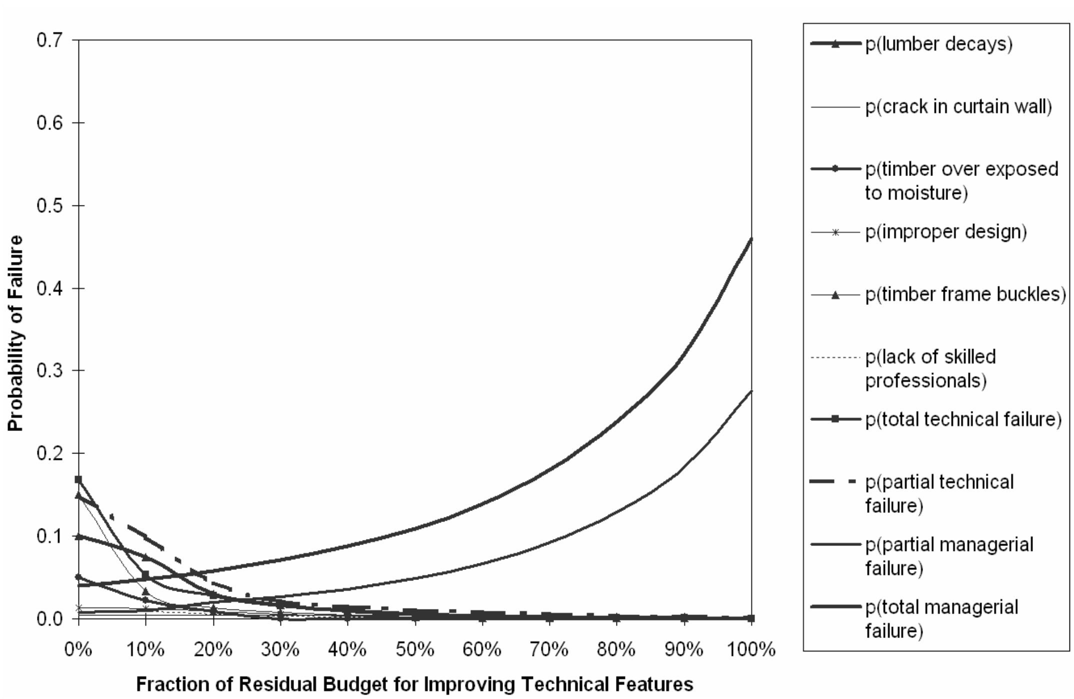


Figure 3.14 Probabilities of Different Failure States versus Fractions of Residual Budget (LCS 2)

Optimization and Determination of Technical Reinforcement Budget

The portion of the residual budget that can be used to reinforce or improve the technical capabilities of the facility is the technical reinforcement budget ($Tech_{rein}$) and this can be expressed as:

$$Tech_{rein} \qquad r \text{ ....} 3.5$$

where α represents the fraction of the residual budget that is used to reduce the risks of technical failure and can range from nothing to the entire residual budget (i.e., 0 • α •1). A non-linear optimization was performed (using excel's solver tool) for all values of α to determine the fraction of the residual budget that will minimize the owner's utility. Utility here refers to the decision maker's preference, which in this case is assumed to be reducing expected cost of failure (E). The expected cost of failure for each allocation of technical reinforcement budget ($Tech_{rein}$) was obtained using the equation:

$$E \qquad _{i} \, (p(TTF_i | Tech_{rein}) \quad C(TTF)) \qquad _{j} \, (p(PTF_j | Tech_{rein}) \quad C(PTF)) \text{ ....} 3.6$$

where,

$p(TTF_i | Tech_{rein})$ - probability of a total technical failure given an investment of the technical reinforcement budget

$p(PTF_j | Tech_{rein})$ - probability of a partial technical failure given an investment of the technical reinforcement budget

$C(TTF)$ - cost of total technical failure

$C(PTF)$ - cost of partial technical failure

Different optimizations were performed for different values of α for each configuration in order to determine the optimal allocation of the technical reinforcement budget ($Tech_{rein}$) among the different failure modes. Detailed results of the optimization of the technical reinforcement budget can be found in Appendix D.

Optimization and Determination of Best Response to Managerial Problems

With $Tech_{rein}$ allocated to the technical system, the portion of the residual budget left was (1-α)r. This is referred to as management reserves ($Mgmt_{res}$). Dillon et al. (2003) used decision analysis to determine the optimal level of the management reserves. This approach, however, used sequential decision trees, that is, an action taken to mitigate a managerial problem led to another problem which required another mitigation action that also led to another problem and so forth. This approach was considered unsuitable for a construction project because construction project development differs from space mission development. Determination of the optimal management reserve using ordinary decision trees was impossible because this required a very large decision tree that could not be resolved. An attempt was therefore made to use the FMEA to determine the optimal level of managerial reserves. Further discussion on why decision trees were not used in this study is provided in Chapter V.

Even though it was possible to assign a fraction of the managerial reserves to each managerial problem with the FMEA based on each risk item's RPN, the FMEA did not take into account the probabilities of the different failure states. The FMEA only helps rank potential failure modes and does not provide a sound basis for allocating resources. The same non-linear optimization used for determining the optimal technical reinforcement budget level was therefore used for allocating managerial reserves. The expected cost of failure was again minimized for this optimization. The expected cost of failure for each allocation of management reserves was obtained from the equation:

$$E = \sum_{i} (p(TMF_i | Mgmt_{res}) \times C(TMF)) + \sum_{j} (p(PMF_j | Mgmt_{res}) \times C(PMF)) \text{ ………...3.7}$$

where,

$p(TMF_i | Mgmt_{res})$ - probability of a total managerial failure given an investment of management reserves

$p(PMF_j | Mgmt_{res})$ - probability of a partial managerial failure given an investment of management reserves

$C(TMF)$ - cost of total managerial failure

$C(PMF)$ - cost of partial managerial failure

Optimizations were performed for each value of α for each configuration. Detailed results of the optimization of management reserves can be found in Appendix E.

Selection of Optimal Alternative and Allocation of Residual Budget That Minimizes Overall Failure Risk

The final step involved the integration of the two separate optimizations in order to identify the optimal allocation of the residual budget. In other words, this step determined the fraction (α) of the residual budget that maximized the owner's utility.

This step also allowed the selection of the best alternative that minimized the expected cost of failure. The order in which failure (both technical and managerial failure) can occur needed to be determined to be able to complete this step. Because a technical failure can be realized only after the facility has been constructed, it is expected that a managerial failure (either partial or total) or no managerial failure will have to occur first. Thus a managerial failure or no managerial failure has to occur before total technical failure, partial technical or no technical failure can occur. An event tree was used to identify the order in which failure can occur for each alternative. Figure 3.15 shows the event tree used for this study.

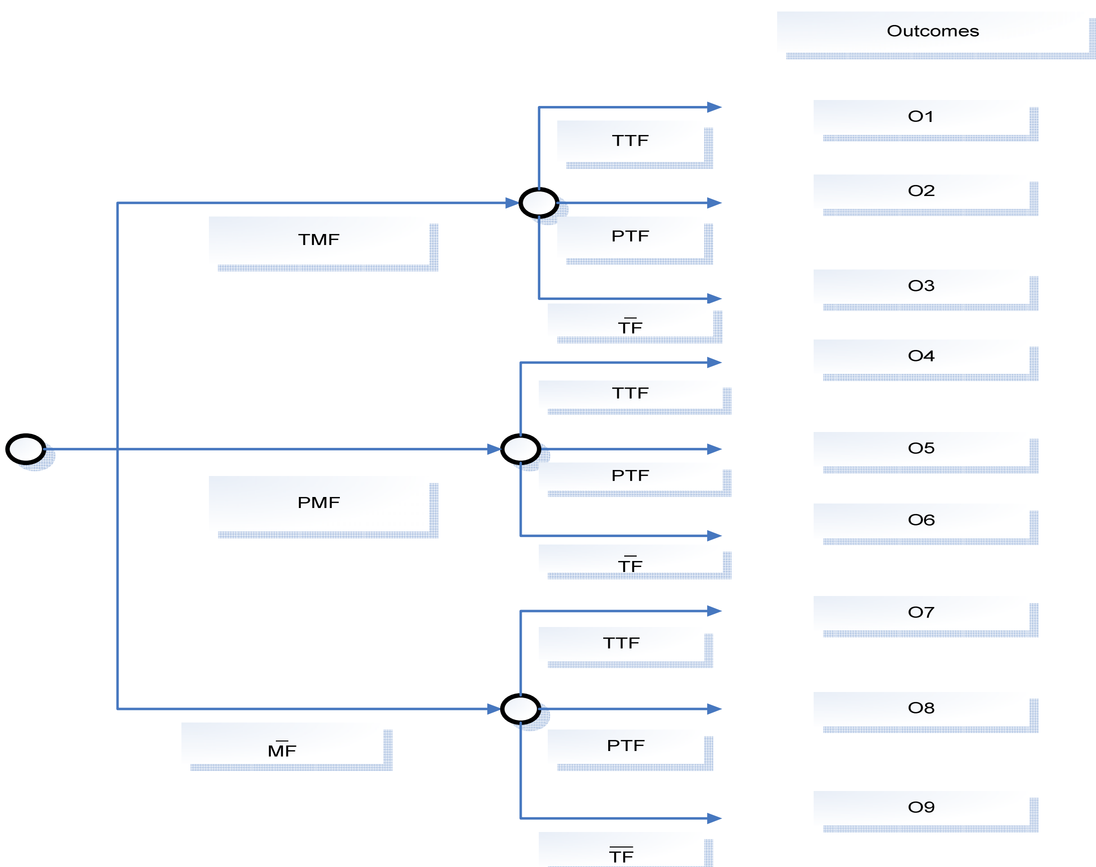


Figure 3.15 Event Tree Showing Possible Failure Outcomes

Paté-Cornell (1984) described an event tree as a tree with a finite number of branches that can be used to place events in a chronological order provided the events are known or predictable.

O_1 to O_9 in Figure 3.15 represent the outcomes of the different failure states and they can be obtained from the equations:

$O_1 \quad C(TMF) \quad C(TTF)$ ……………………………………………………….3.8

$O_2 \quad C(TMF) \quad C(PTF)$ ……………………………………………………….3.9

$O_3 \quad C(TMF) \quad C(\overline{TF})$ ……………………………………………………….3.10

$O_4 \quad C(PMF) \quad C(TTF)$ ……………………………………………………..3.11

$O_5 \quad C(PMF) \quad C(PTF)$ ……………………………………………………….3.12

$O_6 \quad C(PMF) \quad C(\overline{TF})$ ……………………………………………………….3.13

$O_7 \quad C(\overline{MF}) \quad C(TTF)$ ……………………………………………………….3.14

$O_8 \quad C(\overline{MF}) \quad C(PTF)$ ……………………………………………………....3.15

$O_9 \quad C(\overline{MF}) \quad C(\overline{TF})$ ……………………………………………………...3.16

where $\overline{TF}$ - no technical failure

$\overline{MF}$ - no managerial failure

$C(\overline{TF})$ - cost of no technical failure

$C(\overline{MF})$ - cost of no managerial failure

The expected cost of overall project failure for each α (i.e. allocation of the residual budget to technical reinforcement and management reserves) was determined using the equation:

$$\begin{aligned} E \quad & (p(TMF) \quad p(TTF) \quad O_1) \quad (p(TMF) \quad p(PTF) \quad O_2) \quad (p(TMF) \quad p(\overline{TF}) \quad O_3) \\ & (p(PMF) \quad p(TTF) \quad O_4) \quad (p(PMF) \quad p(PTF) \quad O_5) \quad (p(PMF) \quad p(\overline{TF}) \quad O_6) \qquad .....3.17 \\ & (p(\overline{MF}) \quad p(TTF) \quad O_7) \quad (p(\overline{MF}) \quad p(PTF) \quad O_8) \quad (p(\overline{MF}) \quad p(\overline{TF}) \quad O_9) \end{aligned}$$

Deciding How Much to Increase Total Project Budget to Meet Acceptable Failure Levels

In the event that any of the probabilities of managerial failure and technical failure (both partial and total) for the optimal configuration is greater than the acceptable risk thresholds, the decision maker has to determine by how much the total budget has to be increased in order to achieve the expected levels of risk. In order to do this, an analysis can be performed to determine how sensitive the expected cost of failure is to changes (increases in this case) in the total project budget. In this analysis, the total project budget was first set to \$1,450,000 such that the residual budget was \$100,000. The different values of α were optimized to reduce the expected costs of failure for both the technical reinforcement budget and the managerial reserve. The total project budget was then increased in increments of \$100,000 until the total project budget reached twice the initial cost of development of the facility (\$2,700,000 in this case). As an illustration, assume the decision maker's acceptable risk levels for technical failure and managerial failure are 0.05 and 0.2 respectively. It can be inferred from Figure 3.16 that both total and partial technical failures for the Old Hankin Visitor Center Project (project budget = $1.6M) are below acceptable limits. Partial and total managerial failures are however above acceptable limits. The owner should thus be willing to pay a penalty of $180,000 in order to meet acceptable risk levels.

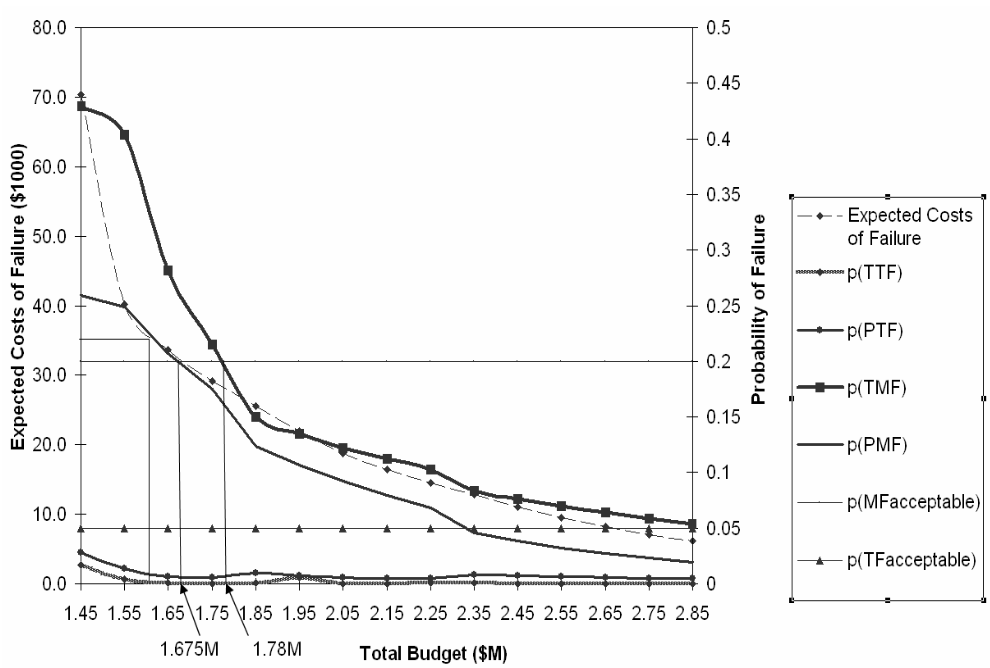


Figure 3.16 Expected Costs of Failure versus Total Project Budget

Expected Cost of Failure Using Percentage of Total Project Costs as Contingency

For the purpose of comparison, the overall expected cost of failure that will minimize the decision maker's utility was also determined without the implementation of the APRAM model. This was performed using the @Risk software to determine contingency funds for the project as described below. Expected costs of failure were then determined for each configuration. It is important to emphasize that the purpose of contingency funds are to help mitigate managerial problems that are results of uncertainties and errors in the cost estimates. Thus no investments were made in improving the technical capabilities of the facility. A summary of the base cost estimate is provided in Table 3.5.

Table 3.5 Summary of Base Cost Estimate

Project Component	Amount	Comment
Direct Field Costs	$ 967,000	
Contractors Overhead and Profit	$ 193,000	20% of Direct Field Costs
Other Project Costs	$ 7,000	Includes protective equipment and field office expenses
Permits	$ 97,000	10% of Direct Field Costs
Insurance	$ 242,000	25% of Direct Field Costs
Office Trailer	$ 1,400	
Total Project Costs	$ 1,500,000	

The Association for the Advancement of Cost Engineering-International (AACEI) defines accuracy parameters of +/- 50% for cost estimating activities at the conceptual phase of construction projects and +/- 10% at the definition phase (detailed scope). Even though the cost estimates prepared for this study were detailed cost estimates, the accuracy parameters of +/- 10% were narrow and yielded a contingency of 4% of the total project costs. The accuracy parameters of +/- 50% were therefore used to obtain inputs for the @ Risk software and these are shown in Table 3.6. Thirty different Monte Carlo Simulations starting from 1,000 to 30,000 iterations (in increments of 1,000) were run for the total project costs. Figure 3.17 shows the distribution for the total project cost. At the 95% confidence level, the total project cost is approximately $1,850,000. This is the mean of the total project cost for all the simulations performed and represents an estimate of the total project cost. The 95% confidence bounds for this estimate are $1,852,606 and $1,855,565. This means that the true average total cost of the project using @ Risk is between $1,852,606 and $1,855,565 with 95% confidence. Appendix F shows the total project cost generated for each replication of the simulation.

Table 3.6 Risk Analysis Inputs

	Category	Low	Most likely	High
A	Direct Field Costs	$484,000	$968,000	$1,451,000
B	Contractor's Overhead & Profit	$97,000	$193,000	$290,000
C	Other Project Costs	$4,100	$8,300	$12,000
D	Permits & Insurance	$169,000	$339,000	$508,000
E	Total Project Cost	$750,000	$1,500,000	$2,300,000

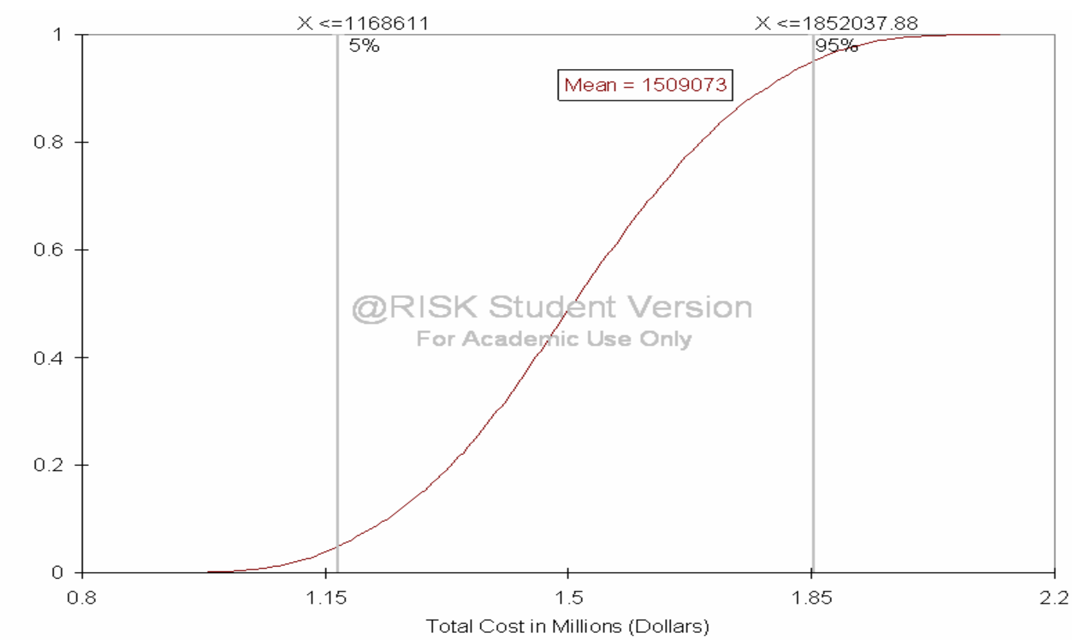


Figure 3.17 Distribution for Total Project Cost

The estimate of the total project cost includes a contingency allowance of 23%. Table 3.7 shows the adjustment of the total project cost for location.

Table 3.7 Location Adjustment for Total Project Cost

Total Cost Based on National Average	$ 1,850,000
Midland Construction Cost Index	77.4%
Adjusted Cost	$ 1,440,000

The adjusted total project cost of approximately $1,440,000 (with 23% contingency) was used to determine the overall expected cost of failure for each configuration. Figure 3.18 shows the costs of failure and associated probabilities for all configurations.

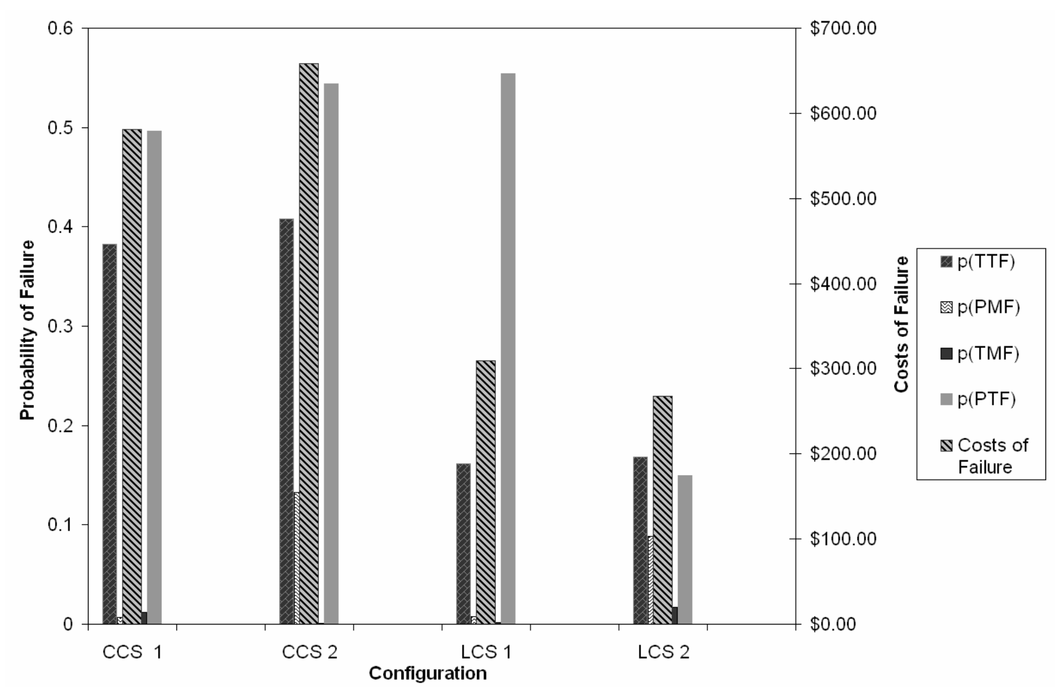


Figure 3.18 Costs of Failure and Associated Probabilities for All Configurations

LIST OF ASSUMPTIONS

In order to clearly illustrate the implementation of APRAM in construction, certain assumptions were made to provide inputs for the model. Probabilities were assumed for all identified failures (Appendix C). In addition, the cost estimates were assumed to be conceptual estimates. The following is a list of all the assumptions made for this study,

1. Probabilities of all identified failures were assumed for the purpose of illustration.
2. The owner was prepared to spend approximately $370,000 in addition to the initial cost of development.
3. The cost of implementing APRAM.
4. The different configurations were identified during the feasibility phase of the project.
5. The following is a list of the costs of different failure states.

$$C(PMF) \quad 0.1Dev_{cost} \qquad (3.18)$$

$$C(TMF) \quad 0.45Dev_{cost} \qquad (3.19)$$

$$C(PTF) \quad 0.15Dev_{cost} \qquad (3.20)$$

$$C(TTF) \quad 0.6Dev_{cost} \qquad (3.21)$$

6. Costs of all partial managerial failures were the same.
7. Costs of all total managerial failures were the same.
8. Same cost for all partial technical failures.
9. Same cost for all total technical failures.

10. Cost estimates were at the conceptual phase (not detailed phase).

These assumptions are further discussed in Chapter V.

SUMMARY

This chapter outlines the methodology for this study. The basis for determining the total project budget has been described. Also the possible configurations for developing this facility were mentioned. The chapter further showed the application of APRAM to the development of the Historic Old Hankin Visitor Center. In addition, the chapter described a method that can be used to determine by how much the total project budget can be increased in order to reduce managerial and technical failures to achieve acceptable risk levels. The chapter concludes with a list of assumptions used for the study.

CHAPTER IV

RESULTS OF ANALYSIS

INTRODUCTION

The results of implementing APRAM in the analysis of possible risks for the development of the Old Rankin Highway Visitor Center facility are presented in this chapter. The chapter also includes results from the alternative approach used to determine the overall expected costs of project failure. The results presented in this chapter are organized as follows:

- Results of Optimizations of Technical Reinforcement Budget
- Results of Optimizations of Managerial Reserves
- Results of Determination of Overall Expected Cost of Failure Using Percentage of Total Project Cost As Contingency

RESULTS OF OPTIMIZATIONS OF TECHNICAL REINFORCEMENT BUDGET

The optimization analyses performed for the technical reinforcement budget were performed to minimize the expected cost of failure for each level of the budget. Constraints were set such that at least 1% of the technical reinforcement budget at each level was allocated to mitigating each of the identified risks. This was to ensure a portion of the residual budget was invested in mitigating all identified risks of technical failure.

Tables 4.1 through 4.4 provide summaries of the optimizations performed for each configuration. Detailed results of all optimizations including probabilities of each of the identified risks at each level of the technical reinforcement budget can be found in Appendix D.

Table 4.1 Summary of Optimization of Technical Reinforcement Budget (CCS 1)

α	p(PTF)	p(TTF)	E(Costs of Failure)
0%	0.496	0.383	$428,000
10%	0.384	0.213	$261,000
20%	0.293	0.155	$194,000
30%	0.242	0.093	$131,000
40%	0.209	0.056	$94,000
50%	0.186	0.034	$71,000
60%	0.170	0.021	$57,000
70%	0.132	0.014	$43,000
80%	0.060	0.012	$25,000
90%	0.031	0.016	$22,000
100%	0.138	0.003	$36,000

Table 4.2 Summary of Optimization of Technical Reinforcement Budget (CCS 2)

α	p(PTF)	p(TTF)	E(Costs of Failure)
0%	0.544	0.408	$497,000
10%	0.486	0.217	$303,000
20%	0.325	0.196	$247,000
30%	0.241	0.183	$214,000
40%	0.168	0.173	$192,000
50%	0.124	0.166	$178,000
60%	0.141	0.070	$96,000
70%	0.128	0.055	$81,000
80%	0.087	0.084	$99,000
90%	0.068	0.073	$85,000
100%	0.054	0.063	$74,000

Table 4.3 Summary of Optimization of Technical Reinforcement Budget (LCS 1)

α	p(PTF)	p(TTF)	E(Costs of Failure)
0%	0.554	0.261	$341,000
10%	0.446	0.203	$268,000
20%	0.286	0.181	$212,000
30%	0.214	0.163	$184,000
40%	0.169	0.147	$164,000
50%	0.136	0.134	$147,000
60%	0.110	0.121	$133,000
70%	0.089	0.111	$122,000
80%	0.073	0.101	$111,000
90%	0.059	0.093	$102,000
100%	0.048	0.085	$94,000

Table 4.4 Summary of Optimization of Technical Reinforcement Budget (LCS 2)

α	p(PTF)	p(TTF)	E(Costs of Failure)
0%	0.149	0.169	$171,000
10%	0.124	0.054	$71,000
20%	0.079	0.028	$41,000
30%	0.048	0.016	$24,000
40%	0.029	0.009	$14,000
50%	0.019	0.005	$9,000
60%	0.013	0.003	$5,000
70%	0.009	0.002	$4,000
80%	0.006	0.001	$2,000
90%	0.004	0.001	$1,500
100%	0.002	0.000	$1000

RESULTS OF OPTIMIZATIONS OF MANAGEMENT RESERVES

Once a fraction (α) of the residual budget (r) was spent on reinforcing the technical elements of the facility, the remaining (1-α)r represented management reserves to be allocated to the mitigation of managerial problems. The management reserves were then optimized for each level of α. Just like the case of the technical reinforcement budget, constraints for optimizing the management reserves were set such that at least 1% of the reserves was allocated to each of the identified managerial problems. Tables 4.5 through 4.8 provide summaries of the optimizations performed for the managerial reserves for each configuration. Detailed results of the optimizations for all levels of the management reserves can be found in Appendix E.

Table 4.5 Summary of Optimization of Management Reserves (CCS 1)

α	p(PMF)	p(TMF)	E(Costs of Failure)
0%	0.500	0.268	$310,720
10%	0.374	0.212	$229,000
20%	0.319	0.153	$166,000
30%	0.254	0.114	$122,000
40%	0.190	0.087	$89,000
50%	0.143	0.067	$66,000
60%	0.111	0.053	$50,000
70%	0.087	0.043	$39,000
80%	0.051	0.035	$28,000
90%	0.055	0.029	$24,000
100%	0.046	0.025	$20,000

Table 4.6 Summary of Optimization of Management Reserves (CCS 2)

α	p(PMF)	p(TMF)	E(Costs of Failure)
0%	0.439	0.345	$313,000
10%	0.392	0.163	$161,000
20%	0.309	0.106	$100,000
30%	0.277	0.071	$67,000
40%	0.255	0.050	$47,000
50%	0.235	0.038	$36,000
60%	0.213	0.031	$27,000
70%	0.203	0.025	$22,000
80%	0.194	0.019	$17,000
90%	0.185	0.015	$13,000
100%	0.177	0.012	$10,000

Table 4.7 Summary of Optimization of Management Reserves (LCS 1)

α	p(PMF)	p(TMF)	E(Costs of Failure)
0%	0.513	0.297	$327,000
10%	0.508	0.101	$171,000
20%	0.461	0.064	$129,000
30%	0.376	0.053	$101,000
40%	0.304	0.045	$79,000
50%	0.244	0.038	$63,000
60%	0.195	0.033	$50,000
70%	0.166	0.024	$39,000
80%	0.126	0.024	$32,000
90%	0.106	0.017	$24,000
100%	0.089	0.014	$19,000

Table 4.8 Summary of Optimization of Management Reserves (LCS 2)

α	p(PMF)	p(TMF)	E(Costs of Failure)
0%	0.276	0.459	$430,000
10%	0.245	0.392	$355,000
20%	0.228	0.342	$302,000
30%	0.215	0.302	$261,000
40%	0.202	0.270	$228,000
50%	0.201	0.265	$220,000
60%	0.179	0.223	$180,000
70%	0.168	0.206	$163,000
80%	0.158	0.193	$149,000
90%	0.129	0.190	$139,000
100%	0.114	0.181	$129,000

Figures 4.1 through 4.4 show the results of the optimizations of the technical reinforcement budget and management reserve for each configuration. The probabilities of the various managerial problems were left out of the graphs in order to make them more legible.

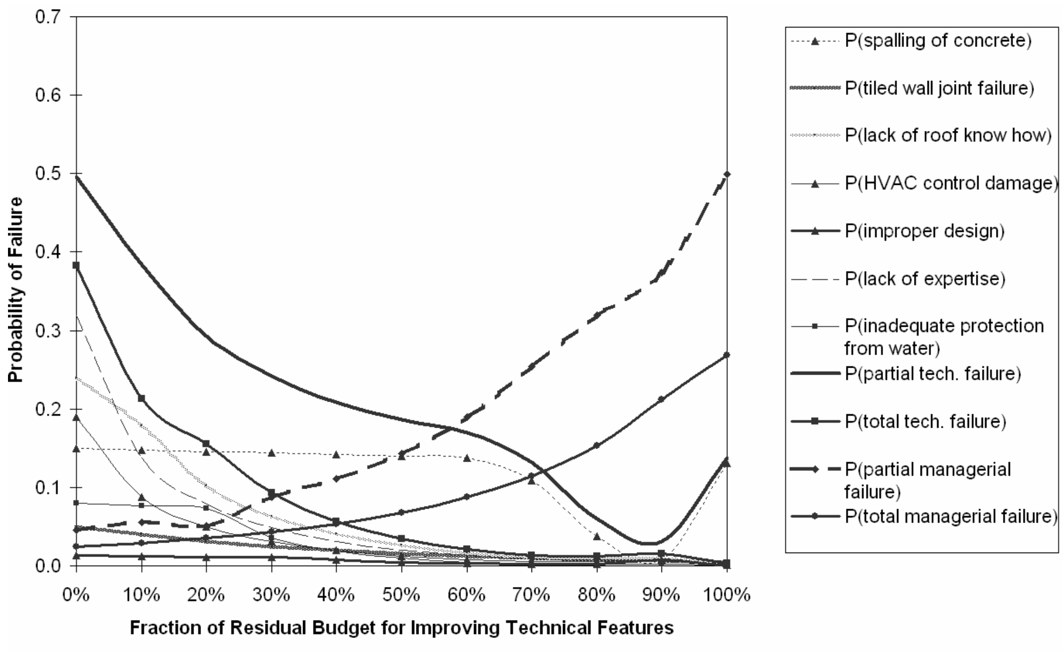


Figure 4.1 Probabilities of Different Failure States versus Investment of Residual Budget (CCS 1)

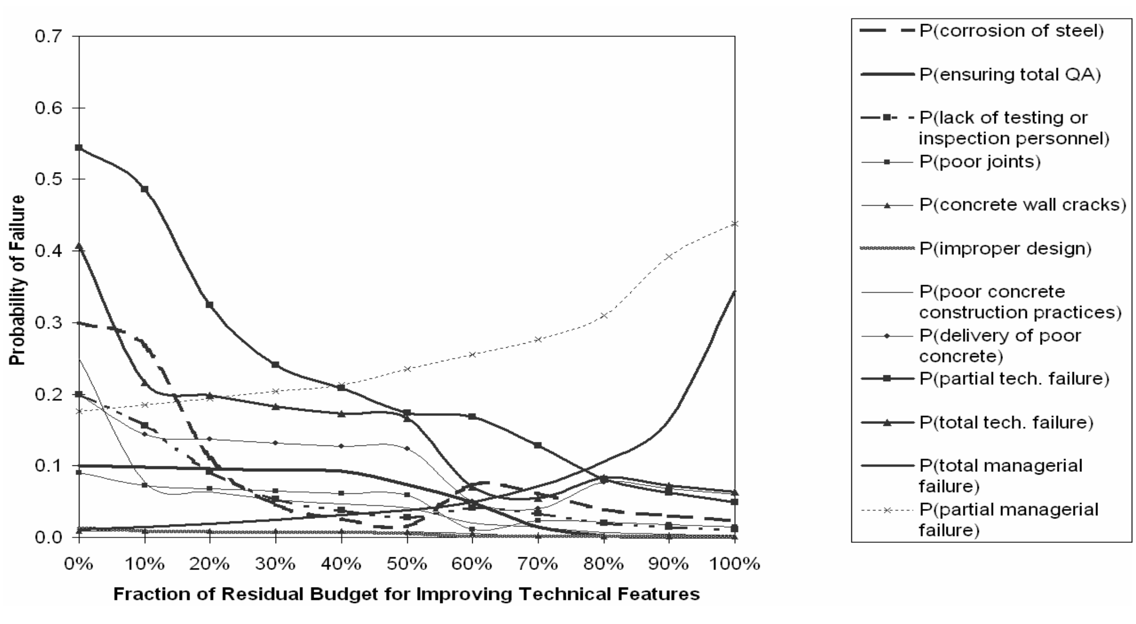


Figure 4.2 Probabilities of Different Failure States versus Investment of Residual Budget (CCS 2)

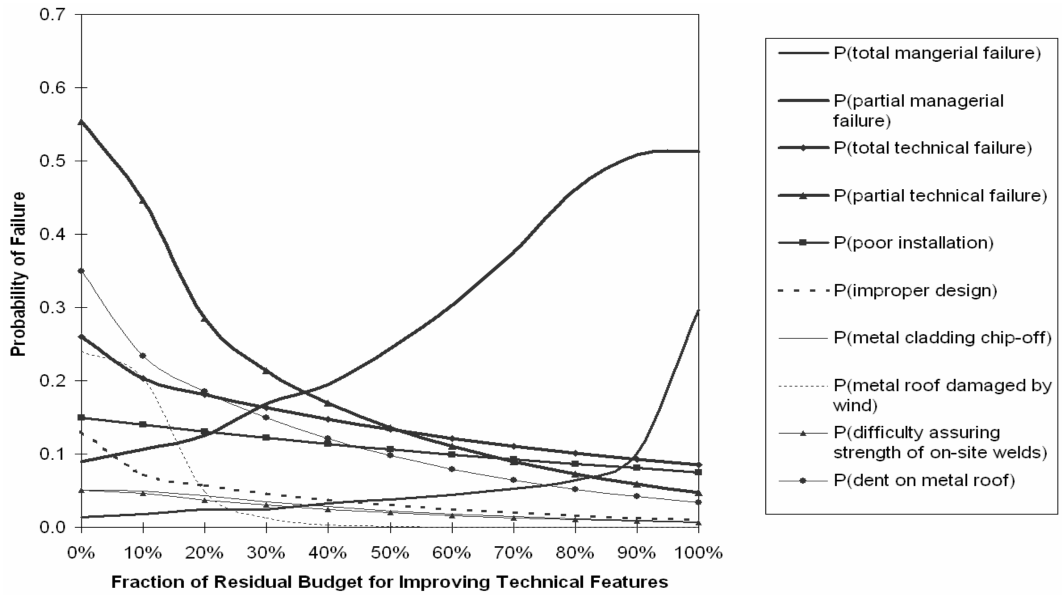


Figure 4.3 Probabilities of Different Failure States versus Investment of Residual Budget (LCS 1)

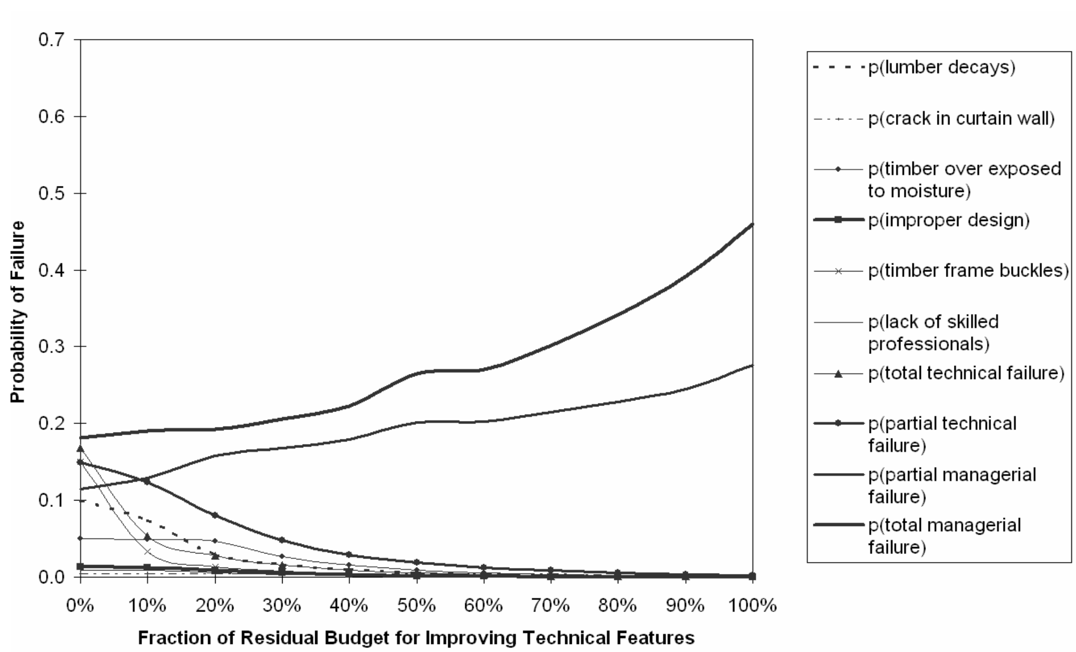


Figure 4.4 Probabilities of Different Failure States versus Investment of Residual Budget (LCS 2)

Table 4.9 provides a summary of the optimal allocation of the residual budget for each alternative and the associated probabilities of technical and managerial failures.

Table 4.9 Summary of the Integration of the Different Optimizations

Configuration	Expected Costs of Failure	α	p(PMF)	p(TMF)	p(PTF)	p(TTF)
Conventional Construction System 1 (CCS 1)	$ 132,000	50%	0.143	0.067	0.186	0.034
Conventional Construction System 2 (CCS 2)	$ 161,000	70%	0.277	0.071	0.128	0.055
Lightweight Construction System 1 (LCS1)	$ 201,000	60%	0.304	0.044	0.110	0.121
Lightweight Construction System 2 (LCS 2)	$ 36,000	80%	0.228	0.342	0.006	0.001

The alternative with the least expected cost of failure is LCS 2 and this is the alternative which will be selected for the development of the facility. For this alternative, 80% of the residual budget will be included in the initial cost of development of the facility and 20% of the residual budget held as management reserves to serve as contingency for events that can result in completing the project behind schedule and/or over budget.

RESULTS OF DETERMINATION OF OVERALL EXPECTED COST OF FAILURE USING PERCENTAGE OF TOTAL PROJECT COST AS CONTINGENCY

With a project contingency allowance of 23% of the total project costs, the total project budget without the use of APRAM was approximately $1,440,000. This contingency allowance was obtained by running a Monte Carlo Simulation with the @ Risk Decision Tool. The contingency allowance was solely for the purpose of handling those problems that were likely to occur but whose impact could not be ascertained at the time of preparing the estimates. Thus none of the contingency funds was allocated to improving the technical capabilities of the facility. Figures 4.5 through 4.8 show the relationship between the probabilities of failure at different levels of the contingency allowance.

Again LCS 2 emerged as the configuration that would reduce the decision maker's expected cost of failure. The overall expected cost of failure using this approach was approximately $270,000. Table 4.10 provides a summary of the total cost of failure and associated probabilities using a contingency allowance of 23%. These results are further discussed in Chapter V.

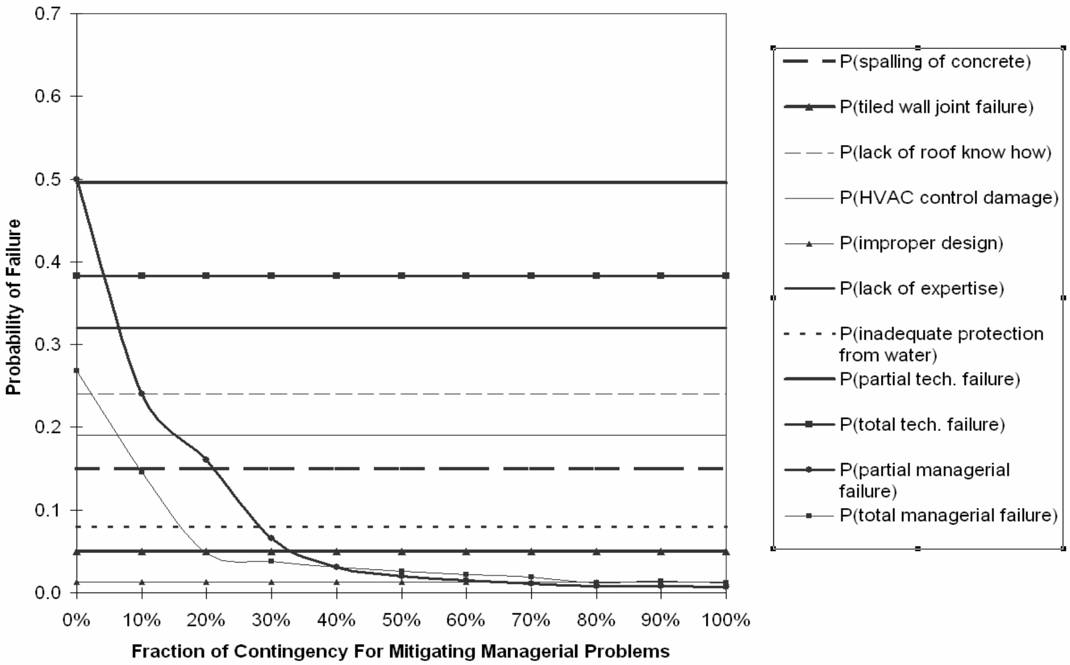


Figure 4.5 Failure Probabilities versus Different Contingency Levels (CCS 1)

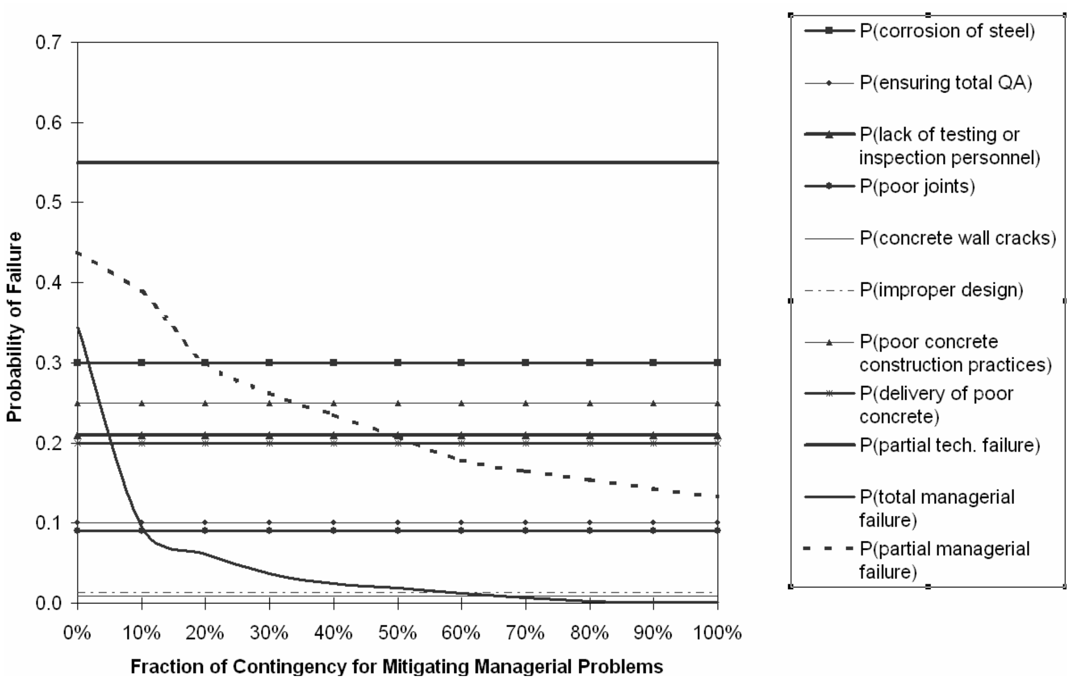


Figure 4.6 Failure Probabilities versus Different Contingency Levels (CCS 2)

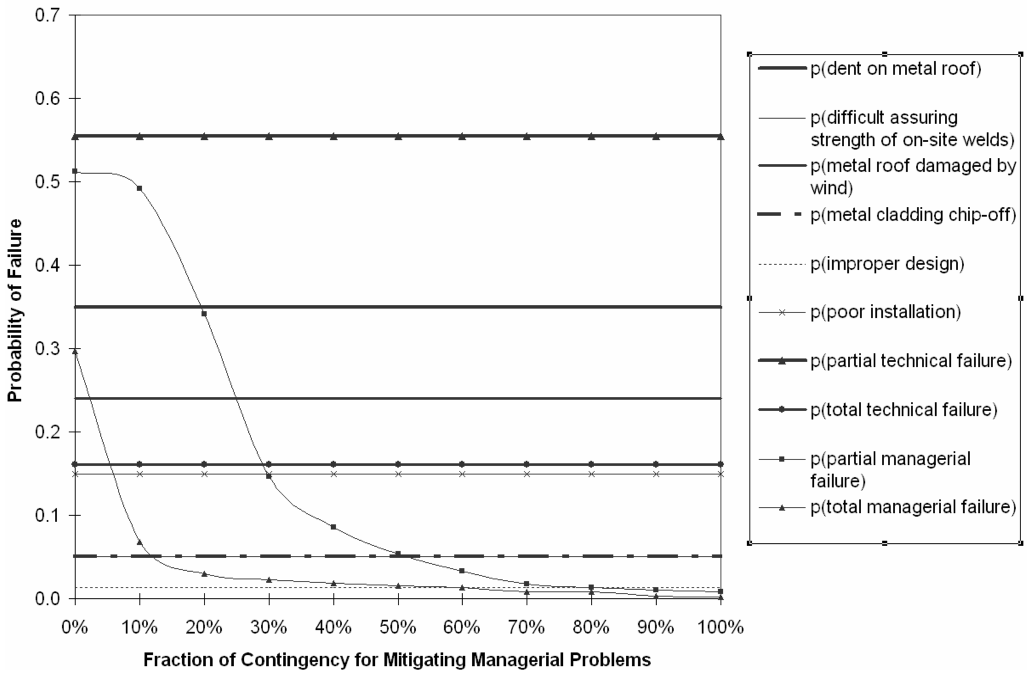


Figure 4.7 Failure Probabilities versus Different Contingency Levels (LCS 1)

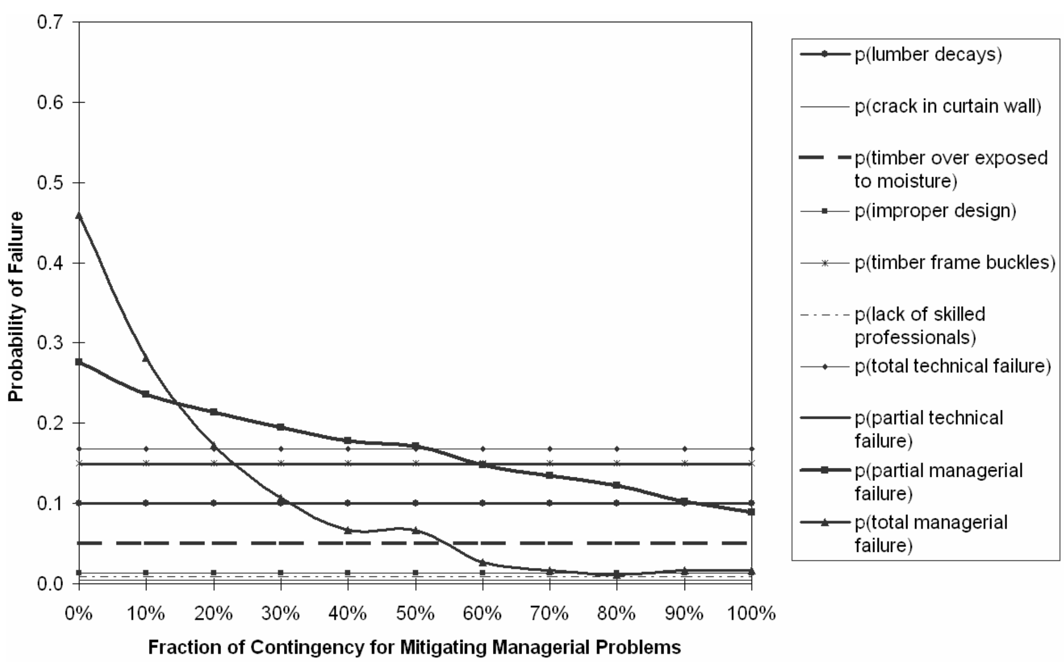


Figure 4.8 Failure Probabilities versus Different Contingency Levels (LCS 2)

Table 4.10 Costs of Failure for All Configurations

Configuration	Costs of Failure	p(PMF)	p(TMF)	p(PTF)	p(TTF)
Conventional Construction System 1 (CCS 1)	$ 581,000	0.007	0.012	0.496	0.383
Conventional Construction System 2 (CCS 2)	$ 658,000	0.132	0.001	0.544	0.408
Lightweight Construction System 1 (LCS1)	$ 309,000	0.008	0.002	0.554	0.161
Lightweight Construction System 2 (LCS 2)	$ 270,000	0.089	0.017	0.149	0.169

SUMMARY

This chapter presented the results from the implementation of APRAM for the development of the Historic Old Rankin Highway Visitor Center. Also, the results of an alternative approach to determine the overall cost of project failure have been presented. The probabilities of all risks that can lead to technical failure (total and partial) were constant for the alternative approach because the contingency allowance was not meant for improving the technical capabilities of the facility. Detailed results of the optimizations performed for the technical reinforcement budget and the management reserves can be found in Appendix D and Appendix E respectively. Results of optimizations performed to allocate the contingency allowance to the various managerial problems can be found in Appendix G.

CHAPTER V

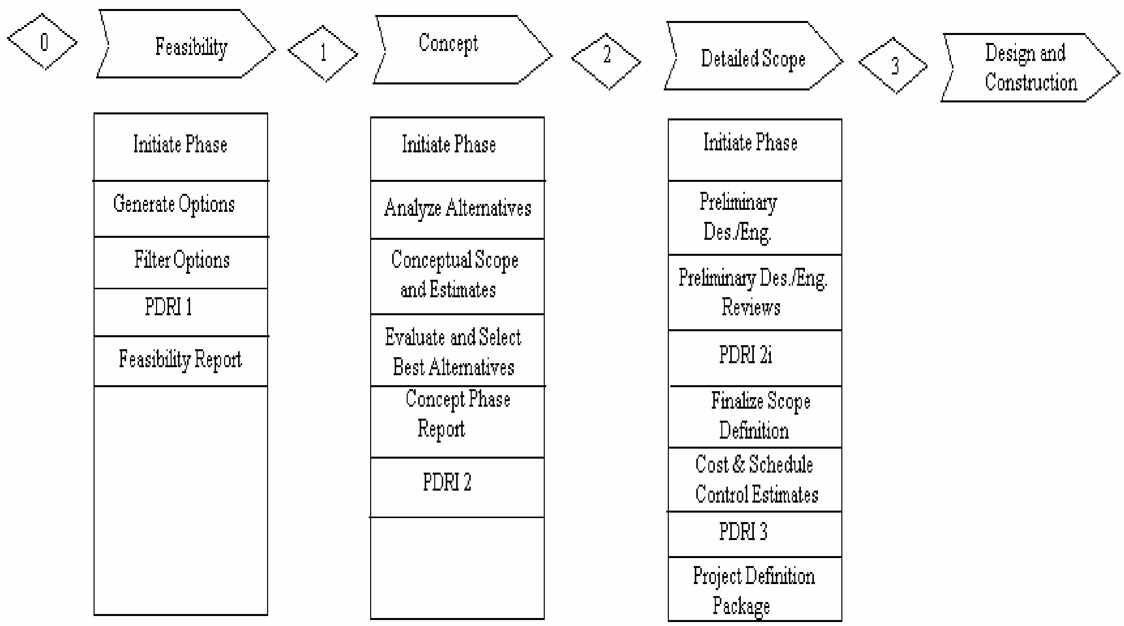
DISCUSSION OF IMPLEMENTATION OF APRAM AND RESULTS

INTRODUCTION

This chapter provides a discussion of the implementation of APRAM and the results of analysis. Discussions on how APRAM can be successfully used in construction are also included in this chapter. The phase of construction project development in which APRAM can be implemented is described. Because the probabilities used in this study were assumed, a discussion of how probabilities can be obtained as inputs to APRAM for construction projects is also presented in this chapter. A discussion of the other assumptions made for this study is also included in this chapter. To add to the above, certain differences in project development in the aerospace and construction industries are noted. Results from the implementation of APRAM will be compared with results from the risk analysis approach used to determine contingency. A discussion is also included on the project delivery strategy most suitable for APRAM. The chapter concludes with a summary of the salient points of the discussions.

PROJECT DEVELOPMENT PHASE FOR IMPLEMENTING APRAM

According to the Construction Industry Institute's (CII) new Front End Planning Tool Kit (Construction Industry Institute 2007), there are four different phases in the development of a construction project before the constructed facility enters the operations phase. These phases are the feasibility phase, the concept phase, the detailed scope phase, and the design and construction phase. Figure 5.1 shows the different phases of a construction project.



Reference – Construction Industry Institute (2007)

Figure 5.1 Phases in Construction Project Development

Even though Figure 5.1 does not show risk analysis in the project development process, it is imperative to conduct a risk analysis of a project during each phase of project development. This will continuously allow project participants to address risk issues that can lead to project failure throughout the duration of a project. The concept phase involves the analysis and selection of project alternatives. APRAM can therefore be performed during this phase of a project before proceeding to the detailed scope phase. Performing further risk analysis in later project phases with APRAM can not realize the full potential of the model since APRAM aids the selection of the optimal system configuration that will reduce the expected cost of project failure. The model could however be used to optimize budget reserves (remaining reserves after initial optimizations) during later phases of construction project development.

OBTAINING PROBABILITIES IN PRACTICE

Organizations that undertake construction projects are increasingly relying on experiences from previous projects to develop management systems that they can use to improve chances of project success. In order to improve the management of construction projects, it is essential to have an effective project control system that can easily be used to collect useful project data in a timely manner to provide important historical databases for the planning and management of future projects (Abudayyeh et al. 2001). Thus, owners or contractors developing construction projects can obtain information or data on projects with similar scope from their historical databases. The HyperCard Information System (Mulholland and Christian 1999) is an example of a database that stores and provides access to information regarding previously experienced schedule problems. This system has a spreadsheet that can be used to perform probability modeling of identified risks. To add to the above, various techniques such as PERT, MCS and Stochastic Project Scheduling Simulation (SPSS) can be used to provide probability distributions for parameters or features of previous projects that are relevant or of interest to current projects.

In the absence of historical data, expert opinion could be sought to obtain failure probabilities. Because project management decisions still need to be made in the absence of past data, construction project managers and engineers can rely to a great extent on their own past experiences or experiences of colleagues in identifying and assessing the probabilities of occurrence of risky events.

Morgan and Henrion (1990) summarized attributes of what they believe to be a good protocol for expert elicitation and this could be employed in the construction industry. First, they suggest that the process be taken seriously and not be considered as routine. A familiarization phase can then be used to introduce the expert to the process of elicitation. During the familiarization phase, the elicitor or eliciting team should explain to the expert approximate procedures that are used to make judgments in the presence of uncertainty. Examples of some of these procedures are availability, representativeness and anchoring and adjustment. The availability procedure refers to probability judgments that are driven by the ease with which individuals can think of previous cases of an event or the ease with which individuals can think of scenarios leading to an event. The representativeness procedure describes the expectation individuals have that details of events should reflect a larger process. Anchoring and adjustment describes the case in which an individual attempting to estimate a quantity starts from a point and then adjusts away from the point as information becomes available. Once familiarization with expert judgment is complete, it is important to ensure that the issue about which the expert is to make a judgment becomes the main focus of the process. Morgan and Henrion (1990) further suggests that it is essential for the elicitation team to have an in-depth understanding of the issue under discussion in order to clearly define the quantity to be elicited. To avoid over confidence in expert judgments, elicitors can ask experts certain questions that can be used to establish upper and lower values for the quantity to be estimated.

Standard probability wheels and classic lottery formulations are examples of methods that can be used to help experts in making probability judgments. Figure 5.2 shows an example of expert elicitation of the probability that an event E will occur using a lottery formulation.

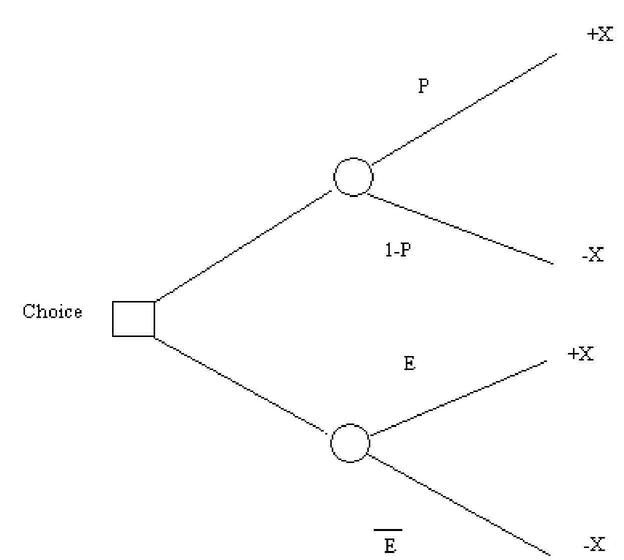


Figure 5.2 Classic Lottery Formulation

In this elicitation process, the expert has to make a choice between two lotteries. The top lottery has a probability p of obtaining a desired outcome '+X' and a probability (1-p) of obtaining an outcome '-X' which is a less desired outcome. The bottom lottery results in an outcome '+X' if event E occurs and an outcome of '-X' if E does not occur. In the lottery formulation, the elicitor assigns a value to p and then asks the expert to make a choice between the two lotteries. The value of p is changed until the expert is indifferent in his choice between the two lotteries. The value of p at which the expert is indifferent between p and the chance of E happening represents the expert's assessed probability that the event E will occur.

In view of all measures that can be taken to limit bias in expert judgments, expert opinion may not be always correct or multiple experts may have different opinions. In such situations, Morgan and Henrion (1999) notes that, opinions of different experts may be combined to obtain a representative average if the range of opinions has no consequences on the outcome of the final model. They further suggest that group probability assessment techniques be used to reach a consensus for diversity in expert opinions in which the range of opinions has consequences on the outcome of the final model.

DISCUSSION OF DETERMINING FAILURE COSTS USING APRAM AND PERCENTAGE CONTINGENCY

The analysis using APRAM for the development of the Historic Old Hankin Visitor Center facility did not select the lowest cost configuration for each construction system for the analysis as the APRAM model proposes. This was mainly because the expected cost of failure is not dependent on initial cost of development alone but also on the likelihood of occurrence of possible risks. In construction, durable materials that improve the performance of a constructed facility are generally expensive, thus an analysis of risks considering impacts on project cost, schedule and quality can not be based only on the lowest cost alternative. This can be true for all industries including aerospace. In addition, the process of determining the optimal response to managerial problems for this study did not employ the use of sequential decision trees as the original APRAM study did.

During project development of space missions, engineers first develop prototypes on which they perform tests or experiments to examine system performance. The prototypes are improved based on test results and this process continues until test results meet the requirements of engineering managers. This concept of project development is referred to as spiral development (Zubrin 2005). During this process of project development, some of the measures taken to mitigate development problems tend to cause other problems, hence the use of sequential decision trees in the APRAM model.

Project development in the construction industry does not involve spiral processes even though, for some complicated projects such as nuclear plants, models might be built before actual construction starts. In view of this, the same approach used to optimize the technical reinforcement budget was used to optimize the management reserves instead of using decision trees as the original APRAM study did. For a construction project, a decision tree for maximizing the decision maker's utility would have as many branches as there are possible allocations of management reserves. Such a decision tree would be very large and impossible to resolve.

The cost of implementing APRAM was assumed based on the size of the project used for this study. The costs of implementing APRAM for very big projects such as the construction of cogeneration plants and dams will be significantly greater than the $80,000 used for this study. This is because bigger projects will involve more risks. In the case of cogeneration plants, APRAM may even be used in the analysis and selection of process technologies.

The APRAM model described total managerial failure as being a potential for cancellation of the project. Total managerial failure for this study was not considered as a potential for project cancellation because there have been some construction projects that have had substantial cost and schedule overruns that were not cancelled. The cost of developing the U.S. Department of Energy's National Ignition facility had risen from $1.2 billion to $3.3 billion as of August 2000 (U.S. Government Accountability Office 2000). The National Ignition facility is currently about seven years behind schedule and almost ten times over it's initial budgeted cost. To add to the above, the U.S. Capitol Visitor Center was not yet completed as of February 5 2007, two years behind schedule and almost two times its budgeted cost. Cancellation of an entire project as a result of total managerial failure will mean that there will not be any technical failures since technical failures can only occur after a facility is constructed. Figure 5.3 shows the possible outcomes if total managerial failure results in cancellation of a project. It can be seen from the figure that cancelling a project as a result of total managerial failure will result in seven possible outcomes compared to nine possible outcomes if the project is not cancelled. This will thus lead to a reduction in the expected costs of failure computed from the event tree and this does not actually capture all the decision maker's risks.

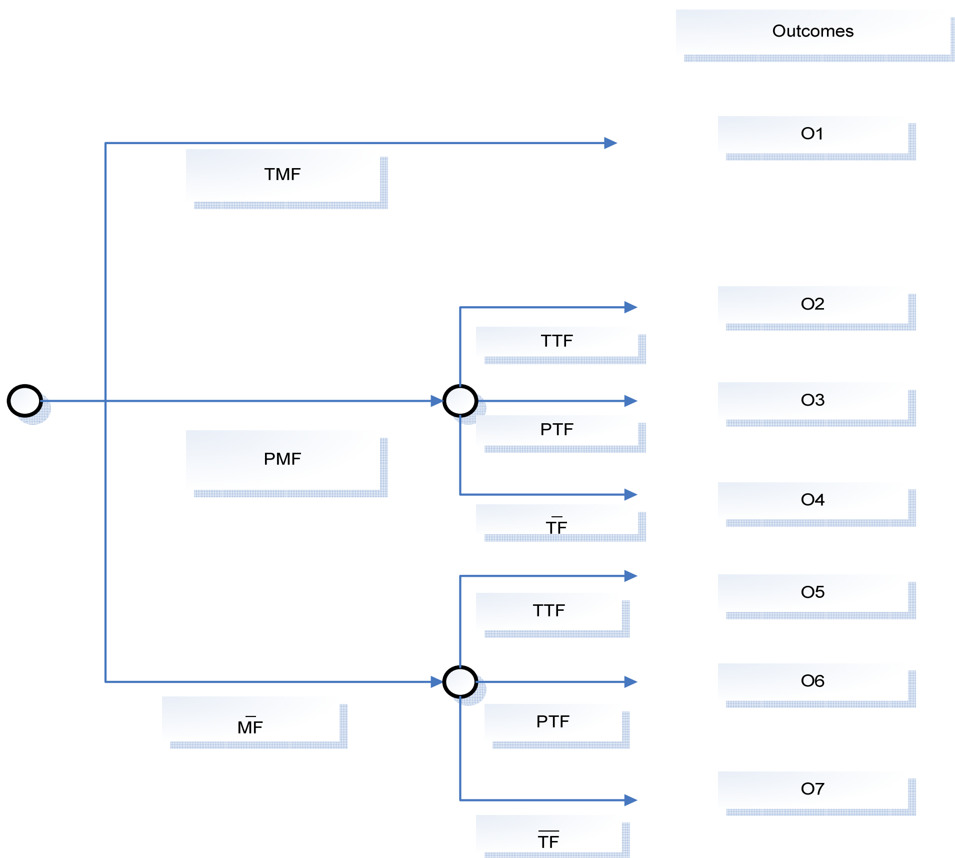


Figure 5.3 Event Tree with Possible Outcomes in the Event of Project Cancellation as a Result of Total Managerial Failure

DISCUSSION OF RESULTS FROM THE IMPLEMENTATION OF APRAM AND ALTERNATIVE RISK ANALYSIS METHOD

The optimizations of the technical reinforcement budget and the management reserves (Figures 4.1 to 4.8 and Tables 4.1 to 4.8) show that the expected costs of technical failure as well as the associated failure probabilities decrease as a greater portion of the residual budget is invested. It can also be seen from Figure 4.2 that the probabilities for the identified technical failures for CCS 2 decrease slightly between α = 20% and α = 60%. This can be attributed to the fact that the optimization resulted in a slight increase in the fraction of the technical reinforcement budget allocated to some of the identified failure modes. Appendix D shows marginal decreases in the probabilities of the failure mode, “difficult to ensure total QA”. It can also be observed from Figure 4.1 that the probabilities of “spalling of concrete” decreases until α = 90% where it sharply increases again. This is due to the fact that the optimization increased the fraction of the technical budget allocated to “spalling of concrete” until the 90% level at which point it significantly increased the amount of investment in that risk item.

It is important to note that the technical elements of the facility need to be reinforced before part of the residual budget can be put aside as management reserves. Table 4.9 shows the optimal allocation of the residual budget for each configuration. For CCS 1, 50% of the residual budget will have to be added to the initial cost of development and the remaining 50% held as reserves since this will minimize the decision maker’s expected costs of failure. Also, 70% of the residual budget will have to be spent improving the technical elements of the facility if it has to be built from cast-in-place concrete (i.e. CCS 2). The remaining 30% will be held as reserves for addressing development problems. LCS 1 would require 60% of the residual budget for technical reinforcement and 40% of the residual budget as reserves in order to reduce the expected cost of failure. The configuration having timber framing (LCS 2) will require the addition of 80% of the residual budget to the initial cost of development. This configuration will require 20% of the residual budget in order to minimize the expected costs of failure. The expected cost of failure ($36,000) for LCS 2 is the least among all the expected failure costs. LCS 2 will therefore have to be used for the development of the facility.

Once the optimal configuration is selected, APRAM further allows the decision maker to check whether probabilities of technical and managerial failures at the optimal allocation of the residual budget meet acceptable risk thresholds. If these probabilities are greater than the acceptable risk levels, Figure 3.16 can give the decision maker an indication of how much to increase the project budget to meet acceptable risk levels.

The reason for performing an alternative risk analysis for this study was to determine what the expected cost of failure would be with another risk analysis technique and also to compare APRAM with a more standard approach. Ideally, performing risk analysis to determine contingency funds would not need alternative construction systems. However, it was necessary to use the same information as that used for APRAM in order to make reasonable comparisons of the two approaches.

As can be seen from Figures 4.5 to 4.8, the probabilities of technical failure for all four configurations remained constant with the alternate approach since no amount of money was spent in reinforcing the technical elements of the structure. The contingency budget was then optimized at the same levels of α used for APRAM to determine the level that would reduce the total cost of failure. As was expected, the optimal level of α for all configurations was 0% which means that the entire contingency funds had to be invested to reduce the overall costs of failure. LCS 2 emerged as the configuration that would reduce the expected costs of failure. However, the expected costs of failure using a percentage of the total project cost as contingency, $267,000 is about eight times the cost of failure using APRAM. Using APRAM therefore can enable the decision maker to assess all risks a project may be exposed to.

COMPARISON OF APRAM WITH OTHER RISK ANALYSIS METHODS

The analysis performed in this study has shown that APRAM can actually be used to identify and also address construction project risks of cost, time and quality. APRAM can also be used to determine the expected cost of failure, and it further offers the decision maker/owner the opportunity to lower expected costs through optimal allocations of the residual budget. APRAM also allows the owner or project initiator to explore all possible options for developing a facility. Application of APRAM during construction project development could also offer the opportunity to involve all project participants at an early stage in the project development process if the owner or decision maker decides to include them in the risk identification process.

FMEA is the only risk analysis technique among the techniques mentioned in this study that can simultaneously handle project risks of cost, time and quality. The

FMEA, however, does not provide sufficient information on the interpretation of results of possible failures. It is appropriate for assessing risks and ranking risks but it does not provide a sound basis for allocating resources to optimally manage risk.

The other risk analysis techniques discussed in this thesis either address only cost or schedule risks or a combination of the two. Also, available construction risk analysis techniques such as JRAP, PERT and SRS only provide probabilities for project parameters but do not offer any means to reduce the probabilities. The ERA methodology can be used to determine project contingency funds but it can be observed from the alternative risk analysis method used in this study that, the project contingency allowance is not meant for improvement of the technical elements of the facility.

PROJECT DELIVERY STRATEGIES SUITABLE FOR APRAM

The APRAM model requires integration of engineering and construction at a very early stage in the project development process. That is, in order to successfully implement APRAM for a construction project, the contractor and the designer are supposed to provide some inputs during the concept phase. This will help to determine the most cost effective as well as most constructible design. The design-build approach in which one entity is usually responsible for both design and construction would therefore be a more effective strategy compared to traditional design-bid-build. This can be mainly attributed to the fact that with the traditional design-bid-build approach, the contractor or builder cannot be identified until detailed design is completed. In the case of design-build however, the design-build firm is selected early in the project development process.

Professional construction management is another project delivery method that can allow the successful implementation of APRAM. Professional construction management is the terminology that describes a project management team that comprises a professional construction manager and other project participants who are responsible for project planning, design and construction in an integrated manner (Hendrickson et Au 2000). A turnkey contract with one entity responsible for both design and construction can also be suitable for implementing APRAM.

LIMITATIONS OF APRAM

Even though this study has shown that APRAM could be useful for analyzing the risks of construction projects, there are some issues that the model does not address. Among these is the issue of safety during construction projects. Safety can be classified as being a managerial failure since incidents like severe accidents on site can result in the suspension of a project pending further investigations. This can lead to substantial schedule delays. Severe accidents may also cause owners to pay large sums of money as compensations. However, no amount of investment of the residual budget can ensure that there are no accidents on site. Accidents can be caused by negligence and carelessness. Lack of commitment to the project at hand could also be the cause of accidents on site. In view of this, the best way to ensure that accidents during construction projects are reduced if not totally eradicated will be ensuring that OSHA regulations and other health and safety measures are strictly enforced on all construction sites.

In addition, APRAM like all other risk analysis techniques, can not be used to fully ensure the owner is secured against unanticipated risks referred to in the literature as “acts of God.” These include risks such as hurricanes, floods and earthquakes. The technical reinforcement budget for example can be used to increase the resistance of constructed facilities to earthquakes or hurricanes. However, management reserves can not be used to reduce the probabilities of schedule overruns as a result of these unanticipated risks. The only way owners can reduce costs of failure as a result of “acts of God” would be through insurance.

APRAM assumes that all risks can be mitigated with money. In practice however, not all technical failures and managerial problems can be effectively handled using money. Some technical failures for instance may require the integration of design and construction as a mitigation measure. A more appropriate way of reducing the impact of delays in materials’ delivery on project duration may be integrating vendors in the project planning process and ensuring continuous communication between the project team and vendors. To add to the above, in the event of increased workload, appropriately allocating the available labor may add more value than hiring new workers.

Finally, APRAM does not address the issue of bad judgment on the part of the construction manager or other project participants. The model assumes that project team members are competent in their various disciplines. In other words, even though the

APRAM model can ensure that more durable construction materials like modified steel and corrosion inhibitors are used during construction, the model does not address failure to comply with good construction practices such as adequate consolidation and curing of concrete. Inadequate consolidation and curing of concrete will still result in low quality constructed facilities even though more money has been spent on acquiring durable materials.

THE CONSTRUCTION INDUSTRY'S USE OF TOOLS DEVELOPED IN OTHER INDUSTRIES

The construction industry has over the years employed different tools that have been developed in other industries. PERT was developed by the U.S. Navy for its Polaris Weapons program while the Critical Path Method was developed by DuPont for the management of chemical plant maintenance projects (Kerzner 2003). PERT has been used in the construction industry to model time variations that have an impact on the completion time of projects while CPM has been extensively used to model the interdependencies between construction activities as well as determining the activities critical to the completion of projects. To add to the above, lean construction techniques are gaining popularity mainly because they improve the chances of project success (Salem et al. 2006). Lean construction follows principles of the lean production system introduced by the Toyota Motor Company in Japan (Womack et al. 1990). Various organizations have been formed to research the application of lean techniques in the construction industry. Among these organizations are the International Group for Lean Construction (IGLC) and the Lean Construction Institute (LCI).

APRAM was developed for use in the aerospace industry and this study has shown that APRAM can be used in making useful construction management decisions. There is the need therefore for a framework that can be used by the construction industry to identify decision support tools developed in other industries that can be useful for construction projects. The construction industry can achieve this by collaborating with academic institutions to research decision support tools that are developed in different fields.

SUMMARY

This chapter provided an explanation of why the implementation of APRAM in the construction setting did not strictly follow the steps involved in the original APRAM process. Certain differences between the development of space programs and the development of construction projects have been discussed. A comparison was also made between the use of APRAM and the use of a percentage contingency to determine costs of failure. A brief discussion was also provided on how to obtain probabilities in practice. Even though APRAM appears to be a more powerful risk analysis tool compared to other tools, limitations of the method exist and have been discussed.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

This study has evaluated the usefulness of using APRAM to make decisions during the development of construction projects. The literature review clearly showed that the construction industry lacks appropriate decision support tools that managers of construction projects can use to simultaneously address project risks due to cost, schedule and quality. None of the risk analysis techniques discussed in the literature review provide a sound basis for the appropriate allocation of project resources. APRAM is however a risk analysis technique that can minimize the expected costs of project failure by integrating project risks of time, budget and quality through the allocation of resources. A risk analysis performed using a more standard approach yielded an expected cost of failure that is almost eight times the expected cost of failure yielded by APRAM. This was mainly because the standard approach did not consider all the forms of project risks, so a decision maker using this approach would still be exposed to some risks even though a complete risk analysis has been performed.

Certain assumptions were required in order to evaluate APRAM in a construction setting. These assumptions have been documented and discussed. The original APRAM model (Dillon and Paté-Cornell 2001; Dillon et al. 2003) required some modifications in order to be effective for construction projects. The main reason for these modifications was the differences between construction project development and the development of space missions. All the necessary modifications made to APRAM to fit a construction setting have been discussed.

RESEARCH CONTRIBUTION

This research has demonstrated that managers of construction projects can use APRAM to make useful decisions that can improve the chances of project success. Among the important features of APRAM are:

i. Simultaneously addresses cost, schedule and budget risks

ii. Provides a sound basis for the allocation of project resources

iii. Can aid the selection of a construction system that would minimize the overall costs of failure

Also, this research highlights the fact that good risk analysis alone is not enough to reduce the chances of project failure. Good management practices must be adhered to. In addition, appropriate health and safety regulations must be strictly enforced and the integration of all project participants early in project development is critical.

Finally this research shows that the construction industry can utilize certain decision support tools developed in other fields to address issues that lead to project failure.

CONCLUSIONS

The effectiveness of APRAM as a useful decision support tool for construction projects has been evaluated in this research. The following is a list of conclusions from this study.

i. Existing risk analysis techniques in the construction industry can not be sufficiently used to address risks relating to costs, schedule and quality. Also, these risk analysis methods do not provide the decision maker any indication of how to allocate resources when they are scarce.

ii. APRAM can be used as a decision support tool for construction projects. This tool will not only help owners/project managers identify project risks but also offer a mechanism that can be used to reduce the probabilities of the identified failures.

iii. The owner organization has to be prepared to increase project costs in order to reduce the probabilities of failure to acceptable levels. In order for the full potential of APRAM to be realized, acceptable levels of failure have to be determined by the owner/decision maker.

iv. The costs of performing risk analysis using APRAM may outweigh the benefits of implementing APRAM on small projects. Since APRAM is meant to be used for the selection of the best system that will minimize the expected cost of failure, using it for very small projects with no alternatives may not be beneficial to the decision maker.

v. APRAM can not be used as a substitute for good construction management practices. The fact that APRAM can help reduce the expected costs of project failure does not mean construction project managers can make injudicious decisions and expert APRAM to minimize the expected costs of failure. APRAM can provide useful results only if it is appropriately applied.

RECOMMENDATIONS

Based on this research, the following recommendations are made to help improve the handling of construction risks.

i. Academic institutions and the construction industry need to collaborate to develop a framework that can be used to identify new decision support tools that are developed in other industries. Some of these tools may be very useful upon refinement to the construction industry.

ii. Organizations that undertake construction projects should ensure they have effective project control systems in place for current projects. These systems can be used to collect data in a timely manner to provide useful data bases for future construction projects. Information can then be obtained from these databases to provide inputs for APRAM.

iii. Since the analysis of project risks using APRAM can only be done during the concept phase of project development, there is some uncertainty in the inputs for APRAM as a result of the lack of information at this phase of the project. Performing uncertainty propagation of the APRAM model would therefore be a good topic for future research. This can provide useful insights about the assumptions of the model as well as inherent uncertainties and thus provide an incentive for improving the model.

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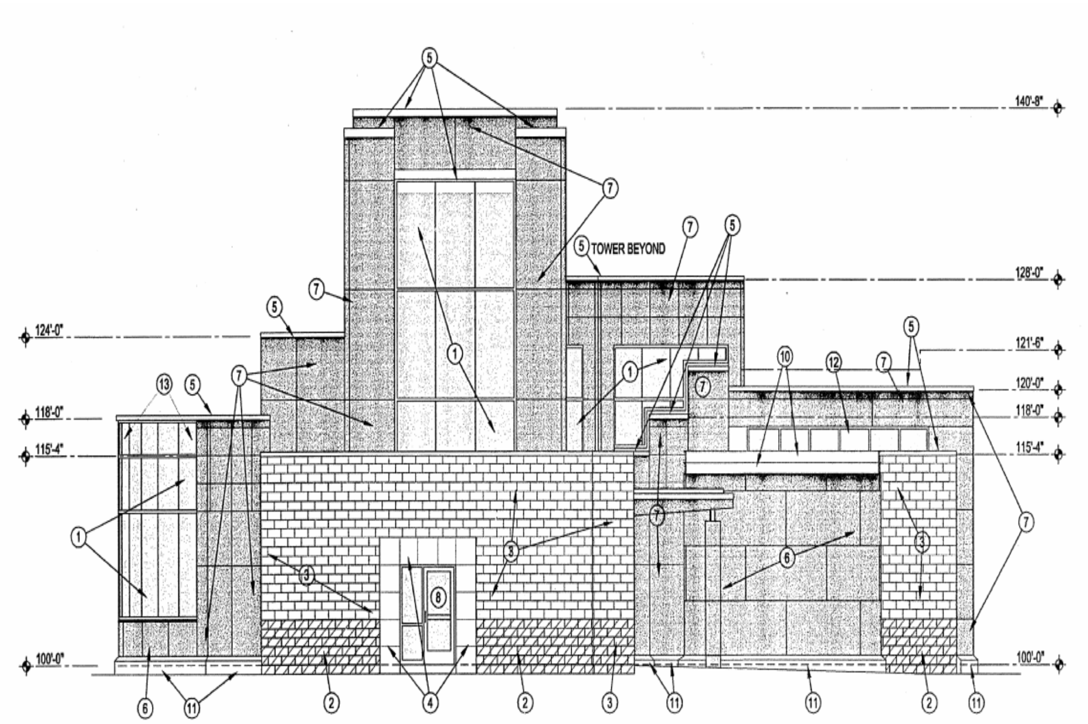
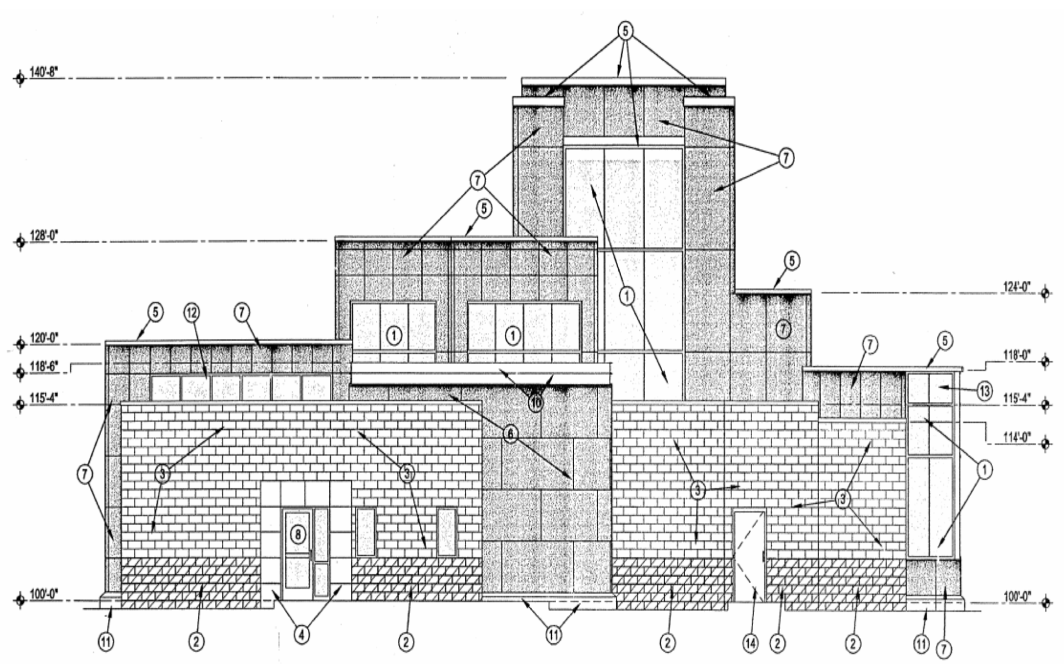
APPENDIX A

VIEWS OF THE HISTORIC OLD RANKIN HIGHWAY VISITOR CENTER

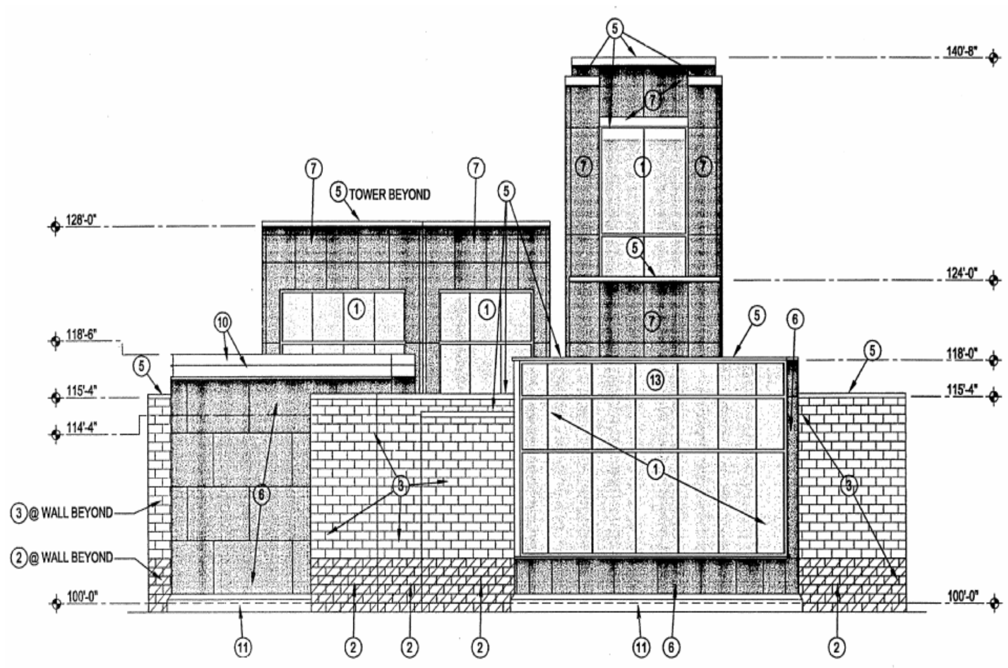
(EXTERIOR ELEVATIONS AND PLAN)



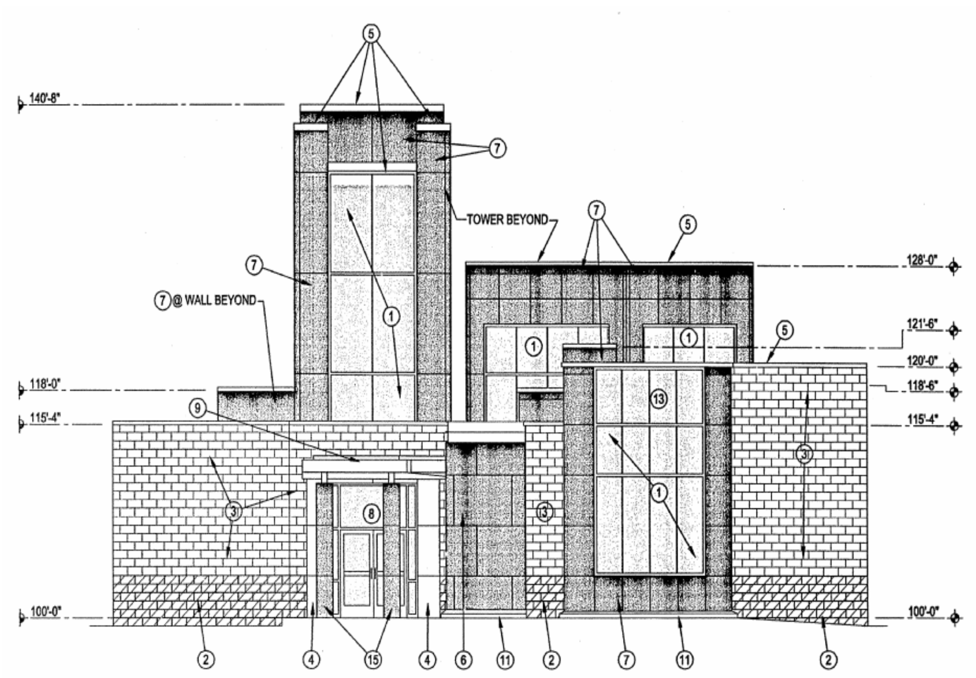
East Elevation (Source - TXDOT 2004)



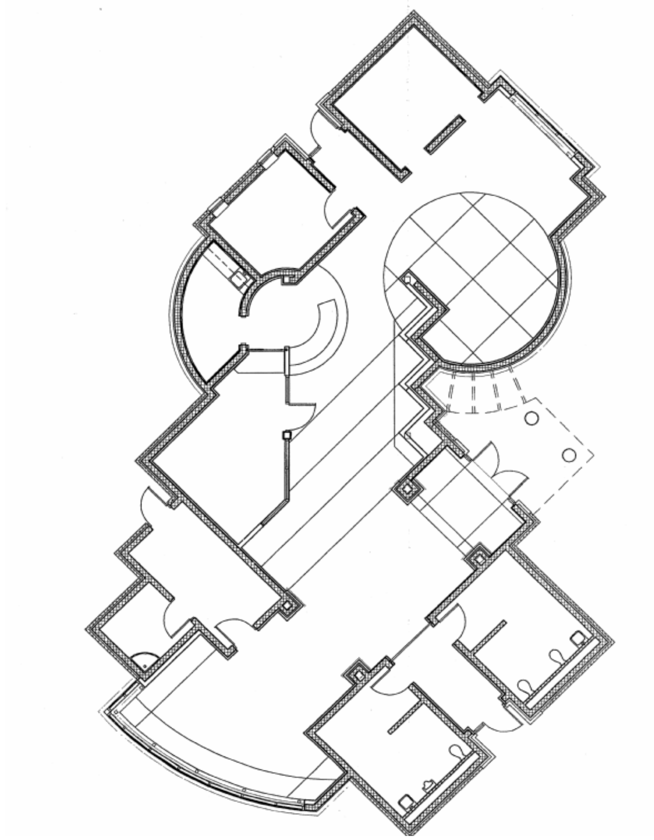
West Elevation (Source - TXDOT 2004)



South Elevation (Source - TXDOT 2004)



North Elevation (Source - TXDOT 2004)



Roof Plan (Source - TXDOT 2004)

APPENDIX B

DETAILED COST ESTIMATES

SUMMARY OF DETAILED COST ESTIMATES

Summary of Cost Estimates

Category	Cost
Site Work	$ 159,000
Concrete	$ 251,000
Metal	$ 127,000
Thermal and Moisture Protection	$60,000
Mechanical	$ 78,000
Masonry	$ 44,000
Doors and Windows	$ 29,000
Finishes	$ 50,000
Specialties	$84,000
Wood & Plastics	$ 45,000
Electrical	$ 56,000
Total	$980,000

SITE WORK

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Mobilization/Demobilization	02305-250-0020	B-34N	4	EA	7		55	112
Site Preparation								
Surveying	01107-700-0010	A-7	3.3	ACRE	5	16.3	269	18.4
Clearing and Grubbing (incl earthworks)								
Selective Tree Removal	02230-300-1500	B-10M	320	EA	34		1.20	3.73
Pavement Removal	02220-250-5200	B-38	255	SY	320		4.70	3.24
Curb Removal	02220-250-6000	B-6	360	LF	245		1.92	0.60
Saw Cut Asphalt	02220-360-0015	B-89	1050	LF	340	0.26	0.46	0.29
Stripping and Stockpiling of Soil	02230-500-0020	B-10B	2300	CY	2600		0.17	0.40
Fencing	02220-220-1750	B-6	70	LF	782.5		9.90	3.08
Gutter Removal	07060-110-2000	1-CLAB	240	LF	98		0.89	0.00
Excavation (backhoe 1cy capacity)	02315-424-0200	B-12A	1123	CY	2340.87		0.83	0.93
Hauling	02315-490-0560	B-34C	1123	LCY	2012		5.65	12.20
Backfill	02315-424-0200	B-12A	1024	BCY	1180		0.83	0.93
Grading	02310-100-0100	B-11L	2000	SY	3050		0.47	0.44
Trenching	02315-620-0150	B-53	750	LF	1205		0.35	0.06
Paving (all sidewalks and curbs)								
1.5" Asphaltic Concrete Pavement (for the adjoining street)	02740-315-0300	B-25C	35000	SF	560.5	0.31	0.04	0.05
3000 PSI Concrete with Fibermesh	02775-275-0350	B-24	545	SF	250.5	1.80	1.38	0.00
Sidewalks	02775-275-0100	B-37	660	SY	578.00	4.630	2.040	0.160
Parking Area Pavement and Base	02740-315-0020	B-25C	9000	SF	5636	1.38	0.16	0.20
Parking Area Pavement Stripping and Markings	02760-300-0020	B-78	20000	LF	108	0.15	0.06	0.02

SITE WORK (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Mobilization/Demobilization	02305-250-0020		784	385	1169	2	14	1.75
Site Preparation								
Surveying	01107-700-0010	81.5	92	1345	1518.5	7.273	36.365	1.515
Clearing and Grubbing (incl earthworks)								
Selective Tree Removal	02230-300-1500	0.00	126.82	40.80	167.62	0.037	1.258	0.106
Pavement Removal	02220-250-5200	0.00	1036.80	1504.00	2540.80	0.157	50.24	1.255
Curb Removal	02220-250-6000	0.00	147.00	470.40	617.40	0.67	164.15	0.681
Saw Cut Asphalt	02220-360-0015	88.40	98.60	156.40	343.40	0.015	5.10	0.324
Stripping and Stockpiling of Soil	02230-500-0020	0.00	39.20	16.66	55.86	0.005	0.49	1.130
Fencing	02220-220-1750	0.00	2410.10	7746.75	10156.85		0.00	11.179
Gutter Removal	07060-110-2000	0.00	0.00	87.22	87.22	0.033	3.23	0.408
Excavation (backhoe 1cy capacity)	02315-424-0200	0.00	2177.01	1942.92	4119.93	0.027	63.20	2.084
Hauling	02315-490-0560	0.00	24546.40	11367.80	35914.20	0.105	211.26	1.792
Backfill	02315-424-0200	0.00	1097.40	979.40	2076.80	0.027	31.86	1.152
Grading	02310-100-0100	0.00	1342.00	1433.50	2775.50	0.008	24.40	1.525
Trenching	02315-620-0150	0.00	72.30	421.75	494.05	0.011	13.26	1.607
Paving (all sidewalks and curbs)								
1.5" Asphaltic Concrete Pavement (for the adjoining street)	02740-315-0300	173.76	28.03	22.42	224.20	0.001	0.56	0.016
3000 PSI Concrete with Fibermesh	02775-275-0350	450.90	0.00	345.69	796.59	1.38	345.69	0.460
Sidewalks	02775-275-0100	2676.14	92.48	1179.12	3947.74	0.73	421.94	0.876
Parking Area Pavement and Base	02740-315-0020	7777.68	1127.20	901.76	9806.64	0.005	28.18	0.626
Parking Area Pavement Stripping and Markings	02760-300-0020	16.20	2.16	6.48	24.84	0.002	0.22	0.005

SITE WORK (Continued)

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Parking Area Stabilized Subgrade	02720-200-0200	B-36C	4600	SY	340	7.95	0.28	0.56
Concrete Curb with Rock Mulch	02770-500-1600	B-29	300	LF	120	4.72	5.35	2.79
Asphalt Paving Blocks	02780-100-0500	D-1	135	SF	532	4.22	3.68	
Landscape and Irrigation								
Trees and Shrubs								
Cedar Elm	02930-310-0300	B17	18	EA	5	179.00	50.50	30.00
Lacebark Elm	02930-410-0800	B17	20	EA	2	109.00	45.50	27.00
Oak	02930-410-1800	B17	5.33	EA	3	240	152	90.5
Mondell Pine	02930-310-0700	B1	50	EA	4	38.5	13.15	
Lucretia Hamilton Desert Willow	02930-410-2800	B17	20	EA	3	59.00	45.50	27.00
Plum	02930-410-2200	B17	20	EA	3	88.00	45.50	27.00
Russian Olive	02930-320-4200	B17	75	EA	27	20.5	12.15	7.25
Texas Mountain Laurel	02930-320-0900	B1	80	EA	4	48.50	8.20	
Grass	02920-310-1300	B81		LB	77	1.10	0.00	
2" Water Tap	N/A			EA	4	34.5		
2" Water Meter	15120-940-2360	1 PLUM	6	EA	1	415.00	54.50	
Irrigation Controller	02810-300-1360	2 SSWK	18.75	EA	1	3.73	29.5	
Rain & Freeze Sensor	N/A			EA	1	89.5		
20" PVC Pipe	02510-750-3060	B-20A	133	LF	130	26	7.75	
42" PVC Pipe	02510-750-3100	B-20A	60	LF	180	109	17.2	
Quick Coupler Valve	02810-300-1340	2 SSWK	18.75	EA	6	42	29.5	
Remote Control Valve	02810-300-1305	2 SSWK	18	EA	10	17.05	31	
Fixed Spray Pop-Up Sprinklers	02810-300-1020	2-SSWK	76	EA	6	7.35		
Rotary Pop-Up Sprinklers	02810-300-1150	2-SSWK	25	EA	32	23	22.5	

SITE WORK (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Parking Area Stabilized Subgrade	02720-200-0200	2703.00	190.40	95.20	2988.60	0.09	30.60	0.074
Concrete Curb with Rock Mulch	02770-500-1600	566.40	334.80	642.00	1543.20	0.187	22.44	0.400
Asphalt Paving Blocks	02780-100-0500	1823.04		1589.76	3412.80	0.119	51.41	3.200
Landscape and Irrigation								
Trees and Shrubs								
Cedar Elm	02930-310-0300	895.00	150.00	252.50	1297.50	1.778	8.89	0.278
Lacebark Elm	02930-410-0800	218.00	54.00	91.00	363.00	1.600	3.20	0.100
Oak	02930-410-1800	720.00	271.50	456.00	1447.50	5.333	16.00	0.563
Mondell Pine	02930-310-0700	154.00	0.00	52.60	206.60	0.480	1.92	0.080
Lucretia Hamilton Desert Willow	02930-410-2800	177.00	81.00	136.50	394.50	1.600	4.80	0.150
Plum	02930-410-2200	264.00	81.00	136.50	481.50	1.600	4.80	0.150
Russian Olive	02930-320-4200	553.50	195.75	328.05	1077.30	0.427	11.53	0.360
Texas Mountain Laurel	02930-320-0900	194.00	0.00	32.80	226.80	0.300	1.20	0.050
Grass	02920-310-1300	84.70	0.00	0.00	84.70		0.00	0.034
2" Water Tap	N/A	138					0.00	
2" Water Meter	15120-940-2360	415.00		54.50	469.50	1.333	1.33	0.167
Irrigation Controller	02810-300-1360	3.73		29.50	33.23	0.853	0.85	0.053
Rain & Freeze Sensor	N/A	89.50		0.00	89.50		0.00	
20" PVC Pipe	02510-750-3060	3380.00		1007.50	4387.50	0.241	31.33	0.977
42" PVC Pipe	02510-750-3100	19620.00		3096.00	22716.00	0.533	95.94	3.000
Quick Coupler Valve	02810-300-1340	252.00		177.00	429.00	0.853	5.12	0.320
Remote Control Valve	02810-300-1305	170.50		310.00	480.50	0.889	8.89	0.556
Fixed Spray Pop-Up Sprinklers	02810-300-1020	44.10		0.00	44.10	0.211	1.27	0.079
Rotary Pop-Up Sprinklers	02810-300-1150	736.00		720.00	1456.00	0.64	20.48	1.280

SITE WORK (Continued)

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Drainage and Utilities (incl SWPP)								
Excavation	02315-424-0200	B-12A	600	CY	110		0.83	0.93
Hauling	02220-240-5600	B-34D	76	CY	96		2.9	5.5
Backfill	02315-424-0200	B-12A	600	CY	43		0.83	0.93
Trenching	02315-620-0150	B-53	750	LF	54.7		0.35	0.06
Manhole	02630-400-0800	C-14H	2	EA	4	445	810	12
6" Sewer Line	02630-530-1010	B-14	265.04	LF	86	4.13	5.1	0.82
#4 Rebar for Manhole	03210-200-0200			TON	8	700		
2" PVC Ducts	02580-420-4600	2-ELEC	240	LF	78.5	1.29	1.36	
Baled Hay	02370-700-1250	A-2	2500	LF	378.67	2.08	0.26	0.05
Silt Fence	02370-700-1000	2-CLAB	1600	LF	420	0.32	0.27	
PVC Piping	02530-780-2120	B-21	330	LF	86	8.75	2.62	0.48
Concrete Headwall	02540-400-1500	B-21	4.7	EA	4	645	184	33.5
Plastic Box W/ Grate Inlet	02540-400-1350	B-13	5	EA	8	910	320	123
Guide and Directional Signs	02890-100-0600	B-80	70	EA	24	35.5	13.15	7.65
Handicap Signs	02890-100-0300	B-80	70	EA	43	112	13.15	7.65
Other signs (parking and on building exterior)	02890-100-1200	B-80	70	EA	40	49.5	13.5	7.65

SITE WORK (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Drainage and Utilities (incl SWPP)								
Excavation	02315-424-0200		102.30	91.30	193.60	0.027	2.97	0.183
Hauling	02220-240-5600		528.00	278.40	806.40	0.105	10.08	1.263
Backfill	02315-424-0200		39.99	35.69	75.68	0.027	1.16	0.072
Trenching	02315-620-0150		3.28	19.15	22.43	0.011	0.60	0.073
Manhole	02630-400-0800	1780.00	48.00	3240.00	5068.00		0.00	2.000
6" Sewer Line	02630-530-1010	355.18	70.52	438.60	864.30	0.181	15.57	0.324
#4 Rebar for Manhole	03210-200-0200	5600.00	0.00	0.00	5600.00		0.00	
2" PVC Ducts	02580-420-4600	101.27	0.00	106.76	208.03	0.033	2.59	0.327
Baled Hay	02370-700-1250	787.63	18.93	98.45	905.02	0.01	3.79	0.151
Silt Fence	02370-700-1000	134.40	0.00	113.40	247.80	0.01	4.20	0.263
PVC Piping	02530-780-2120	752.50	41.28	225.32	1019.10	0.085	7.31	0.261
Concrete Headwall	02540-400-1500	2580.00	134.00	736.00	3450.00	3.5	14.00	0.851
Plastic Box W/ Grate Inlet	02540-400-1350	7280.00	984.00	2560.00	10824.00	11.2	89.60	1.600
Guide and Directional Signs	02890-100-0600	852.00		315.60	1167.60	0.457	10.97	0.343
Handicap Signs	02890-100-0300	4816.00		565.45	5381.45	0.457	19.65	0.614
Other signs (parking and on building exterior)	02890-100-1200	1980.00		540.00	2520.00	0.457	18.28	0.571
			Sitework Sub Total		$159,000			

CONCRETE

Project Component	Means Reference Number	Crew	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Earthwork							
Drilling	02465-800-0110	B-43	VLF	86	6.55	7.00	15.90
Trenching	02315-620-0150	B-53	LF	298	0.00	0.35	0.06
Sand on Clay Fill for Pouring Surface	02060-150-0400	B-15	CY	234	26.50	1.37	3.12
Backhoe	02305-250-1150	A-3D	EA	2	0.00	53.50	43.50
Equip, Exc., Labor, Conc., Rebar	02465-800-0110	B-43	VLF	79	11.7	7.35	16.75
Excav. (Bell Shape)	02465-800-1020	B-43	EA	19	36	70	159
Haul Exc.	02315-490-0200	B34-A	LCY	84.8	0	3.15	4.67
Excavation - Beam Trenches	02315-620-2850	B-54	LF	130	0	0.36	0.29
Haul Exc. Mat'l.	02315-490-0200	B34-A	LCY	56.8	0	3.15	4.67
Formwork							
Plywood (8"x8")	03110-410-5000	C-1	SFCA	1545	2.11	6.30	0.00
Shoring	03150-600-1000	2-CARP	EA	78	0.00	9.95	0.00
Scafolding	01540-750-0090	3-CARP	CSF	102	24.50	34.50	0.00
Form Ties and Clamps	N/A	3-CARP	EA	98	1.43	0.89	0.00
Reinforcement							
Rebar (footings)	03210-600-0500	4-RODM	TON	20	760	580	0.00
Rebar (slabs)	03210-600-0600	4-RODM	TON	20	760	530	0.00
Dowels	03210-600-2430	2-RODM	EA	342	1.32	1.69	0.00
Slip Covers for Dowels	03210-600-2620	1-RODM	EA	564	0.33	1.73	0.00
Anchor Bolts	03150-080-0400	1-CARP	EA	186	1.74	3.91	0.00
Concrete (incl admixtures)	03310-220-0150		CY	1550	81	0	0.00
Concrete Placement (pumped)	03310-700-3250	C-20	CY	1550	0	10.2	4.18
Concrete Finishing (machine trowel)	03350-300-0250	C-10B	SF	5850	0	0.48	0.00
Curing	03390-200-0200	2-CLAB	CSF	585	6	6.1	0.00

CONCRETE (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Daily Output	Duration (days)
Earthwork									
Drilling	02465-800-0110	563.30	1367.40	602.00	2532.70	0.240	20.64	200	0.430
Trenching	02315-620-0150	0.00	17.88	104.30	122.18	0.011	3.28	750	0.397
Sand on Clay Fill for Pouring Surface	02060-150-0400	6201.00	730.08	320.58	7251.66	0.047	11.00	600	0.390
Backhoe	02305-250-1150	0.00	87.00	107.00	194.00	2.000	4.00	4	0.500
Equip, Exc., Labor, Conc., Rebar	02465-800-0110	924.3	1323.25	580.65	2828.20	0.24	18.96	200	0.395
Excav. (Bell Shape)	02465-800-1020	684	3021	1330	5035.00	2.4	45.60	20	0.950
Haul Exc.	02315-490-0200	0	396.016	267.12	663.14	0.114	9.67	70	1.211
Excavation - Beam Trenches	02315-620-2850	0	37.7	46.8	84.50	0.011	1.43	725	0.179
Haul Exc. Mat'l.	02315-490-0200	0	265.256	178.92	444.18	0.114	6.4752	70	0.811
Formwork									
Plywood (8"x8")	03110-410-5000	3259.95	0.00	9733.5	12993.45	0.194	299.73	165	9.364
Shoring	03150-600-1000	0.00	0.00	776.10	776.10	0.291	22.698	55	1.418
Scafolding	01540-750-0090	2499.00	0.00	3519.00	6018.00	1.000	102	24	4.250
Form Ties and Clamps	N/A	140.14	0	87.22	227.36	0.029	2.842		
Reinforcement									
Rebar (footings)	03210-600-0500	15200	0	11600	26800	15.238	304.76	2.1	9.524
Rebar (slabs)	03210-600-0600	15200	0	10600	25800	13.193	263.86	2.3	8.696
Dowels	03210-600-2430	451.44	0	577.98	1029.42	0.044	15.048	360	0.950
Slip Covers for Dowels	03210-600-2620	186.12	0	975.72	1161.84	0.046	25.944	175	3.223
Anchor Bolts	03150-080-0400	323.64	0	727.26	1050.9	0.114	21.204	70	2.657
Concrete (incl admixtures)	03310-220-0150	125550	0	0	125550		0		
Concrete Placement (pumped)	03310-700-3250	0	6479	15810	22289	0.356	551.8	180	8.611
Concrete Finishing (machine trowel)	03350-300-0250	0	0	2808	2808	0.015	87.75	550	10.636
Curing	03390-200-0200	3510	0	3568.5	7078.5	0.168	98.28	70	8.357
			Concrete SubTotal		$251,000				

METALS

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Structural Steel								
Columns								
TS 4X4X1/4"	05120-260-4500	E-2	54	EA	30	144	35.5	23
TS 8x8x3/8"	05120-260-4600	E-2	50	EA	54	46	510	26.5
TS 5x3x1/4"	05120-260-5500	1 SSWK	58	EA	22	140	35.5	23
K-Bracing	05120-260-5200	E-2	12000	LB	585.6	0.88	0.17	0.11
Beams								
W12x14	05120-640-1100	E-2	880	LF	798	13.5	2.35	1.51
W14x22	05120-640-1900	E-2	990	LF	146	3.05	25	2.09
W8X10	05120-640-0300	E-2	600	LF	436	9.65	3.45	2.21
W16x40	05120-640-3100	E-2	800	LF	124.56	38.5	2.59	1.66
Connections								
3/4" A325 Bolts	05090-420-0250	1 SSWK	110	EA	102	1	2.77	
1" A325 Bolts	05090-420-0450	1-SSWK	95	EA	45	1.84	3.24	
Angles								
L4x4x3/8 by 12"long	05120-440-0400	E-3	440	LB	345	0.51	2.12	0.18
L4x4x3/8 by 6"long	05120-440-0400	E-3	440	LB	456	0.51	2.12	0.18
L2x2x1/4 (4")	05120-440-0716	E-3	89	LF	58	1.67	10.45	0.91
L3"x3"x3/8 (4")	05120-440-0476	E-3	57	LF	36	3.78	16.35	1.42
Metal Studs								
3 5/8" metal studs (16" o.c.)	05410-400-5110	2-CARP	77	LF	290	8.95	7.1	
6" metal studs	05410-400-5200	2-CARP	73	LF	40	14.15	7.5	
6" metal studs (16" o.c)	05410-400-7400	2-CARP	48	LF	250	25	11.4	
Metal Plates								
10x6x3/8 Bent PL w/ 6 1/2" Leg	05120-560-2200	E-4		CWT	13.8	41		
8x8x3/8 by 9" Long bent PL	05120-560-2200	E-4		CWT	8.42	41		

METALS (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Structural Steel								
Columns								
TS 4X4X1/4"	05120-260-4500	4320	690	1065	6075	0.966	28.98	0.556
TS 8x8x3/8"	05120-260-4600	2484	1431	27540	31455	1.12	60.48	1.080
TS 5x3x1/4"	05120-260-5500	3080	506	781	4367	0.966	21.252	0.379
K-Bracing	05120-260-5200	515.328	64.416	99.552	679.296	0.005	2.9280	0.049
Beams					0			
W12x14	05120-640-1100	10773	1204.98	1875.3	13853.28	0.064	51.072	0.907
W14x22	05120-640-1900	445.3	305.14	3650	4400.44	0.57	83.22	0.147
W8X10	05120-640-0300	4207.4	963.56	1504.2	6675.16	0.93	405.48	0.727
W16x40	05120-640-3100	4795.56	206.7696	322.6104	5324.94	0.07	8.7192	0.156
Connections								
3/4" A325 Bolts	05090-420-0250	102		282.54	384.54	0.073	7.446	0.927
1" A325 Bolts	05090-420-0450	82.8		145.8	228.6	0.084	3.78	0.474
Angles								
L4x4x3/8 by 12"long	05120-440-0400	175.95	62.1	731.4	969.45	0.055	18.975	0.784
L4x4x3/8 by 6"long	05120-440-0400	232.56	82.08	966.72	1281.36	0.055	25.08	1.036
L2x2x1/4 (4")	05120-440-0716	96.86		606.1	702.96	0.27	15.66	0.652
L3"x3"x3/8 (4")	05120-440-0476	136.08		588.6	724.68	0.421	15.156	0.632
Metal Studs								
3 5/8" metal studs (16" o.c.)	05410-400-5110	2595.5		2059	4654.5	0.208	60.32	3.766
6" metal studs	05410-400-5200	566		300	866	0.219	8.76	0.548
6" metal studs (16" o.c)	05410-400-7400	6250		2850	9100	0.333	83.25	5.208
Metal Plates								
10x6x3/8 Bent PL w/ 6 1/2" Leg	05120-560-2200	565.8			565.8	0.007	0.0966	
8x8x3/8 by 9" Long bent PL	05120-560-2200	345.22			345.22	0.007	0.05894	

METALS (Continued)

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
10 1/2x6x3/8 Bent PL w/ 6 1/5"leg	05120-560-2200	E-4		CWT	12.9	41		
12x6x3/8 Bent PL w/ 6 1/5"leg	05120-560-2200	E-4		CWT	17.34	41		
4x9x5/16 PL	05120-560-2150	E-4		CWT	8	43		
4x12x3/8 PL	05120-560-2200	E-4		CWT	7	41		
Base Plate (1/2" A36 Plate)	05120-560-2250	E-4		CWT	7.45	41.00		
Typical Anchor Bolt (3/4"x18")	05090-080-0310	2 CARP	40	EA	106	1.67	13.7	
Steel Joists								
8K1	05210-600-0130	E-7	1200	LF	524.50	3.11	2.50	1.24
10K1	05210-600-0140	E-7	1200	LF	236	3.05	2.50	1.24
Steel Decking								
1.5 B22 Steel Decking	05310-300-2100	E-4	4500	SF	3530	1.47	0.27	0.02
Fencing	02820-410-0300	B-80C	300	LF	685	2.95	2.14	
Roof Framing	05420-300-0300	2-CARP	180	L.F	254.8	7.15	3.04	
Roof Trusses	05425-600-1250	2-CARP	7	EA	13	166.00	78.50	
Boxed Headers/Beams	05420-300-0500	2-CARP	110	LF	134.5	13.20	4.98	
Joists	05420-410-1240	2 CARP	80	EA	24	6.85		
Web Stiffener	05420-500-5330	1-CARP	65	EA	36	5.15	4.22	
Fireproofing								
Columns	07812-600-0800	G-2	700	SF	305	0.88	0.97	0.15
Beams	07812-600-0400	G-2	1500	SF	548	0.41	0.45	0.07
Decking	07812-600-0200	G-2	2400	SF	3530	0.41	0.28	0.04
Galvanizing Structural Steel	05950-650-6100	1-PSST	1100	SF	5045	0.07	0.23	

METALS (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
10 1/2x6x3/8 Bent PL w/ 6 1/5"leg	05120-560-2200	528.9			528.9	0.007	0.0903	
12x6x3/8 Bent PL w/ 6 1/5"leg	05120-560-2200	710.94			710.94	0.007	0.12138	
4x9x5/16 PL	05120-560-2150	344			344	0.008	0.064	
4x12x3/8 PL	05120-560-2200	287			287	0.007	0.049	
Base Plate (1/2" A36 Plate)	05120-560-2250	305.45			305.45	0.007	0.05215	
Typical Anchor Bolt (3/4"x18")	05090-080-0310	177.02		1452.2	1629.22	0.4	42.4	2.650
Steel Joists								
8K1	05210-600-0130	1631.20	650.38	1311.25	3592.825	0.067	35.1415	0.437
10K1	05210-600-0140	719.8	292.64	590	1602.44	0.067	15.812	0.197
Steel Decking								
1.5 B22 Steel Decking	05310-300-2100	5189.1	70.6	953.1	6212.8	0.007	24.71	0.784
Fencing	02820-410-0300	2020.75		1465.9	3486.65	0.08	54.8	2.283
Roof Framing	05420-300-0300	1821.82		774.592	2596.412	0.089	22.6772	1.416
Roof Trusses	05425-600-1250	2158		1020.5	3178.5	2.286	29.718	1.857
Boxed Headers/Beams	05420-300-0500	1775.4		669.81	2445.21	0.145	19.5025	1.223
Joists	05420-410-1240	164.4			164.4	0.2	4.8	0.300
Web Stiffener	05420-500-5330	185.4		151.92	337.32	0.123	4.428	0.554
Fireproofing								
Columns	07812-600-0800	268.4	45.75	295.85	610	0.034	10.37	0.436
Beams	07812-600-0400	224.68	38.36	246.6	509.64	0.016	8.768	0.365
Decking	07812-600-0200	1447.3	141.2	988.4	2576.9	0.1	353	1.471
Galvanizing Structural Steel	05950-650-6100	353.15		1160.35	1513.5	0.007	35.315	4.586
				Metal SubTotal	$127,000			

THERMAL AND MOISTURE PROTECTION

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Bituminous Dampproofing								
Bituminous Asphalt Coating	07110-100-0100	1-ROFC	500	SF	3530	0.1	0.47	
Cold Applied Emulsion	07520-200-0800			GAL	3	4.25		
Elastomeric Sheet Roofing	07130-200-1500	1-ROFC	580	SF	3530	1.2	0.81	
Building Insulation								
Rigid Thermal Insulation	07220-700-1715	1-ROFC	1250	SF	1265.42	0.8	0.27	
Flexible Thermal Insulation	07210-950-0460	1-CARP	1350	SF	2264.58	0.45	0.2	
Tappered Rigid Insulation	07220-700-1600	1-ROFC	600	BF	95	1.1	0.39	
Masonry Insulation	07210-550-0100	D-1	4800	SF	452	0.19	0.1	
Composite Panels								
Aluminium Panel Fascia	07460-300-0100	1-SHEE	145	SF	243.56	2.14	2.22	
Aluminium Soffit	07460-750-0010	1-CARP	210	SF	243.56	1.01	1.3	
Steel Siding	07460-800-1500	G-3	380	SF	855.5	4.66	2.82	
Modified Bitumen Roofing								
Modified Bitumen Roofing	07550-500-1500	G-1	3000	SF	3530	0.42	0.77	0.15
Roof Insulation	07220-700-1715	1-ROFC	2250	SF	3530	0.35	0.19	
Sheet Metal								
Membrane Flashing	07510-700-0600	1-ROFC	16	SQ	75.3	25	14.75	
Zinc Roofing (copper alloy)	07610-900-0400	1-SHEE	1.05	SQ	26.35	835	305	
Joint Sealers								
Acrylic Latex Caulk Sealant	07920-800-0200			EA	40	1.88		
Silicon Rubber Sealant	07920-800-4200			GAL	6	40.5		
Acoustical Sealant	07920-800-0020			EA	4	2.21		

THERMAL AND MOISTURE PROTECTION (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Bituminous Dampproofing								
Bituminous Asphalt Coating	07110-100-0100	353		1659.1	2012.1	0.016	56.48	7.06
Cold Applied Emulsion	07520-200-0800	12.75			12.75			
Elastomeric Sheet Roofing	07130-200-1500	4236		2859.3	7095.3	0.028	98.84	0.164
Building Insulation								
Rigid Thermal Insulation	07220-700-1715	1012.34		341.663	1354	0.008	10.123	0.988
Flexible Thermal Insulation	07210-950-0460	1019.061		452.916	1472	0.006	13.588	0.596
Tappered Rigid Insulation	07220-700-1600	104.5		37.05	141.55	0.013		6.316
Masonry Insulation	07210-550-0100	85.88		45.2	131.08	0.003		10.619
Composite Panels								
Aluminium Panel Fascia	07460-300-0100	521.218		540.703	1061.9	0.055	13.396	0.595
Aluminium Soffit	07460-750-0010	245.995		316.628	562.62	0.38	92.553	0.862
Steel Siding	07460-800-1500	3986.63		2412.51	6399.1	0.084	71.862	0.444
Modified Bitumen Roofing								
Modified Bitumen Roofing	07550-500-1500	1482.6	529.5	2718.1	4730.2	0.028	98.84	0.849
Roof Insulation	07220-700-1715	1235.5		670.7	1906.2	0.006	21.18	0.637
Sheet Metal								
Membrane Flashing	07510-700-0600	1882.5		1110.675	2993.2	0.5	37.65	0.212
Zinc Roofing (copper alloy)	07610-900-0400	22002.25		8036.75	30039	7.619	200.761	0.039
Joint Sealers								
Acrylic Latex Caulk Sealant	07920-800-0200	75.2			75.2			
Silicon Rubber Sealant	07920-800-4200	243			243			
Acoustical Sealant	07920-800-0020	8.84			8.84			
			Sub Total		$60,000			

MECHANICAL

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Heating, Ventilating and Cooling								
Exhaust Fan	15830-100-2540	Q-20	19	EA	3.00	143.00	37.00	
Supply Grille	15850-500-3000	1-SHEE	24	EA	9.00	39.00	13.40	
Return Grille	15850-500-1000	1-SHEE	26	EA	6.00	13.00	12.35	
Roof Top Unit	15760-500-0500	Q-6	0.8	EA	2.00	5535.00	1150.00	
Centrifugal Roof Fans	15830-100-7100	Q-20	7	EA	4.00	320.00	106.00	
Duct Heater	15760-200-0100	Q-20	16	EA	2.00	540.00	46.50	
Electric Heater	15760-250-1400	1-ELEC	8	EA	2.00	34.50	41.00	
Fire/Smoke Damper	15820-300-3000	1-SHEE	24	EA	8.00	13.40	13.40	
Air Devices (ceiling/walls)								
Air Supply	15850-700-1120	1-SHEE	18	EA	4.00	34.00	17.85	
Air Return	15850-700-5060	1-SHEE	19	EA	2.00	26.00	16.95	
New Ductwork	15810-100-0110	Q-10	80	LB	360.00	2.00	11.25	
Flexible Ducts	15810-500-1910	Q-9	340	LF	238.50	1.23	1.70	
Testing Adjusting and Balancing of Air Systems and Measurement of Final Operating Conditions of HVAC systems	N/A							
Mechanical Identification	N/A							
Plumbing								
Backflow Preventer	15140-100-5660	Q-10	5	EA	1.00	1750.00	118.00	
1" Water Meter	15120-940-2100	1-PLUM	12	EA	1.00	94.00	27.00	
Ball Valve	15110-160-1480	1-PLUM	15		11.00	17.15	22.00	
Pressure Valve	15110-160-6000	1-PLUM	30	EA	7.00	13.55	10.90	
Union for pipe	15107-420-2300	1-PLUM	56	LF	76.00	17.25	10.50	
Water Hammer Arrestor	15120-800-0800	1-PLUM	8	EA	8.00	58.50	41.00	
Floor Drain w/sediment bucket	15150-300-2420	Q-1	9	EA	4.00	272.00	65.50	
Vent Flashing	15150-900-1050	1-PLUM	17	EA	13.00	7.90	19.20	

MECHANICAL (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Heating, Ventilating and Cooling								
Exhaust Fan	15830-100-2540	429.00		111.00	540.00	1.053	3.159	0.158
Supply Grille	15850-500-3000	351.00		120.60	471.60	0.333	2.997	0.375
Return Grille	15850-500-1000	78.00		74.10	152.10	0.308	1.848	0.231
Roof Top Unit	15760-500-0500	11070.00		2300.00	13370.00	30.000	60	2.5
Centrifugal Roof Fans	15830-100-7100	1280.00		424.00	1704.00		0	0.571
Duct Heater	15760-200-0100	1080.00		93.00	1173.00	1.250	2.5	0.125
Electric Heater	15760-250-1400	69.00		82.00	151.00	1.000	2	0.25
Fire/Smoke Damper	15820-300-3000	107.20		107.20	214.40	0.333	2.664	0.333
Air Devices (ceiling/walls)								
Air Supply	15850-700-1120	136.00		71.40	207.40	0.444	1.776	0.222
Air Return	15850-700-5060	52.00		33.90	85.90	0.421	0.842	0.105
New Ductwork	15810-100-0110	720.00		4050.00	4770.00	0.300	108	4.5
Flexible Ducts	15810-500-1910	293.36		405.45	698.81	0.470	112.095	0.701
Testing Adjusting and Balancing of Air Systems and Measurement of Final Operating Conditions of HVAC systems	N/A				1978.00			
Mechanical Identification	N/A				1250.00			
Plumbing								
Backflow Preventer	15140-100-5660	1750.00		118.00	1868.00	3.200	3.2	0.2
1" Water Meter	15120-940-2100	94.00		27.00	121.00	0.667	0.667	0.083
Ball Valve	15110-160-1480	188.65		242.00	430.65	0.533	5.863	0.733
Pressure Valve	15110-160-6000	94.85		76.30	171.15	0.267	1.87	0.233
Union for pipe	15107-420-2300	1311.00		798.00	2109.00	0.286	21.74	1.357
Water Hammer Arrestor	15120-800-0800	468.00		328.00	796.00	1.000	8.00	1
Floor Drain w/sediment bucket	15150-300-2420	1088.00		262.00	1350.00	1.778	7.11	0.444
Vent Flashing	15150-900-1050	102.70		249.60	352.30	0.471	6.12	0.765

MECHANICAL (Continued)

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Cast Iron Vent Caps	15150-900-0180	1-PLUM	21	EA	28.00	35.00	15.55	
P- Trap Standard Pattern	15150-800-5240	1-PLUM	17	EA	4.00	27.00	19.20	
4" P-Trap	15150-800-1150	Q1	13	EA	10.00	70.00	45.50	
2" P-Trap	15150-800-1100	Q1	16	EA	8.00	25.00	37.00	
Clean-out Tee	15150-250-0200	1-PLUM	4	EA	17.00	105.00	81.50	
Water Closets (WC-2)	15418-900-0200	Q-1	5.3	EA	14.00	390.00	111.00	
Water Closets (WC-1)	15418-900-1000	Q-1	5.3	EA	12.00	495.00	111.00	
Urinals	15411-700-3100	Q-1	3	EA	10.00	298.00	196.00	
Electric Water Coolers	15413-900-0160	Q-1	4	EA	5.00	630.00	147.00	
Water Heaters	15480-200-4140	Q-1	1.8	EA	1.00	2475.00	182.00	
Sinks w/faucets and drains (incl service sinks)	15418-600-4960	Q-1	4.8	EA	8.00	161.70	123.00	
3" Roof Drain	15160-500-3890	Q-1	14	EA	9.00	155.00	42.00	
4" Roof Drain	15160-500-5000	Q-1	16	EA	1.00	111.00	37.00	
Downspout	07710-400-4800	1-SHEE	190	LF	385.50	0.75	1.69	
Mechanical Insulation								
Duct Insulation	15080-200-3070	Q-14	320	SF	456.45	0.88	1.67	
Insulation Jacket	15080-200-3320	Q-14	330	SF	456.45	0.45	1.62	
Duct Liner	15080-200-3520	Q-14	150	SF	456.45	1.44	3.56	
Piping Insulation	15080-600-6870	Q-14	220	LF	837.00	0.83	2.43	

MECHANICAL (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Cast Iron Vent Caps	15150-900-0180	980.00		435.40	1415.40	0.381	10.67	1.333
P- Trap Standard Pattern	15150-800-5240	108.00		76.80	184.80	0.471	1.88	0.235
4" P-Trap	15150-800-1150	700.00		455.00	1155.00	1.231	12.31	0.769
2" P-Trap	15150-800-1100	200.00		296.00	496.00	2.231	17.85	0.5
Clean-out Tee	15150-250-0200	1785.00		1385.50	3170.50	2.000	34.00	4.25
Water Closets (WC-2)	15418-900-0200	5460.00		1554.00	7014.00	3.019	42.27	2.641
Water Closets (WC-1)	15418-900-1000	5940.00		1332.00	7272.00	3.019	36.23	2.264
Urinals	15411-700-3100	2980.00		1960.00	4940.00	5.333	53.33	3.333
Electric Water Coolers	15413-900-0160	3150.00		735.00	3885.00	4.000	20.00	1.25
Water Heaters	15480-200-4140	2475.00		182.00	2657.00	4.444	4.44	0.556
Sinks w/faucets and drains (incl service sinks)	15418-600-4960	1293.60		984.00	2277.60	3.333	26.66	1.667
3" Roof Drain	15160-500-3890	1395.00		378.00	1773.00	1.143	10.29	0.645
4" Roof Drain	15160-500-5000	111.00		37.00	148.00	1.000	1.00	0.063
Downspout	07710-400-4800	289.13		651.50	940.62	0.042	16.19	2.029
Mechanical Insulation								
Duct Insulation	15080-200-3070	401.68		762.27	1163.95	0.050	22.822	1.426
Insulation Jacket	15080-200-3320	205.40		739.45	944.85	0.052	23.74	1.383
Duct Liner	15080-200-3520	657.29		1624.96	2282.25	0.107	48.84	3.043
Piping Insulation	15080-600-6870	694.71		2033.91	2728.62	0.073	61.10	3.805
			Sub Total		$78,000			

MASONRY

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Standard Face Brick (including mortar)	04810-650-0800	D-8	215	SF	2035.00	2.83	5.95	
Gypsum Board	09250-700-0500	2-CARP	2000	SF	2035.00	0.22	0.27	
1/2 " Exterior Gypsum	09250-200-0080	2-CARP	525	SF	1485.00	1.04	1.04	
Plastic Membrane Flashing	07130-200-2500	2-ROFC	570	SF	2035.00	0.22	0.83	
Wall Ties	04080-650-0010	1-BRIC	10.5	C	23.00	5.75	27.00	
CMU - 8" Bond Beam (w/ 2000psi grout and 2#5 bars)	04810-175-2150	D-9	250	LF	20.00	2.57	2.87	
CMU-12" Bond Beam (w/ 2000psi grout and 2#6 bars)	04810-175-2550	D-9	255	LF	12.00	4.62	5.85	
CMU - 8"x16"x8" thick Back-up Reinforced Block	04810-172-1150	D-8	395	SF	112.00	1.67	3.23	
Decorative Block - 8"x16"x4" thick(split 8 fluted, score add on)	04810-182-6100	D-8	350	SF	152.00	2.03	3.65	
Grout	04070-420-0250	D-4	680	SF	152.00	0.85	1.44	0.20
Grout (Steel Door and Window Frames)	04070-420-0850	D-4	45	SF	94.00	11.55	21.50	
Reinforcing Steel (#4 bars 32")	04080-200-0010	1-BRIC	450	LB	252.00	0.40	0.63	
Bituminous Dampproofing	07110-100-0600	1-ROFC	500	SF	152.00	0.16	0.47	
Masonry Cleaning	04930-220-0400	B-9	2000	SF	964.70	0.00	0.54	0.07
Scaffolding	01540-755-3000			EA	3.00	1150.00	0.00	

MASONRY (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Standard Face Brick (including mortar)	04810-650-0800	5759.05		12108.25	17867.30	0.186	378.51	9.465
Gypsum Board	09250-700-0500	447.70		549.45	997.15	0.008	16.28	1.018
1/2 " Exterior Gypsum	09250-200-0080	1544.40		1544.40	3088.80	0.03	44.55	2.829
Plastic Membrane Flashing	07130-200-2500	447.70		1689.05	2136.75	0.028	56.98	3.570
Wall Ties	04080-650-0010	132.25		621.00	753.25	0.762	17.53	2.190
CMU - 8" Bond Beam (w/ 2000psi grout and 2#5 bars)	04810-175-2150	51.40		57.40	108.80	0.092	1.84	0.080
CMU-12" Bond Beam (w/ 2000psi grout and 2#6 bars)	04810-175-2550	55.44		70.20	125.64	0.188	2.26	0.047
CMU - 8"x16"x8" thick Back-up Reinforced Block	04810-172-1150	187.04		361.76	548.80	0.101	11.31	0.284
Decorative Block - 8"x16"x4" thick(split 8 fluted, score add on)	04810-182-6100	308.56		554.80	863.36	0.114	17.33	0.434
Grout	04070-420-0250	129.20	30.40	218.88	378.48	0.047	7.14	0.224
Grout (Steel Door and Window Frames)	04070-420-0850	1085.70		2021.00	3106.70	0.711	66.83	2.089
Reinforcing Steel (#4 bars 32")	04080-200-0010	100.80		158.76	259.56	0.04	10.08	0.560
Bituminous Dampproofing	07110-100-0600	24.32		71.44	95.76	0.016	2.43	0.304
Masonry Cleaning	04930-220-0400		67.53	520.94	588.47	0.02	19.29	0.482
Scaffolding	01540-755-3000	3450.00			3450.00			
			Masonry Sub Total		$44,000			

DOORS AND WINDOWS

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Doors and Finish Hardware								
Type A Door (3.0x7.2), SCTF	08210-900-2480	2-CARP	12	EA	3	124.50	45.50	
Type A Door (3.0x7.2), HMPF	08110-200-0640	2-CARP	17	EA	1	197.00	32.00	
Type B Door (3.0x7.2), SCTF	08210-900-2480	2-CARP	12	EA	1	124.50	45.50	
Type C Door (3.0x7.2), ALUM	08410-130-0020	2-SSWK	2	EA	3	535.00	305.00	
Type D Door (3.0x7.2), ALUM	08410-130-0520	2-SSWK	2	EA	1	715.00	305.00	
Type E Door (4 1/2 x 7.2), ALUM	08410-130-0560	2-SSWK	2	EA	3	760.00	305.00	
Door Frames								
Hollow Metal, Paint Finish	08110-200-0640	2-CARP	17	EA	6	197.00	32.00	
Aluminium, Bronze Anodized Finish	08180-100-0500	2-CARP	14	EA	6	184.80	0.00	
Aluminium Entrances and Storefronts								
Aluminium Storefronts	08410-110-0020	2-SSWK	7	OPNG	10	243.00	87.00	
Overhead Coiling Grille								
Aluminium Top Coiling (6' long)	08330-640-0030	2-SSWK	3.2	0PNG	1	1175.00	191.00	
Windows (incl frames and glazing)								
Aluminium Enamel Finish (4'-5"x5'x3")	08520-120-2500	2-SSWK	10	EA	1	287.00	76.50	
9'x5' Opening (standard glazed)	08520-120-5000)	2-SSWK	4	EA	3	445.00	153.00	
3'x5'-4" Standard Glass	08520-120-3930	2-SSWK	10	EA	1	495.00	61.00	
2'-8"x6'-8" Opening (standard glazed)	08520-120-3300	2-SSWK	8	EA	2	305.00	76.50	
12'-0"x6'-0"	08550-150-2100	2-CARP	6	EA	3	1775.00	91.50	

DOORS AND WINDOWS (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Doors and Finish Hardware								
Type A Door (3.0x7.2), SCTF	08210-900-2480	373.50		136.50	510.00	1.333	4.00	0.250
Type A Door (3.0x7.2), HMPF	08110-200-0640	197.00		32.00	229.00	0.941	0.94	0.059
Type B Door (3.0x7.2), SCTF	08210-900-2480	124.50		45.50	170.00	1.333	1.33	0.083
Type C Door (3.0x7.2), ALUM	08410-130-0020	1605.00		915.00	2520.00	8.000	24.00	1.500
Type D Door (3.0x7.2), ALUM	08410-130-0520	715.00		305.00	1020.00	8.000	8.00	0.500
Type E Door (4 1/2 x 7.2), ALUM	08410-130-0560	2280.00		915.00	3195.00	8.000	24.00	1.500
Door Frames								
Hollow Metal, Paint Finish	08110-200-0640	1182.00		192.00	1374.00	0.941	5.65	0.353
Aluminium, Bronze Anodized Finish	08180-100-0500	1108.80		0.00	1108.80	1.143	6.86	0.429
Aluminium Entrances and Storefronts								
Aluminium Storefronts	08410-110-0020	2430.00		870.00	3300.00	2.386	23.86	1.429
Overhead Coiling Grille								
Aluminium Top Coiling (6' long)	08330-640-0030	1175.00		191.00	1366.00	5.000	5.00	0.313
Windows (incl frames and glazing)								
Aluminium Enamel Finish (4'-5"x5'x3")	08520-120-2500	287.00		76.50	363.50	2.000	2.00	0.100
9'x5' Opening (standard glazed)	08520-120-5000)	1335.00		459.00	1794.00	4.000	12.00	0.750
3'x5'-4" Standard Glass	08520-120-3930	495.00		61.00	556.00	1.778	1.78	0.100
2'-8"x6'-8" Opening (standard glazed)	08520-120-3300	610.00		153.00	763.00	2.000	4.00	0.250
12'-0"x6'-0"	08550-150-2100	5325.00		274.50	5599.50	2.667	8.00	0.500
		Doors and Windows SubTotal			$29,000			

FINISHES

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Suspended Acoustical Ceiling								
Grid Suspension System (incl fire rated grid)	09130-100-0360	1-CARP	650	SF	2513	0.69	0.42	
Ceiling Panels	09250-500-0400	1-CARP	615	SF	2513	0.25	0.89	
Hanging Wire	09130-100-1040	1-CARP	65	CSF	25.13	5.25	4.22	
Recessed Light Fixtures	09130-100-0900	1-CARP	65	SF	2513	0.23	0.6	
Suspended Metal Woven Lay-In Panels (10'x2")	10605-100-0900	2-CARP	25	EA	1	93.5	22	
Suspended Metal Woven Lay-In Panels (10'x4')	10605-100-1000	2-CARP	15	EA	1	114	36.5	
Gypsum Wall Board Ceiling	09250-500-0700	2-CARP	600	SF	585.6	0.87	0.91	
Fire Resistant Gypsum Board	09250-700-2050	2-CARP	965	SF	1870	0.27	0.57	
Water Resistant Gypsum Board	09250-700-2200	2-CARP	2000	SF	780.5	0.26	0.27	
Furring Beams and Columns	09205-530-0030	1-LATH	170	SF	786	0.24	1.62	
Furring Ceilings	09205-530-0100	1-LATH	210	SF	2102	0.22	1.2	
Portland Cement Plaster	09220-200-1000	J-1	200	SY	243.5	3.25	5.95	0.52
Resilient Tile Flooring	09658-100-7550	1-TILF	500	SF	540	3.45	0.52	
Standard Colors Resilient Base	09651-200-1150	1-TILF	315	LF	735.5	0.51	0.83	
Resilient Base Corners	09651-200-1600	1-TILF	315	EA	12	1.17	0.83	
Resilient Sheet Flooring	09653-100-8700	1-TILF		GAL	2	16.35		
Concrete Floor Sealer	03060-100-1600			GAL	3	7.1		
Floor Tile	09310-100-3310	D-7	190	SF	975	4.07	2.44	
Wall Tile	09310-100-5800	D-7	200	SF	1070	2.37	2.62	
Carpet Pad	09680-600-9000	1-TILF	150	SY	465.5	8.25	1.74	
Carpet	09680-800-3730	1-TILF	70	SY	465.5	22	3.74	

FINISHES (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Suspended Acoustical Ceiling								
Grid Suspension System (incl fire rated grid)	09130-100-0360	1733.97		1055.46	2789.4	0.012	30.156	3.866
Ceiling Panels	09250-500-0400	628.25		2236.57	2864.8	0.026	65.338	4.086
Hanging Wire	09130-100-1040	131.9325		106.0486	237.98	0.123	3.09099	0.387
Recessed Light Fixtures	09130-100-0900	577.99		1507.8	2085.8	0.017	42.721	38.662
Suspended Metal Woven Lay-In Panels (10'x2")	10605-100-0900	93.5		22	115.5	0.64	0.64	0.040
Suspended Metal Woven Lay-In Panels (10'x4')	10605-100-1000	114		36.5	150.5	1.067	1.067	0.067
Gypsum Wall Board Ceiling	09250-500-0700	509.472		532.896	1042.4	0.027	15.8112	0.976
Fire Resistant Gypsum Board	09250-700-2050	504.9		1065.9	1570.8	0.017	31.79	1.938
Water Resistant Gypsum Board	09250-700-2200	202.93		210.735	413.67	0.008	6.244	0.390
Furring Beams and Columns	09205-530-0030	188.64		1273.32	1462	0.052	40.872	4.624
Furring Ceilings	09205-530-0100	462.44		2522.4	2984.8	0.038	79.876	10.010
Portland Cement Plaster	09220-200-1000	791.375	126.62	1448.825	2366.8	0.2	48.7	1.218
Resilient Tile Flooring	09658-100-7550	1863		280.8	2143.8	0.016	8.64	1.080
Standard Colors Resilient Base	09651-200-1150	375.105		610.465	985.57	0.025	18.3875	2.335
Resilient Base Corners	09651-200-1600	14.04		9.96	24	0.025	0.3	0.038
Resilient Sheet Flooring	09653-100-8700	32.7		0	32.7		0	
Concrete Floor Sealer	03060-100-1600	21.3		0	21.3		0	
Floor Tile	09310-100-3310	3968.25		2379	6347.3	0.084	81.9	5.132
Wall Tile	09310-100-5800			2803.4		0.08	85.6	5.350
Carpet Pad	09680-600-9000	3840.375		809.97	4650.3	0.53	246.715	3.103
Carpet	09680-800-3730	10241		1740.97	11982	0.114	53.067	6.650

FINISHES (Continued)

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Cabinets	09910-100-1000	1-PORD	650	SF	302	0.05	0.38	
Doors and Windows (frames)	09910-300-0130	1-PORD	300	LF	88	0.11	0.82	
Doors	09910-300-0310	1-PORD	3	EA	20	12.5	81.5	
Windows	09910-300-0450	1-PORD	6	EA	28	2.46	49	
Miscellaneous	09910-630-2600	2-PORD	6000	SF	34	0.06	0.08	
Masonry (CMU)	09910-910-0480	1-PORD	2990	SF	157.5	0.03	0.08	
Concrete Wall or Plaster	09910-920-0840	1-PORD	800	SF	344.8	0.1	0.31	
Ceiling	09910-940-0490	1 PORD	650	SF	3099	0.09	0.38	
Structural Steel	09910-940-0580	1-PORD	1040	SF	876	0.09	0.24	
Glazed Coatings	09963-200-0100	1-PORD	525	SF	832.9	0.26	0.47	
Structural Steel	05950-650-6540	2-PSST	3200	SF	243	0.05	0.16	

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Cabinets	09910-100-1000	15.1		114.76	129.86	0.012	3.624	0.465
Doors and Windows (frames)	09910-300-0130	9.68		72.16	81.84	0.27	23.76	0.293
Doors	09910-300-0310	250		1630	1880	2.667	53.34	6.667
Windows	09910-300-0450	68.88		1372	1440.9	1.6	44.8	4.667
Miscellaneous	09910-630-2600	2.04		2.72	4.76	0.14	4.76	0.006
Masonry (CMU)	09910-910-0480	4.7235		12.596	17.32	0.003	0.47235	0.053
Concrete Wall or Plaster	09910-920-0840	34.48		106.888	141.37	0.01	3.448	0.431
Ceiling	09910-940-0490	278.874		1177.468	1456.3	0.012	37.1832	4.767
Structural Steel	09910-940-0580	78.84		210.24	289.08	0.008	7.008	0.842
Glazed Coatings	09963-200-0100	216.5436		391.4442	607.99	0.015	12.4929	1.586
Structural Steel	05950-650-6540	12.15		38.88	51.03	0.005	1.215	0.076
			Finishes	Sub Total	$50,000			

WOOD AND PLASTICS

Project Component	Means Reference Number	Crew	Daily Output	Qty	Unit	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Wood Blocking	06110-100-2740	1-CARP	1.4	15	MBF	510	1950	
Wood and Plastic Fastenings								
Dry Wall Nails	06090-600-1400			20	LB	0.79		
Finish Nails	06090-600-1800			28	LB	0.94		
Siding Nails	06090-600-3600			25	LB	1.45		
Roofing Nails	06090-600-2900			12	LB	1.35		
Sheet Metal Screws	06090-700-0700			15	LB	10.2		
Wood Screws	06090-750-0600			20	LB	7.65		
Plastic Laminate Covered Casework								
Cabinet Units	06410-100-1800	2-CARP	18	12	EA	291	29	
Cabinet Hardware	06410-230-2240	2-CARP	68	26	EA	6.95	4.03	
Solid Surface Countertops	06620-810-0700	2-CARP	23	44	LF	48	24	
Millwork								
Exterior Moldings	06220-500-3100	1-CARP	200	78	LF	1	1.37	
Door Moldings	06220-800-2800	1-CARP	17	15	SET	81	16.1	
Window Trim Set	06220-800-5950	1-CARP	10	10	OPNG	23.5	27.5	

WOOD AND PLASTICS (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Wood Blocking	06110-100-2740	7650.00		29250.00	36900.00	0.154	2.31	10.71
Wood and Plastic Fastenings		0.00		0.00	0.00			
Dry Wall Nails	06090-600-1400	15.80		0.00	15.80			
Finish Nails	06090-600-1800	26.32		0.00	26.32			
Siding Nails	06090-600-3600	36.25		0.00	36.25			
Roofing Nails	06090-600-2900	16.20		0.00	16.20			
Sheet Metal Screws	06090-700-0700	153.00		0.00	153.00			
Wood Screws	06090-750-0600	153.00		0.00	153.00			
Plastic Laminate Covered Casework		0.00		0.00	0.00			
Cabinet Units	06410-100-1800	3492.00		348.00	3840.00	0.023	0.28	0.67
Cabinet Hardware	06410-230-2240	180.70		104.78	285.48	0.118	3.07	0.38
Solid Surface Countertops	06620-810-0700	2112.00		1056.00	3168.00	0.696	30.62	1.91
Millwork								
Exterior Moldings	06220-500-3100	78.00		106.86	184.86	0.040	3.12	0.39
Door Moldings	06220-800-2800	1215.00		241.50	1456.50	0.470	7.05	0.88
Window Trim Set	06220-800-5950	235.00		275.00	510.00	0.800	8.00	1.00
		Wood and Plastics Sub Total			$45,000			

SPECIALTIES

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Plastic Laminate Toilet Compartment								
Floor Mounted plastic laminate	10165-100-1800	2-CARP	7	EA	20.00	585.00	78.50	
Handicap Units (PLB)	10165-100-1400	2-CARP	5	EA	6.00	287.00	110.00	
Headrails	10165-100-5400	2-CARP	8	EA	26.00	355.00	68.50	
Urinal Screen	10165-100-4800	2-CARP	8	EA	10.00	293.00	68.50	
Pilaster (for concealing floor fastenings)	10165-100-5900	2-CARP	10	EA	30.00	360.00	55.00	
Toilet Accessories								
Surface Mounted Hand Dryer	10810-100-2300	1-CARP	4	EA	6.00	485.00	68.50	
Diaper Changing Station	10810-100-0400	1-CARP	10	EA	2.00	174.00	27.50	
Dispenser units, mirror and shelf	10810-100-0500	1-CARP	10	EA	30.00	330.00	27.50	
Hat and Coat Strip	10810-100-2600	1-CARP	24	EA	20.00	48.00	11.40	
Towel Dispenser	10810-100-6700	1-CARP	16	EA	16.00	41.00	17.15	
Toilet Paper Dispenser	10810-100-6100	1-CARP	30	EA	26.00	10.80	9.15	
Waste Receptacle	10810-100-8100	1-CARP	8	EA	8.00	345.00	34.50	
Mirror (with stainless steel)	10810-100-3100	1-CARP	15	EA	4.00	104.00	18.25	
Grab Bars	10810-100-0800	1-CARP	24	EA	52.00	18.75	11.40	
Fire Protection								
Fire Extnguishers	10525-300-1080			EA	22.00	80.00		
Fire Equipment Cabinets	10525-200-5100	Q-12	5	EA	16.00	265.00	117.00	
Louvers and Vents	10210-800-2340	1-CARP	200	LF	86.50	0.44	1.37	
Air Conditioning Grille	10275-150-1100	1-CARP	17	EA	13.00	58.00	16.10	
Aluminium Flagpole	10355-400-0100	K-1	2	EA	8.00	820.00	244.00	88.00

SPECIALTIES (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Plastic Laminate Toilet Compartment								
Floor Mounted plastic laminate	10165-100-1800	11700.00	0.00	1570.00	13270.00	2.286	45.72	2.86
Handicap Units (PLB)	10165-100-1400	1722.00	0.00	660.00	2382.00	3.200	19.20	1.20
Headrails	10165-100-5400	9230.00	0.00	1781.00	11011.00	2.000	52.00	3.25
Urinal Screen	10165-100-4800	2930.00	0.00	685.00	3615.00	2.000	20.00	1.25
Pilaster (for concealing floor fastenings)	10165-100-5900	10800.00	0.00	1650.00	12450.00	1.600	48.00	3.00
Toilet Accessories								
Surface Mounted Hand Dryer	10810-100-2300	2910.00	0.00	411.00	3321.00	2.000	12.00	1.50
Diaper Changing Station	10810-100-0400	348.00	0.00	55.00	403.00	0.800	1.60	0.20
Dispenser units, mirror and shelf	10810-100-0500	9900.00	0.00	825.00	10725.00	0.800	24.00	3.00
Hat and Coat Strip	10810-100-2600	960.00	0.00	228.00	1188.00	0.333	6.66	0.83
Towel Dispenser	10810-100-6700	656.00	0.00	274.40	930.40	0.500	8.00	1.00
Toilet Paper Dispenser	10810-100-6100	280.80	0.00	237.90	518.70	0.267	6.94	0.87
Waste Receptacle	10810-100-8100	2760.00	0.00	276.00	3036.00	1.000	8.00	1.00
Mirror (with stainless steel)	10810-100-3100	416.00	0.00	73.00	489.00	0.533	2.13	0.27
Grab Bars	10810-100-0800	975.00	0.00	592.80	1567.80	0.333	17.32	2.17
Fire Protection								
Fire Extnguishers	10525-300-1080	1760.00	0.00	0.00	1760.00		0.00	
Fire Equipment Cabinets	10525-200-5100	4240.00	0.00	1872.00	6112.00	3.200	51.20	3.20
Louvers and Vents	10210-800-2340	38.06	0.00	118.51	156.57	0.040	3.46	0.43
Air Conditioning Grille	10275-150-1100	754.00	0.00	209.30	963.30	0.471	6.12	0.76
Aluminium Flagpole	10355-400-0100	6560.00	704.00	1952.00	9216.00	8.000	64.00	4.00
			Specialties Sub Total		$84,000			

ELECTRICALS

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Panel Board								
Panel A	16440-700-0100	1-ELEC	10	EA	1	11	32.5	
Panel DP	16440-700-0700	1-ELEC	6.2	EA	1	76.5	52.5	
Pad-Mounted Utility Service Transformer	16270-600-0400	R-3	0.38	EA	1	16700	2100	415
Power Measurement and Control	16290-800-1300	1-ELEC	8	EA	1	780	41	
Enclosed Motor Controllers	16420-220-0100	1-ELEC	6.2	EA	2	165	52.5	
Enclosed Switches (fusible)	16410-800-2910	1-ELEC	3.2	EA	2	213	142	
Rod Copper Clad	16060-800-0030	1-ELEC	5.5	EA	10	13.5	59.5	
Brazed Connections	16060-800-3000	1-ELEC	10	EA	16	15.55	32.5	
Electrical Identification (incl name plates, labels and markers)	N/A							
2'x4' two 40watt (with flourescence fixture 2 lamps)	16510-440-0400	1-ELEC	5.3	EA	3	51.5	61.5	
2'x4' two 40 watt (with emergency ballast 2 lamps)	16510-440-7500	1-ELEC	10	EA	3	32.5	23.5	
2'x4' two 40watt (with flourescence fixture 4 lamps)	16150-440-1300	1-ELEC	6.2	EA	14	90.5	52.5	
2'x4' two 40watt (with emergency ballast 4 lamps)	16150-440-2300	1-ELEC	8	EA	3	30.5	41	
2'x2' two 40watt (with flourescence fixture 3 lamps)	16150-440-1200	1-ELEC	7	EA	14	79	46.5	
2'x2' two 40watt (with emergency ballast 3 lamps)	16150-440-0300	1-ELEC	5.7	EA	6	51.5	57	
Pendent Mounted 4' two 40 watt	16510-440-3100	1-ELEC	5.7	EA	24	46.5	57	
Two 40 watt reducer (ballast replacement)	16510-440-7500	1-ELEC	10	EA	13	23	34.5	
Flouresecent RS 4' long two 40 watt	16510-440-6100	1-ELEC	3.2	EA	7	94.5	102	

ELECTRICALS (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Panel Board								
Panel A	16440-700-0100	11	0	32.5	43.5	0.8	0.8	0.1
Panel DP	16440-700-0700	76.5	0	52.5	129	1.29	1.29	0.161
Pad-Mounted Utility Service Transformer	16270-600-0400	16700	415	2100	19215	52.632	52.632	2.632
Power Measurement and Control	16290-800-1300	780	0	41	821	1	1	0.125
Enclosed Motor Controllers	16420-220-0100	330	0	105	435	1.29	2.58	0.323
Enclosed Switches (fusible)	16410-800-2910	426	0	284	710	3.478	6.956	0.625
Rod Copper Clad	16060-800-0030	135	0	595	730	1.455	14.55	1.818
Brazed Connections	16060-800-3000	248.8	0	520	768.8	0.667	10.672	1.6
Electrical Identification (incl name plates, labels and markers)	N/A			1805	1805			
2'x4' two 40watt (with flourescence fixture 2 lamps)	16510-440-0400	154.5	0	184.5	339	1.509	4.527	0.566
2'x4' two 40 watt (with emergency ballast 2 lamps)	16510-440-7500	97.5	0	70.5	168	0.8	2.4	0.3
2'x4' two 40watt (with flourescence fixture 4 lamps)	16150-440-1300	1267	0	735	2002	1.29	18.06	2.258
2'x4' two 40watt (with emergency ballast 4 lamps)	16150-440-2300	91.5	0	123	214.5	1	3	0.375
2'x2' two 40watt (with flourescence fixture 3 lamps)	16150-440-1200	1106	0	651	1757	1.143	16.002	2
2'x2' two 40watt (with emergency ballast 3 lamps)	16150-440-0300	309	0	342	651	1.404	8.424	1.053
Pendent Mounted 4' two 40 watt	16510-440-3100	1116	0	1368	2484	1.404	33.696	4.211
Two 40 watt reducer (ballast replacement)	16510-440-7500	299	0	448.5	747.5	0.851	11.063	1.3
Flouresecent RS 4' long two 40 watt	16510-440-6100	661.5	0	714	1375.5	2.5	17.5	2.188

ELECTRICALS (Continued)

Project Component	Means Reference Number	Crew	Daily Output	Unit	Qty	Average Materials Cost/Unit	Average Labor Cost/Unit	Average Equipment Cost/Unit
Area Light Mounted on 20' pole	16520-300-3000	R-3	2.9	EA	3	675	276	
L.E.D. w/battery unit (double face)	16530-320-0260	1-ELEC	4	EA	6	111	81.5	
Wiring and Cable								
No. 700 Metal Surface Raceway	16133-800-0110	1-ELEC	100	LF	765	0.91	3.26	
Wiring Connections	16150-275-0200	1-ELEC	2.7	EA	3	9.05	77.5	
Cable	16120-700-0050	2-ELEC	4.4	CLF	23	142	148	
Wire	16120-900-0050	1-ELEC	13	CLF	75	6.9	29.5	
Outlet Boxes	16136-600-0150	1-ELEC	20	EA	5	2.14	16.3	
Cast IronPull Boxes	16136-700-3050	1-ELEC	4	EA	2	214	102	
PVC Conduit	16132-230-3300	1-ELEC	170	LF	234	1.09	1.92	
Metal Conduit	16132-240-0400	1-ELEC	100	LF	132.56	15.45	3.26	
EMT Conduit	16132-205-5040	1-ELEC	115	LF	86.2	1.86	2.84	

ELECTRICALS (Continued)

Project Component	Means Reference Number	Material Cost	Equipment Cost	Labor Cost	Total	Labor Hr/Unit	Labor Hours	Duration (days)
Area Light Mounted on 20' pole	16520-300-3000	2025		828	2853	6.897	20.691	1.034
L.E.D. w/battery unit (double face)	16530-320-0260	666		489	1155	2	12	1.5
Wiring and Cable								
No. 700 Metal Surface Raceway	16133-800-0110	696.15		2493.9	3190.05	0.08	61.2	7.65
Wiring Connections	16150-275-0200	27.15		232.5	259.65	2.963	8.889	1.111
Cable	16120-700-0050	3266		3404	6670	3.636	83.628	5.227
Wire	16120-900-0050	517.5		2212.5	2730	0.615	46.125	5.769
Outlet Boxes	16136-600-0150	10.7		81.5	92.2	0.4	2	0.25
Cast IronPull Boxes	16136-700-3050	428		204	632	2.5	5	0.5
PVC Conduit	16132-230-3300	462		449.28	704.34	0.047	10.998	1.376
Metal Conduit	16132-240-0400	255.06		432.146	2480.2	0.08	10.6048	1.326
EMT Conduit	16132-205-5040	160.32		244.808	405.14	0.07	6.034	0.749
			Sub Total		$56,000			

APPENDIX C

IDENTIFIED FAILURES AND ASSIGNED PROBABILITIES

CONVENTIONAL CONSTRUCTION SYSTEM			
CCS 1			
Technical Failures/Risks	Probability	Managerial Problems/Failures	Probability
Spalling of Concrete	0.150	Accident Installing Precast Panels	0.009
Tiled Wall Joint Fracture	0.050	High Rework and Change Orders	0.035
Lack of Roof Know How	0.240	No Availability of Reliable Precast Vendor	0.100
HVAC Control Damage	0.190	Incompatible Precast Panels	0.150
Improper Design	0.025	High Cost of Roofing Tiles	0.250
Lack of Precast Expertise	0.320	High Cost of Modified Steel	0.200
Inadequate Protection from Water	0.080	Lengthy Tile Roof Installation	0.150
		Damage of Precast During Transportation	0.009
		HVAC Malfunctions	0.010
CCS 2			
Technical Failures/Risks	Probability	Managerial Problems/Failures	Probability
Corrosion of Steel	0.300	Lowest Bidding Concrete Producer Defaults	0.010
Difficult Ensuring Total QA	0.100	High Rework/Change Orders	0.045
Lack of Testing or Inspection Personnel	0.200	Inclement Weather	0.300
Poor Construction, Isolation and Contraction Joints	0.090	Concrete Sets in Transit	0.010
Cracking in Concrete Wall	0.009	High Cost of Multiple HVAC Units	0.015
Improper Design	0.025	Excessive Corrosion Inhibitors and SCMs to Increase Corrosion Resistance	0.050
Poor Concrete Construction Practices	0.250	Late Delivery of Steel	0.250
Delivery of Bad Quality Concrete	0.200	Erecting Forms & Preparing Steel on Site Time Consuming	0.200

LIGHTWEIGHT CONSTRUCTION SYSTEM			
LCS 1			
Technical Failures/Risks	Probability	Managerial Problems/Failures	Probability
Dent on Metal Roof	0.350	High Cost of Highly Skilled Professionals Potential for Cost Overrun	0.010
Difficulty Assuring Strength of On-site Welds	0.050	High Rework and Change Orders	0.045
Wind Damages Metal Roof	0.240	Late Delivery of Steel	0.250
Metal Cladding Chip-off	0.130	In Available Materials for Metal Cladding	0.009
Improper Design	0.025	High Cost of Installing Metal Roof	0.150
Poor Installation	0.150	Excessive Galvanizing to Improve Corrosion Resistance of Steel	0.180
		On-site Welding Slows Other Activities	0.300
		HVAC Malfunctions	0.002
LCS 2			
Technical Failures/Risks	Probability	Managerial Problems/Failures	Probability
Decay of Lumber	0.100	High Uncertainty with Lumber Cost	0.300
Crack in Curtain Wall	0.005	High Rework/Change Orders	0.015
Timber Over Exposed to Moisture	0.050	Lumber Unavailable	0.200
Improper Design	0.013	Longer Time Required for Design	0.020
Timber Frame Buckles Under Fire	0.150	High Cost of Slate Roofing	0.050
Lack of Skilled Professionals	0.009	Excessive Treatment to Protect Timber From Rotting	0.025
		Slate Roofs Slow Work Rate	0.150
		Lack of Qualified Inspection Personnel	0.080

APPENDIX D

RESULTS OF TECHNICAL OPTIMIZATION

PROBABILITIES OF TECHNICAL FAILURES GIVEN INVESTMENT IN TECHNICAL REINFORCEMENT (CCS 1)

α		P(Spalling of Concrete)	P(Tiled Wall Joint Failure)	P(Lack of Roof Know How)	P(HVAC Control Damage)	P(Improper Design)	P(Lack of Precast Expertise)	P(Inadequate Protection from Water)
0%	p (F |i=0)	0.150	0.050	0.240	0.190	0.013	0.320	0.080
10%	p (F |i=0.1*r)	0.148	0.039	0.179	0.087	0.012	0.137	0.078
20%	p (F |i=0.2*r)	0.1459	0.031	0.102	0.049	0.011	0.078	0.073
30%	p (F |i=0.3*r)	0.144	0.025	0.064	0.031	0.011	0.049	0.035
40%	p (F |i=0.4*r)	0.141	0.019	0.041	0.019	0.007	0.031	0.018
50%	p (F |i=0.5*r)	0.139	0.016	0.026	0.012	0.005	0.021	0.009
60%	p (F |i=0.6*r)	0.138	0.012	0.017	0.008	0.003	0.013	0.005
70%	p (F |i=0.7*r)	0.108	0.009	0.012	0.005	0.002	0.009	0.003
80%	p (F |i=0.8*r)	0.038	0.007	0.011	0.005	0.002	0.008	0.002
90%	p (F |i=0.9*r)	0.009	0.006	0.010	0.007	0.007	0.006	0.003
100%	p (F |i=r)	0.130	0.005	0.003	0.0013	0.001	0.002	0.001

α	P(Partial Technical Failure)	P(Total Technical Failure)	P(Technical Failure)	Costs of Development	E(Costs of failure)
0%	0.496	0.382	0.688	$ 1,250,000	$ 427,875
10%	0.384	0.212	0.515	$ 1,285,000	$ 261,490
20%	0.293	0.155	0.403	$ 1,320,000	$ 194,029
30%	0.242	0.092	0.312	$ 1,355,000	$ 131,253
40%	0.208	0.056	0.253	$ 1,390,000	$ 93,845
50%	0.185	0.033	0.213	$ 1,425,000	$ 70,850
60%	0.169	0.020	0.186	$ 1,460,000	$ 56,613
70%	0.132	0.013	0.144	$ 1,495,000	$ 42,761
80%	0.059	0.012	0.071	$ 1,530,000	$ 25,270
90%	0.030	0.015	0.046	$ 1,565,000	$ 22,146
100%	0.137	0.003	0.140	$ 1,600,000	$ 36,494

PROBABILITIES OF TECHNICAL FAILURES GIVEN INVESTMENT IN TECHNICAL REINFORCEMENT (CCS 2)

α		P(Corrosion of Steel)	P(Difficult Ensuring Total QA)	P(Lack of Testing or Inspection Personnel)	P(Poor Construction, Isolation and Contraction Joints)	P(Cracking in Concrete Wall)	P(Poor Concrete Construction Practices)
0%	p (F |i=0)	0.300	0.100	0.200	0.090	0.009	0.250
10%	p (F |i=0.1*X)	0.2670	0.098	0.156	0.072	0.008	0.077
20%	p (F |i=0.2*X)	0.110	0.096	0.091	0.068	0.008	0.064
30%	p (F |i=0.3*X)	0.045	0.094	0.053	0.064	0.008	0.053
40%	p (F |i=0.4*X)	0.025	0.045	0.037	0.061	0.008	0.047
50%	p (F |i=0.5*X)	0.015	0.019	0.027	0.059	0.008	0.042
60%	p (F |i=0.6*X)	0.073	0.018	0.040	0.011	0.005	0.020
70%	p (F |i=0.7*X)	0.062	0.014	0.033	0.023	0.002	0.014
80%	p (F |i=0.8*X)	0.038	0.008	0.019	0.021	0.001	0.006
90%	p (F |i=0.9*X)	0.023	0.006	0.014	0.012	0.001	0.004
100%	p (F |i=X)	0.023	0.004	0.011	0.014	0.001	0.002

α	P(Delivery of Bad Concrete)	P(Partial Technical Failure)	P(Total Technical Failure)	P(Technical Failure)	Costs of Development	E(Costs of Failure)
0%	0.200	0.543	0.407	0.729	$ 1,300,000	$ 497,445
10%	0.143	0.485	0.216	0.597	$ 1,330,000	$ 303,478
20%	0.133	0.336	0.198	0.458	$ 1,360,000	$ 246,685
30%	0.131	0.240	0.182	0.379	$ 1,390,000	$ 214,354
40%	0.127	0.206	0.173	0.345	$ 1,420,000	$ 191,772
50%	0.122	0.173	0.165	0.311	$ 1,450,000	$ 177,773
60%	0.049	0.167	0.070	0.226	$ 1,480,000	$ 96,144
70%	0.039	0.127	0.054	0.175	$ 1,510,000	$ 80,516
80%	0.076	0.081	0.083	0.158	$ 1,540,000	$ 98,521
90%	0.067	0.062	0.072	0.130	$ 1,570,000	$ 85,146
100%	0.060	0.049	0.063	0.109	$ 1,600,000	$ 74,087

PROBABILITIES OF TECHNICAL FAILURES GIVEN INVESTMENT IN TECHNICAL REINFORCEMENT (LCS 1)

α		P(Dent on Metal Roof)	P(Difficulty Assuring Strength of On-site Welds)	P(Metal Roof Damaged by Wind)	P(Metal Cladding Chip-off)	P(Improper Design)	P(Poor Installation)
0%	p (F |i=0)	0.350	0.050	0.240	0.050	0.130	0.150
10%	p (F |i=0.1*X)	0.234	0.046	0.202	0.041	0.072	0.139
20%	p (F |i=0.2*X)	0.186	0.037	0.048	0.042	0.057	0.130
30%	p (F |i=0.3*X)	0.1499	0.030	0.012	0.034	0.046	0.121
40%	p (F |i=0.4*X)	0.121	0.024	0.003	0.025	0.037	0.113
50%	p (F |i=0.5*X)	0.097	0.019	0.000	0.022	0.030	0.106
60%	p (F |i=0.6*X)	0.079	0.015	0.000	0.018	0.024	0.099
70%	p (F |i=0.7*X)	0.063	0.012	0.000	0.014	0.019	0.092
80%	p (F |i=0.8*X)	0.051	0.010	0.000	0.011	0.016	0.086
90%	p (F |i=0.9*X)	0.041	0.008	0.000	0.009	0.013	0.080
100%	p (F |i=X)	0.033	0.006	0.000	0.007	0.010	0.075

α	P(Partial Technical Failure)	P(Total Technical Failure)	P(Technical Failure)	Costs of Development	E(Costs of Failure)
0%	0.554	0.260	0.670	$ 1,255,000	$ 340,732
10%	0.446	0.202	0.558	$ 1,289,500	$ 267,721
20%	0.285	0.181	0.415	$ 1,324,000	$ 212,154
30%	0.214	0.163	0.342	$ 1,358,500	$ 183,859
40%	0.169	0.147	0.291	$ 1,393,000	$ 163,657
50%	0.136	0.133	0.251	$ 1,427,500	$ 147,307
60%	0.110	0.121	0.218	$ 1,462,000	$ 133,460
70%	0.089	0.110	0.190	$ 1,496,500	$ 121,503
80%	0.072	0.101	0.162	$ 1,531,000	$ 111,074
90%	0.058	0.092	0.145	$ 1,565,500	$ 101,931
100%	0.047	0.084	0.128	$ 1,600,000	$ 93,865

PROBABILITIES OF TECHNICAL FAILURES GIVEN INVESTMENT IN TECHNICAL REINFORCEMENT (LCS 2)

α		P(Decay of Lumber)	P(Crack in Curtain Wall)	P(Timber Over Exposed to Moisture)	P(Improper Design)	P(Timber Frame Buckles Under Fire)	P(Lack of Skilled Professionals)
0%	p (F |i=0)	0.100000	0.005000	0.050000	0.013000	0.150000	0.009000
10%	p (F |i=0.1*X)	0.074303	0.004897	0.048462	0.012679	0.033436	0.008633
20%	p (F |i=0.2*X)	0.029880	0.004796	0.046971	0.008973	0.013456	0.005383
30%	p (F |i=0.3*X)	0.016980	0.004697	0.027168	0.005094	0.007641	0.003056
40%	p (F |i=0.4*X)	0.009675	0.004600	0.015480	0.002903	0.004354	0.001742
50%	p (F |i=0.5*X)	0.005513	0.004505	0.008820	0.001654	0.002481	0.000992
60%	p (F |i=0.6*X)	0.003141	0.004412	0.005026	0.000942	0.001413	0.000565
70%	p (F |i=0.7*X)	0.001790	0.004305	0.002867	0.000538	0.000806	0.000322
80%	p (F |i=0.8*X)	0.001147	0.002751	0.001835	0.000344	0.000516	0.000206
90%	p (F |i=0.9*X)	0.000733	0.001761	0.001174	0.000220	0.000330	0.000132
100%	p (F |i=X)	0.000470	0.001127	0.000751	0.000141	0.000211	0.000085

α	P(PTF)	P(TTF)	P(TF)	Costs of Development	E(Costs of Failure)
0%	0.149	0.168	0.293	$ 1,350,000	$ 170,707
10%	0.123	0.053	0.170	$ 1,375,000	$ 71,497
20%	0.079	0.027	0.105	$ 1,400,000	$ 40,507
30%	0.048	0.015	0.063	$ 1,425,000	$ 23,942
40%	0.029	0.008	0.038	$ 1,450,000	$ 14,299
50%	0.018	0.005	0.023	$ 1,475,000	$ 8,705
60%	0.012	0.002	0.015	$ 1,500,000	$ 5,459
70%	0.008	0.001	0.010	$ 1,525,000	$ 3,574
80%	0.005	0.001	0.006	$ 1,550,000	$ 2,324
90%	0.003	0.000	0.004	$ 1,575,000	$ 1,511
100%	0.002	0.000	0.002	$ 1,600,000	$ 982

APPENDIX E

RESULTS OF OPTIMIZATION FOR MANAGEMENT RESERVES

PROBABILITIES OF MANAGERIAL FAILURES GIVEN INVESTMENT OF MANAGEMENT RESERVES (CCS 1)

α		P(Accident Installing Precast Panels)	P(High Rework and Change Orders)	P(No Availability of Reliable Precast Vendor)	P(Incompatible Precast Panels)	P(High Cost of Roofing Tiles)	P(High Cost of Modified Steel)
0%	p (F |i=0)	0.009	0.035	0.100	0.150	0.250	0.200
10%	p (F |i=0.1*X)	0.009	0.034	0.099	0.087	0.135	0.138
20%	p (F |i=0.2*X)	0.009	0.029	0.067	0.064	0.099	0.114
30%	p (F |i=0.3*X)	0.009	0.025	0.033	0.051	0.076	0.098
40%	p (F |i=0.4*X)	0.009	0.021	0.018	0.040	0.059	0.083
50%	p (F |i=0.5*X)	0.0089	0.018	0.010	0.031	0.044	0.070
60%	p (F |i=0.6*X)	0.008	0.016	0.005	0.024	0.033	0.059
70%	p (F |i=0.7*X)	0.008	0.013	0.003	0.019	0.025	0.050
80%	p (F |i=0.8*X)	0.008	0.008	0.007	0.012	0.013	0.031
90%	p (F |i=0.9*X)	0.008	0.009	0.000	0.011	0.013	0.035
100%	p (F |i=X)	0.008	0.008	0.000	0.008	0.010	0.029

α	P(Lengthy Tile Roof Installation)	P(Damage of Precast During Transportation)	P(HVAC Malfunctions)	P(Partial Managerial Failure)	P(Total Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.150	0.009	0.010	0.499	0.268	$ 1,600,000	$ 310,720
10%	0.144	0.006	0.009	0.373	0.212	$ 1,565,000	$ 229,162
20%	0.135	0.005	0.008	0.319	0.152	$ 1,530,000	$ 166,414
30%	0.094	0.003	0.008	0.254	0.113	$ 1,495,000	$ 121,760
40%	0.050	0.002	0.007	0.189	0.087	$ 1,460,000	$ 88,774
50%	0.025	0.002	0.007	0.143	0.067	$ 1,425,000	$ 65,601
60%	0.013	0.001	0.006	0.110	0.053	$ 1,390,000	$ 49,796
70%	0.006	0.001	0.006	0.087	0.042	$ 1,355,000	$ 38,717
80%	0.000	0.000	0.005	0.051	0.035	$ 1,320,000	$ 28,185
90%	0.000	0.000	0.005	0.055	0.029	$ 1,285,000	$ 24,150
100%	0.000	0.000	0.004	0.045	0.024	$ 1,250,000	$ 19,844

PROBABILITIES OF MANAGERIAL FAILURES GIVEN INVESTMENT OF MANAGEMENT RESERVES (CCS 2)

α		P(Lowest Concrete Bidder Defaults)	P(High Rework/Change Order)	P(Inclement Weather)	P(Concrete Sets in Transit)	P(High Cost of Multiple HVAC Units)	P Excessive Corrosion Inhibitors & SCMs
0%	p (F |i=0)	0.009	0.045	0.300	0.010	0.015	0.050
10%	p (F |i=0.1*X)	0.009	0.043	0.107	0.009	0.014	0.049
20%	p (F |i=0.2*X)	0.009	0.040	0.050	0.009	0.014	0.048
30%	p (F |i=0.3*X)	0.008	0.023	0.029	0.009	0.014	0.047
40%	p (F |i=0.4*X)	0.008	0.013	0.017	0.009	0.013	0.046
50%	p (F |i=0.5*X)	0.008	0.008	0.011	0.009	0.013	0.039
60%	p (F |i=0.6*X)	0.006	0.006	0.008	0.009	0.013	0.020
70%	p (F |i=0.7*X)	0.007	0.004	0.006	0.007	0.013	0.019
80%	p (F |i=0.8*X)	0.004	0.003	0.004	0.005	0.012	0.014
90%	p (F |i=0.9*X)	0.002	0.003	0.003	0.004	0.010	0.012
100%	p (F |i=X)	0.001	0.002	0.003	0.003	0.008	0.010

α	P(Late Delivery of Steel)	P(Forms, Steel Consume Time)	P(Partial Managerial Failure)	P(Total Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.250	0.200	0.438	0.344	$ 1,600,000	$ 312,840
10%	0.193	0.195	0.391	0.163	$ 1,570,000	$ 161,307
20%	0.090	0.190	0.309	0.107	$ 1,540,000	$ 99,524
30%	0.053	0.186	0.276	0.070	$ 1,510,000	$ 66,804
40%	0.032	0.180	0.254	0.049	$ 1,480,000	$ 47,373
50%	0.020	0.176	0.235	0.037	$ 1,450,000	$ 35,556
60%	0.016	0.172	0.213	0.031	$ 1,420,000	$ 27,380
70%	0.010	0.167	0.203	0.024	$ 1,390,000	$ 21,604
80%	0.008	0.163	0.1942	0.018	$ 1,360,000	$ 16,534
90%	0.007	0.159	0.1849	0.014	$ 1,330,000	$ 12,833
100%	0.006	0.155	0.1765	0.011	$ 1,300,000	$ 10,030

PROBABILITIES OF MANAGERIAL FAILURES GIVEN INVESTMENT OF MANAGEMENT RESERVES (LCS 1)

α		P(High Cost of Highly Skilled Professionals Potential for Cost Overrun)	P(High Rework and Change Orders)	P(Late Delivery of Steel)	P(Unavailable Materials for Metal Cladding)	P(High Cost of Installing Metal Roof)	P(Excessive Galvanizing to Improve Corrosion Resistance of Steel)
0%	p (F |i=0)	0.010	0.045	0.250	0.009	0.150	0.180
10%	p (F |i=0.1*X)	0.009	0.044	0.042	0.008	0.146	0.178
20%	p (F |i=0.2*X)	0.008	0.025	0.022	0.008	0.084	0.176
30%	p (F |i=0.3*X)	0.008	0.019	0.017	0.008	0.066	0.139
40%	p (F |i=0.4*X)	0.007	0.015	0.013	0.008	0.052	0.109
50%	p (F |i=0.5*X)	0.007	0.012	0.01	0.008	0.040	0.085
60%	p (F |i=0.6*X)	0.006	0.010	0.008	0.008	0.032	0.067
70%	p (F |i=0.7*X)	0.001	0.007	0.006	0.008	0.026	0.045
80%	p (F |i=0.8*X)	0.0051	0.005	0.005	0.007	0.020	0.042
90%	p (F |i=0.9*X)	0.001	0.005	0.004	0.006	0.016	0.035
100%	p (F |i=X)	0.001	0.004	0.003	0.005	0.0136	0.031

α	P(On-Site Welding Slows Other Activities)	P(HVAC Malfunctions)	P(Partial Managerial Failure)	P(Total Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.300	0.001	0.512	0.297	$ 1,600,000	$ 327,120
10%	0.297	0.001	0.508	0.101	$ 1,565,500	$ 171,331
20%	0.283	0.001	0.460	0.063	$ 1,531,000	$ 128,591
30%	0.221	0.001	0.375	0.053	$ 1,496,500	$ 100,699
40%	0.173	0.001	0.303	0.044	$ 1,462,000	$ 79,174
50%	0.136	0.001	0.243	0.037	$ 1,427,500	$ 62,519
60%	0.107	0.001	0.195	0.032	$ 1,393,000	$ 49,622
70%	0.104	0.001	0.168	0.023	$ 1,358,500	$ 38,847
80%	0.067	0.001	0.125	0.023	$ 1,324,000	$ 31,560
90%	0.056	0.001	0.105	0.015	$ 1,289,500	$ 24,301
100%	0.045	0.000	0.089	0.013	$ 1,255,000	$ 19,257

PROBABILITIES OF MANAGERIAL FAILURES GIVEN INVESTMENT OF MANAGEMENT RESERVES (LCS 2)

α		P(High Uncertainty with Lumber Cost)	P(High Rework/Change Orders)	P(Lumber Unavailable)	P(Longer Time Required for Design)	P(High Cost of Slate Roofing)	P(Excessive Treatment to Protect Timber From Rotting)	P(Slate Roofs Slow Work Rate)
0%	p (F |i=0)	0.300	0.015	0.200	0.020	0.050	0.025	0.150
10%	p (F |i=0.1*X)	0.237	0.002	0.193	0.013	0.047	0.003	0.139
20%	p (F |i=0.2*X)	0.182	0.000	0.182	0.008	0.045	0.000	0.130
30%	p (F |i=0.3*X)	0.141	0.000	0.182	0.005	0.043	0.000	0.121
40%	p (F |i=0.4*X)	0.110	0.000	0.176	0.003	0.040	0.000	0.112
50%	p (F |i=0.5*X)	0.085	0.011	0.171	0.018	0.038	0.013	0.104
60%	p (F |i=0.6*X)	0.066	0.000	0.165	0.001	0.037	0.000	0.097
70%	p (F |i=0.7*X)	0.052	0.000	0.160	0.001	0.035	0.000	0.090
80%	p (F |i=0.8*X)	0.040	0.000	0.155	0.003	0.033	0.000	0.084
90%	p (F |i=0.9*X)	0.033	0.000	0.150	0.014	0.001	0.008	0.078
100%	p (F |i=X)	0.024	0.000	0.146	0.016	0.000	0.001	0.073

α	P(Lack of Qualified Inspection Personnel)	P(Total Managerial Failure)	P(Partial Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.080	0.459	0.275	$ 1,600,000	$ 430,000
10%	0.075	0.391	0.244	$ 1,575,000	$ 355,345
20%	0.070	0.341	0.228	$ 1,550,000	$ 302,317
30%	0.066	0.301	0.214	$ 1,525,000	$ 261,099
40%	0.062	0.269	0.202	$ 1,500,000	$ 228,324
50%	0.058	0.264	0.200	$ 1,475,000	$ 220,177
60%	0.054	0.222	0.178	$ 1,450,000	$180,405.
70%	0.051	0.205	0.168	$ 1,425,000	$ 162,749
80%	0.043	0.192	0.158	$ 1,400,000	$ 149,147
90%	0.045	0.189	0.129	$ 1,375,000	$ 139,466
100%	0.042	0.180	0.114	$ 1,350,000	$ 129,417

APPENDIX F

RESULTS OF MONTE CARLO SIMULATIONS

No. of Replications	Total Project Cost
1000	$ 1,849,765
2000	$ 1,857,643
3000	$ 1,843,367
4000	$ 1,847,987
5000	$ 1,853,910
6000	$ 1,855,148
7000	$ 1,857,096
8000	$ 1,856,609
9000	$ 1,854,815
10000	$ 1,853,224
11000	$ 1,863,665
12000	$ 1,853,177
13000	$ 1,859,083
14000	$ 1,852,989
15000	$ 1,852,038
16000	$ 1,847,747
17000	$ 1,854,810
18000	$ 1,851,096
19000	$ 1,860,480
20000	$ 1,855,623
21000	$ 1,853,387
22000	$ 1,854,271
23000	$ 1,855,653
24000	$ 1,854,568
25000	$ 1,855,998
26000	$ 1,851,605
27000	$ 1,856,475
28000	$ 1,856,906
29000	$ 1,852,134
30000	$ 1,851,286

APPENDIX G

RESULTS OF OPTIMIZATION FOR CONTINGENCY BUDGET

RESULTS OF OPTIMIZING CONTINGENCY BUDGET (CCS 1)

α		P(Accident Installing Precast Panels)	P(High Rework and Change Orders)	P(No Availability of Reliable Precast Vendor)	P(Incompatible Precast Panels)	P(High Cost of Roofing Tiles)	P(High Cost of Modified Steel)
0%	p (F |i=0)	0.009	0.035	0.100	0.150	0.250	0.200
10%	p (F |i=0.1*X)	0.001	0.034	0.083	0.028	0.056	0.060
20%	p (F |i=0.2*X)	0.007	0.031	0.000	0.013	0.026	0.032
30%	p (F |i=0.3*X)	0.006	0.027	0.000	0.006	0.013	0.019
40%	p (F |i=0.4*X)	0.005	0.024	0.000	0.003	0.007	0.011
50%	p (F |i=0.5*X)	0.004	0.021	0.000	0.001	0.004	0.007
60%	p (F |i=0.6*X)	0.004	0.018	0.000	0.001	0.002	0.004
70%	p (F |i=0.7*X)	0.003	0.015	0.000	0.000	0.001	0.002
80%	p (F |i=0.8*X)	0.002	0.010	0.000	0.000	0.000	0.000
90%	p (F |i=0.9*X)	0.002	0.011	0.000	0.000	0.000	0.001
100%	p (F |i=X)	0.002	0.010	0.000	0.000	0.000	0.000

α	P(Damage of Precast During Transportation)	P(HVAC Malfunctions)	P(Partial Managerial Failure)	P(Total Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.009	0.010	0.499	0.268	$ 1,537,500	$ 298,582
10%	0.007	0.009	0.240	0.145	$ 1,508,750	$ 143,154
20%	0.00	0.009	0.161	0.048	$ 1,480,000	$ 57,531
30%	0.004	0.008	0.067	0.038	$ 1,451,250	$ 34,875
40%	0.003	0.008	0.031	0.031	$ 1,422,500	$ 24,620
50%	0.003	0.008	0.020	0.026	$ 1,393,750	$ 19,321
60%	0.002	0.007	0.015	0.022	$ 1,365,000	$ 15,718
70%	0.002	0.007	0.011	0.019	$ 1,336,250	$ 13,045
80%	0.001	0.006	0.008	0.012	$ 1,307,500	$ 8,423
90%	0.001	0.006	0.008	0.014	$ 1,278,750	$ 9,151
100%	0.001	0.006	0.007	0.012	$ 1,250,000	$ 7,783

RESULTS OF OPTIMIZING CONTINGENCY BUDGET (CCS 2)

α		P(Lowest Concrete Bidder Defaults)	P(High Rework/Change Order)	P(Inclement Weather)	P(Concrete Sets in Transit)	P(High Cost of Multiple HVAC Units)
0%	p (F |i=0)	0.001	0.045	0.300	0.010	0.015
10%	p (F |i=0.1*X)	0.009	0.044	0.036	0.009	0.014
20%	p (F |i=0.2*X)	0.008	0.038	0.007	0.009	0.014
30%	p (F |i=0.3*X)	0.008	0.018	0.003	0.008	0.013
40%	p (F |i=0.4*X)	0.007	0.009	0.001	0.008	0.013
50%	p (F |i=0.5*X)	0.007	0.005	0.000	0.007	0.012
60%	p (F |i=0.6*X)	0.002	0.003	0.000	0.007	0.012
70%	p (F |i=0.7*X)	0.003	0.002	0.000	0.001	0.011
80%	p (F |i=0.8*X)	0.001	0.001	0.000	0.000	0.010
90%	p (F |i=0.9*X)	0.000	0.001	0.000	0.000	0.007
100%	p (F |i=X)	0.000	0.001	0.000	0.000	0.005

α	P(Excessive Corrosion Inhibitors & SCMs)	P(Late Delivery of Steel)	P(Forms, Steel Consume Time)	P(Partial Managerial Failure)	P(Total Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.050	0.250	0.200	0.439	0.344	$ 1,599,000	$ 312,644
10%	0.048	0.194	0.190	0.388	0.095	$ 1,569,100	$ 109,373
20%	0.046	0.091	0.181	0.300	0.062	$ 1,539,200	$ 66,777
30%	0.045	0.054	0.172	0.262	0.036	$ 1,509,300	$ 41,938
40%	0.043	0.032	0.164	0.236	0.024	$ 1,479,400	$ 29,376
50%	0.029	0.020	0.156	0.207	0.019	$ 1,449,500	$ 21,196
60%	0.006	0.017	0.148	0.178	0.013	$ 1,419,600	$ 13,101
70%	0.006	0.011	0.141	0.165	0.006	$ 1,389,700	$ 7,874
80%	0.004	0.009	0.134	0.154	0.002	$ 1,359,800	$ 4,543
90%	0.002	0.007	0.128	0.142	0.001	$ 1,329,900	$ 3,010
100%	0.001	0.006	0.122	0.132	0.001	$ 1,300,000	$ 2,104

RESULTS OF OPTIMIZING CONTINGENCY BUDGET (LCS 1)

α		P(High Cost of Highly Skilled Professionals Potential for Cost Overrun)	P(High Rework and Change Orders)	P(Late Delivery of Steel)	P(Inavailable Materials for Metal Cladding)	P(High Cost of Installing Metal Roof)	P(Excessive Galvanizing to Improve Corrosion Resistance of Steel)
0%	p (F |i=0)	0.010	0.045	0.250	0.009	0.150	0.180
10%	p (F |i=0.1*X)	0.009	0.043	0.009	0.008	0.143	0.176
20%	p (F |i=0.2*X)	0.009	0.011	0.003	0.007	0.045	0.1732
30%	p (F |i=0.3*X)	0.008	0.006	0.002	0.007	0.027	0.109
40%	p (F |i=0.4*X)	0.008	0.003	0.001	0.006	0.016	0.068
50%	p (F |i=0.5*X)	0.007	0.002	0.001	0.006	0.009	0.042
60%	p (F |i=0.6*X)	0.007	0.001	0.000	0.005	0.006	0.026
70%	p (F |i=0.7*X)	0.002	0.001	0.000	0.005	0.004	0.012
80%	p (F |i=0.8*X)	0.006	0.000	0.000	0.002	0.002	0.011
90%	p (F |i=0.9*X)	0.002	0.000	0.000	0.000	0.002	0.008
100%	p (F |i=X)	0.001	0.000	0.000	0.000	0.001	0.006

α	P(On-Site Welding Slows Other Activities)	P(HVAC Malfunctions)	P(Partial Managerial Failure)	P(Total Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.300	0.002	0.513	0.297	$ 1,543,650	$ 315,599
10%	0.279	0.001	0.492	0.068	$ 1,514,785	$ 138,282
20%	0.164	0.001	0.342	0.030	$ 1,485,920	$ 77,401
30%	0.013	0.001	0.147	0.023	$ 1,457,055	$ 37,136
40%	0.001	0.001	0.086	0.019	$ 1,428,190	$ 24,403
50%	0.000	0.001	0.053	0.016	$ 1,399,325	$ 17,397
60%	0.000	0.001	0.034	0.014	$ 1,370,460	$ 13,020
70%	0.000	0.001	0.017	0.008	$ 1,341,595	$ 7,055
80%	0.000	0.001	0.014	0.007	$ 1,312,730	$ 6,960
90%	0.000	0.001	0.009	0.003	$ 1,283,865	$ 3,264
100%	0.000	0.001	0.008	0.002	$ 1,255,000	$ 2,040

RESULTS OF OPTIMIZING CONTINGENCY BUDGET (LCS 2)

α		P(High Uncertainty with Lumber Cost)	P(High Rework/Change Orders)	P(Lumber Unavailable)	P(Longer time required for Design)	P(High Cost of Slate Roofing)	P(Excessive Treatment to Protect Timber From Rotting)
0%	p (F |i=0)	0.300	0.015	0.200	0.020	0.050	0.025
10%	p (F |i=0.1*X)	0.161	0.0013	0.136	0.007	0.044	0.002
20%	p (F |i=0.2*X)	0.087	0.002	0.092	0.002	0.039	0.001
30%	p (F |i=0.3*X)	0.047	0.000	0.062	0.001	0.034	0.000
40%	p (F |i=0.4*X)	0.025	0.000	0.042	0.000	0.030	0.000
50%	p (F |i=0.5*X)	0.013	0.011	0.029	0.015	0.027	0.011
60%	p (F |i=0.6*X)	0.007	0.000	0.0195	0.000	0.024	0.000
70%	p (F |i=0.7*X)	0.004	0.000	0.013	0.000	0.021	0.000
80%	p (F |i=0.8*X)	0.002	0.000	0.009	0.001	0.018	0.000
90%	p (F |i=0.9*X)	0.001	0.000	0.006	0.009	0.000	0.006
100%	p (F |i=X)	0.001	0.000	0.004	0.012	0.000	0.001

α	P(Slate Roofs Slow Work Rate)	P(Lack of Qualified Inspection Personnel)	P(Total Managerial Failure)	P(Partial Managerial Failure)	Costs of Development	E(Costs of Failure)
0%	0.150	0.080	0.459	0.276	$ 1,660,500	$ 446,259
10%	0.135	0.074	0.281	0.236	$ 1,629,450	$ 265,448
20%	0.121	0.068	0.173	0.214	$ 1,598,400	$ 167,031
30%	0.109	0.063	0.107	0.195	$ 1,567,350	$ 109,992
40%	0.099	0.059	0.067	0.178	$ 1,536,300	$ 75,659
50%	0.089	0.054	0.067	0.172	$ 1,505,250	$ 72,144
60%	0.081	0.050	0.027	0.148	$ 1,474,200	$ 40,528
70%	0.073	0.046	0.017	0.134	$ 1,443,150	$ 31,343
80%	0.066	0.043	0.011	0.123	$ 1,412,100	$ 25,110
90%	0.060	0.040	0.017	0.102	$ 1,381,050	$ 24,009
100%	0.053	0.037	0.017	0.089	$ 1,350,000	$ 22,276

VITA

William Kweku Ansah Imbeah received his Bachelor's Degree from the Kwame Nkrumah University of Science and Technology in Ghana in 2003. He began his studies towards a Master of Science Degree at Texas A&M University, College Station in August 2005. His research interest areas include construction risk analysis and project management. During his stay at the Texas A&M University, Mr. Imbeah worked as Graduate Teaching Assistant for two undergraduate classes, Portland Cement Concrete Material Systems for Civil Engineers and Civil Engineering Project Management. He graduated with a Master of Science degree in Civil Engineering in May, 2007.

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