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Decision Support Model For Construction Crew Reassignments

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DECISION SUPPORT MODEL
FOR CONSTRUCTION CREW REASSIGNMENTS

by

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ABSTRACT

The reassignment of crews on a construction project in response to changes occurs on a frequent basis. The factors that affect the crew reassignment decision can be myriad and most are not known with certainty. This research addresses the need for a decision support model to assist construction managers with the crew reassignment problem. The model design makes use of certainty factors in a decision tree structure. The research helped to determine the elements in the decision tree, the appropriate combination rules to use with the certainty factors, and the method for combining the certainty factors and costs to develop a measure of cost for each decision option.

The research employed surveys, group meetings, and individual interviews of experienced construction managers and superintendents to investigate the current methods used by decision makers to identify and evaluate the key elements of the construction crew reassignment decision. The initial research indicated that the use of certainty factors was preferred over probabilities for representing the uncertainties. Since certainty factors have not been used in a traditional decision tree context, a contribution of the research is the development and testing of techniques for combining certainty factors, durations, and costs in order to represent the uncertainty and to emulate the decision process of the experts interviewed. The developed model provides the decision maker with an estimate of upper and lower bounds of costs for each crew reassignment option.

The model was applied contemporaneously to six changes on three ongoing construction projects to test the model and assess its usefulness. The model provides a previously unavailable tool for the prospective identification and estimation of productivity losses and potential costs that emanate from changes. The users indicated the model process resulted in concise and complete compilations of the elements of the crew reassignment decision and that the model outputs were consistent with the users' expectations.

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CHAPTER 1: INTRODUCTION

The purpose of this research was to develop, demonstrate, and evaluate a decision support model for the crew reassignment problem on construction projects. Although crew reassignment decisions occur on a frequent basis on almost all construction projects and can affect the schedule as well as labor and equipment costs, there has been no codification of the considerations in making these decisions. The decision support model presented assists in the identification of cost-effective crew reassignment options while addressing decision-maker preferences and the effects of uncertainty. In addition, the decision support model developed includes a method for the application of certainty factors to a decision tree structure.

1.1. Overview

It is the rare construction project that does not undergo a number of changes during the course of construction. These changes can range from a simple modification of the specifications, allowing the substitution of one manufactured component for another, to a change so significant that it is viewed as a cardinal change to the scope of work.

When a change occurs, the price for the change work frequently is determined using the estimated cost of materials plus the estimated labor based on the contractor’s unit rates.

However, most contractors, indeed, many would say all prudent contractors, will reserve their rights to identify at a later date any other impacts resulting from the change work. These impacts usually consist of delays and/or labor inefficiencies that are not captured in the unit rates used to price the change. Typically, these impacts are identified at the end of the project in the form of a claim for both delays and inefficiencies allegedly emanating from the effects of the changes. These impacts often are referred to as the cumulative impact of the changes made over the course of the project.

The inefficiencies experienced as a result of changes are most often the point of contention in settling a claim. Frequently, the owner denies the contractor's claim by taking the stance that the contractor had the responsibility to mitigate the effects of the changes. Usually, the owner's position is supported, at least in part, by the terms of the contract. The contractor is then faced with the requirement of proving that appropriate mitigating actions were taken and the resulting inefficiencies were incurred in spite of the best efforts of the contractor. Unfortunately for the contractor, the typical documentation maintained on a construction project rarely provides evidence of a clear link between changes and the alleged resulting inefficiencies or that mitigating actions were undertaken in direct response to changes.

The objective of this study was to develop a framework for a decision support model that will assist contractors with the prospective identification and evaluation of the factors that may contribute to a potential loss of construction resource productivity, specifically manpower and equipment, resulting from change work. The model is intended to assist the contractor in determining the most prudent action regarding the reassignment of resources when a change in the planned course of construction occurs.

A prospectively-applied crew reassignment decision support model allows the identification of potential causes of productivity loss and the estimation of the potential losses prior to the final definition of the change and the performance of the work. In addition to providing the contractor with assistance in assessing the crew reassignment alternatives, the information provided by the model aides both the contractor and the owner in the pricing and settlement of change orders prior to the end of a project, reducing the likelihood of an inefficiency claim. Also, through greater awareness of labor assignments and changes to planned resource usage, the contractor may realize opportunities for increased productivity on both change order and non-change order work. Finally, the output from the decision support model may provide previously unquantified information regarding the actual productivity rates for certain types of work and realized profit on change work. This information may prove valuable to the efforts of planners and estimators for future bid preparation.

1.2. Problem Statement

Change work on a construction project frequently affects the planned usage of resources, including manpower, materials, and equipment. The effects can be of minor consequence, such as several minutes of standby time for a single crew, or of major significance, such as project-wide productivity losses due to excessive overtime, shiftwork, or demobilization from the site. After the fact, the actual productivity loss associated with any particular change can be difficult to measure without detailed record keeping. An accurate estimate of the potential productivity loss prior to the performance of a change is even more difficult to calculate using presently available tools.

Although changes occur on almost every construction project and contractors are required to submit change order proposals prior to the performance of the work, there are no widely-accepted or empirically-based models or methods to assist in the prospective identification and quantification of the potential loss of construction labor productivity ensuing from change work. Appendix A, which provides information on the measurement of construction labor productivity and the factors that affect labor productivity, lists and discusses the general methods for the measurement of productivity losses and provides descriptions of several of the models that have been developed. As presented in Chapter 3 of Appendix A, the only commonly-used methods that can be applied prospectively are Industry Standards, Factor-Based Methods, and Expert Testimony. However, all of these methods are highly subjective. In addition, many of the existing industry published factors are not based on empirical data and/or may not be applicable for construction.

Due to the unique circumstances of each construction project and the vast number of simultaneously-occurring events on a project, attempts to develop a prospective model for the quantification of productivity losses due to specific changes have not been successful. As discussed in Chapter 3 of Appendix A, the instructions that accompany the existing prospective models indicate that the models are intended to serve as guidelines only; the particular circumstances of the project and the specific experience of the contractor must be taken into consideration when applying the models. Thus, efforts to date have not been successful in developing a general-use prospective model that provides an accurate estimate of the expected productivity loss resulting from a specific change.

Due to a lack of a simple-to-use prospective model, when pricing a change order a contractor typically reserves the right to identify at a later time the loss of efficiency resulting from change work. Usually these ‘unidentified’ inefficiencies are accumulated at the end of a project and presented as a proposed change order. Most often, the inefficiency costs are computed using the format of a total cost calculation. That is, the contractor simply subtracts the planned labor costs from the actual labor costs to establish the alleged costs of the inefficiencies due to changes. For obvious reasons, the owner rarely accepts such a calculation. As a result, the contractor files a claim, using the total cost calculation as the basis for the claim. This scenario persists throughout the construction industry in spite of the fact that many courts have imposed strict application of the qualifications to allow a total cost claim, specifically when it is determined that it may be possible to calculate the alleged damages by another method.

Although there are no available data of the costs incurred by contractors and owners in asserting and defending productivity loss claims, based on the author's personal experience in the construction claims industry, productivity loss claims usually are the most time-consuming to develop and analyze. In addition, perhaps due to the subjective nature of most productivity-loss analysis methods, these claims are the most difficult to settle without legal action.

A model that aids the contractor in making crew reassignment decisions when a change occurs may function as an alternative to the desired general-use prospective model. The main purpose of a crew reassignment decision support model would be the identification of potential causes of productivity loss prior to the final definition of the change and the performance of the work. This would allow the contractor to develop complete pricing of the change work, including costs and time for productivity loss. In turn, the complete pricing provides crucial information to the owner regarding the true costs of the change. Thus, both parties would be able to make more informed decisions regarding change work.

In addition, through the documentation of the crew reassignment decision process, the contractor is provided a means to show 'cause and effect' of productivity losses stemming from change work. The steps of the process will provide an outline of the crew reassignment decisions made in response to the change. In the event of a claim, this type of documentation can provide supporting evidence of the actions taken in an effort to mitigate productivity losses stemming from changes.

Perhaps of even greater value is that through a conscious consideration of the available crew reassignment options and the ramifications of each option, the contractor will have the necessary information to develop plans to mitigate many of the adverse effects of changes. Also, a greater awareness of resource assignments might result in the identification of opportunities to revise the overall resource plan and achieve higher productivity project-wide. Since the direct labor costs of the typical construction project are in the range of 35% - 40% of the total project cost, any increase in productivity can have a measurable effect on the final costs of a project [Adrian, 1987]. Further, since the norm on commercial construction is 55% productive time, there is ample opportunity for productivity improvement on construction projects [Strandell, 1976].

In addition, a crew reassignment decision support model that supports the quantification of potential causes of productivity loss may provide previously-unavailable information for planners and estimators. This information may provide new insight into the full range of costs incurred during the performance of change work and an assessment of the actual profit realized on change work. Armed with this additional information, the contractor will be able to develop supportable estimates for proposed change work.

Currently, there are no established models or methods to assist the contractor with decisions concerning crew reassignments when a change arises on a construction project. The literature contains no record of attempts to codify the many considerations required in the evaluation of the circumstances on a construction project between the time when a potential change is identified and the issuance of a change order and/or the subsequent performance of the change work.

However, research has identified a number of factors that can affect construction labor productivity, ranging from crew size to material delivery and from weather to quality of management [Arditi and Mochtar, 2000; Borcherding and Alarcon, 1991; Herbsman and Ellis, 1991; Thomas and Smith, 1990; Tucker, Haas, Borcherding, Allmon, and Goodrum, 1999]. In addition, a number of studies have been performed on the effect of a single-factor occurrence on labor productivity. Among the best-known of these studies are Bureau of Labor Statistics Bulletin No. 917, “Hours of Work and Output” [1947] and The Business Roundtable Report C-2, “Scheduled Overtime Effect on Construction Projects” [1989]. Due to the fact that data from a manufacturing plant forms the basis for the Bureau of Labor Statistics report and the Business Roundtable report is based on data from a single project site, two of the most-frequently cited studies in construction productivity claims may not provide a sound basis for the calculation of inefficiencies resulting from overtime on a construction project. Chapter 2 of Appendix A contains a discussion of these and other related studies.

The dearth of reliable information is even more pronounced in the consideration of the effect of multiple factors on construction labor productivity. Although a few studies have been undertaken on the development of multiple-factor models (See Appendix A, Chapter 3), the literature contains no record of a prospective model that has been validated across a broad range of applications, as typically is encountered in construction.

Although it may not be possible to develop a general-purpose prospective model that will provide a calculation of the productivity loss due to a particular change, a crew reassignment decision support model will assist in the evaluation of the crew reassignment decision as well as the identification of the potential productivity losses associated with the decision. Through the use of a flexible framework for the crew reassignment decision support model, the decision maker will have control of a tool that will aide in the pursuit of better decisions and increased labor productivity, while providing a method to document productivity losses.

1.3. Research Objectives

The primary objective of this research was to address the need for a decision support model to assist the contractor in making crew reassignments when changes arise on a construction project. The model will be suitable for prospective application in order to determine the potential causes of productivity losses due to changes on a construction project. Through the identification and understanding of the potential causes and effects of productivity loss, the decision support model will provide the contractor with a tool to assist in more-informed decision making regarding construction resource assignments. As discussed, there currently exist no models that can perform this function.

A second objective of this research was the application of the theories of uncertainty, specifically the use of certainty factors on a decision tree structure. As discussed in Chapter 2, it was determined that the appropriate framework for the crew reassignment decision consisted of a decision tree structure. Typically, Bayesian probabilities are the quantitative method used for decision trees. However, the crew reassignment problem required a quantitative method that supported a straightforward method of elicitation of information and calculation on a flexible framework that is easy to update and use. Although Bayesian probabilities offer a strong theoretical foundation to modeling uncertainty, the 'uniqueness' of each construction change circumstance precludes the development of probability frequency distributions. The use of subjective probabilities presents the problem that experts have in expressing their knowledge in a numerical form that fully represents the nature of probabilities [Lauritzen and Spiegelhalter, 1988]. Finally, it is generally accepted that many people have difficulty interpreting probabilities, especially very low probabilities [Starr and Whipple, 1980]. As a result, it was determined that the model should employ methods of expression that are compatible with the non-probabilistic orientation of the information and the decision makers. Although there are numerous publications addressing recent developments regarding fuzzy decision trees, pruning decision trees, and combining multiple decision trees, the literature review indicated that there are no published studies on the subject of the application of certainty factors to decision trees [Benbrahim and Bensaid, 2000; Crockett, Bandar, and Mclean, 2002; Lee, Lee, Lee, and Kwang, 1999; Yuan and Shaw, 1995].

Initial informal research showed that even when construction management personnel were not willing to state the probability that something will or will not occur, given the same circumstances, they were comfortable with expressing a likelihood or level of belief or disbelief in the event. Thus, it appeared that the use of certainty factors provided the most suitable quantitative method. Since the literature contained no information regarding the application of certainty factors to decision trees, an additional research objective was to establish the methodology for this process.

1.4. Outline of the Dissertation

The research activities and results are presented in Chapters 2 through 5:

Chapter 2: Decision Support Models and Uncertainty

Chapter 3: Development of Crew Reassignment Decision Support Model

Chapter 4: Application and Validation of Crew Reassignment Decision Support Model

Chapter 5: Summary and Conclusions

Each chapter is summarized below.

1.4.1. Chapter 2: Decision Support Models and Uncertainty

As discussed in part 1.2, there are no established decision support models or methods to assist the contractor with the decision of crew reassignments when a change is identified on a construction project. The problem analysis, which is presented in Chapter 2, discusses the various available frameworks for decision problems. This discussion is combined with a definition of the issues to be considered by the decision maker and an examination of the characteristics and desired attributes of the crew reassignment problem. In addition, the results of a study of the concepts of uncertainty in relation to decision support in general and the crew reassignment problem in particular are presented. The results of this analysis and study provide the foundation for the development of the decision support model framework and quantitative method.

1.4.2. Chapter 3: Development of Crew Reassignment Decision Support Model

Based on the findings of the research described in Chapter 2, the methodology that appeared to provide the best fit for the crew reassignment problem was comprised of a set of decision trees. Preliminary influence diagrams and decision trees were constructed for various construction change scenarios. These preliminary models, which are presented in Chapter 3, provided a detailed description of the different steps and stages of the crew reassignment decision.

Using the results of the literature research and the author's experience, questionnaires were developed and issued to members of the construction industry. Samples of the questionnaires are presented in Figure 5. The responses to the questionnaires, which were discussed in group sessions, allowed refinement of the proposed model.

The next step in the design of the decision support model framework involved the development of the quantitative method to be used in the model. Based on the results of research on the representation of uncertainty, as presented in Chapter 2, and the specific characteristics of the crew reassignment problem, it was determined that certainty factors provided the most appropriate quantitative method. Since there were no published works regarding the use of certainty factors with decision trees, this phase of the research developed and tested a process for use of certainty factors with decision trees. As part of this phase of the research, the proposed model first was discussed and evaluated in the group sessions. Based on information obtained during the group sessions, the model was revised. The revised model then was reviewed, analyzed, and evaluated in individual sessions with construction industry experts.

1.4.3. Chapter 4: Application and Validation of the Crew Reassignment Decision Support Model

The final stage of the research included the testing of the model. During this stage the decision support model was applied to six crew reassignment decisions on three on-going construction projects. The scenarios to which the model was applied are presented in Chapter 4, along with the model outcomes. In addition, the model outcomes are compared to the actual crew reassignment decisions that were enacted. The assessments of the model by the representatives from each project are presented.

1.4.4. Chapter 5: Summary and Conclusions

Chapter 5 presents a summary of the research and conclusions of the model development and evaluation. In addition, the contributions of the research in the area of the application of certainty factors to a decision tree structure and opportunities for potential future research are discussed.

CHAPTER 2: DECISION SUPPORT MODELS AND UNCERTAINTY

2.1. Introduction

A decision implies choosing one action from a set of possible actions of either finite or infinite number. Most decisions are made without knowledge or consideration of all existing factors, conditions, and alternatives. As a result, these decisions are made under conditions of uncertainty.

The typical crew reassignment decisions made on a construction project are complex decisions, as they must consider a web of inter-related internal issues and ever-changing external conditions. The internal issues include project-specific circumstances, such as the stage of the project and the availability of alternative work assignments for a crew, while the external conditions include market-related concerns such as labor and material availability.

This section presents an examination of the various available frameworks and analytical tools for decision problems along with an evaluation of the available models relative to the characteristics and desired attributes of the crew reassignment decision problem. Also included is a discussion of the concepts of uncertainty in relation to decision support in general and the crew reassignment problem in particular. This discussion includes identification of the issues to be considered by the crew-assignment decision maker.

2.2. Decision Support Models

Decision support is defined by Andriole [1989, p3] as consisting of "*any and all data, information, expertise and activities that contribute to option selection*." From the starting point of this broad description, one can project that a well-constructed decision support model can assist decision makers in the identification of the availability and consequences of each alternative, while facilitating the search process for robust strategies [Van Asselt, 2000]. Grimes [2001, p1] added that decision support models "*encapsulate methods of deriving meaning from the information*. . . . [providing] *an analytic framework for optimizing system and process performance, for evaluation of 'what if?' scenarios, and for goal-seeking studies that concoct a recipe for your desired outcome*."

A decision support model consists of the following elements: (1) alternatives, (2) state descriptions, (3) relationships, and (4) outcomes and preferences [Gottinger and Weimann, 1991]. The alternatives represent the distinct resource allocations from which the decision maker can choose. The state descriptions, which are intertwined with the relationships, provide the concepts that frame the decision. The relationships provide a mapping of beliefs between and among the state descriptions. Finally, the outcomes and preferences include the decision maker's rankings of the possible outcomes. Depending on which state of the world turns out to be the true state, the decision maker's actions lead to different outcomes.

Decision support encompasses a wide range of available tools, including analytic methods such as Bayesian analysis, belief network modeling, fuzzy set theory, and a variety of different model forms such as regression, forecasting, scheduling, selection, simulation, and optimization models. A review of the major analytic methods and model frameworks is presented in the following sections. Included is a discussion of the applicability of the methods and frameworks to the crew reassignment decision model.

The construction industry in general employs a select few decision support models in its day-to-day operation [Libertore, Pollack-Johnson, and Smith, 2001]. The most commonly used model is for scheduling of construction activities [Wyatt, 2003; Longworth, 2002]. Almost every medium-to-large construction project uses critical path method scheduling software to identify the planned sequence of construction and compile progress updates on a regular interval, usually monthly. On the occasion that formal resource planning is undertaken, typically, the resources are added as part of the schedule development. This process usually takes the form of adding finish-to-start logic ties among the activities that are planned to be performed by a single crew, precluding these activities from appearing as concurrent work. Less frequently, the effort required by each individual work activity is quantified. For example, the schedule activity for the installation of large diameter pipe will include the number of linear feet of pipe that is to be installed. This activity is then resource loaded with information regarding the manpower and equipment that is planned for the performance of that particular activity. This results in a productivity unit rate for the planned manpower and equipment.

Although resource loading a schedule is a very time consuming undertaking, it does allow the utilization of additional features found in scheduling software, such as resource leveling and resource smoothing that can be applied only to resource-loaded schedules. As previously noted, the original resource plan rarely is revised, even when significant logic changes and/or new activities are incorporated into the schedule or when demonstrated productivity does not meet expectations.

Several other decision support systems proposed for use in construction include a prototype decision support system for construction management that links company information in a data warehouse with a decision support system [Chau, Cao, Anson, and Zhang, 2003]; a system developed to provide advice regarding differing site conditions claims [Diekmann and Kraiem, 1990]; and a model intended to provide the most cost-effective ratio of overtime to added personnel [Tse and Love, 2003]. Also, a prototype construction labor monitoring system, that was intended to aide contractors and owners in project planning, recently was developed for Puget Sound, Washington [Pace, 2003]. To date, none of these systems have been widely adopted by the construction industry.

Other decision support models and systems used by the construction industry are the same models and systems used throughout the general business world. These models generally are for financial management purposes and include forecasting models for cost trending and financial planning, estimating models for bid preparation, and inventory models for material control.

The available literature revealed no information on the development of a crew reassignment model for use in situations when changes occur on a construction project.

2.3. Decision Support Model Frameworks

A basic principle of modeling is the ability to build a simplified representation of reality. A good model will access and accumulate data from a variety of sources and will transform that data into information that can be used to assist in making better decisions. In addition, a critical part of the philosophy of modeling is that the choice of a particular model and type of analytic technique is a decision to exclude all other possibilities. The appropriate model must include not only an accurate representation of the problem, but also must address the issue of being user-friendly. After all, the purpose of the model is to provide assistance to the decision maker.

Decision models can be classified in several different ways. One high-level classification is to define the models as either static or dynamic, depending on whether or not time is an element of the model. Another method of classification is based on the mathematical or logical focus of the model. The highest level of this type of classification would include abstract decision models, which focus on mathematical precision, and conceptual decision models, which can be defined as analogies to the problem context [Marakas, 1999]. The classification of abstract decision models would include deterministic, stochastic, simulation, and domain-specific models. A third method of classification is to group the decision models based upon the model architecture. The groups would include purely descriptive models, explanatory models, predictive models, and goal-seeking or solvable models [Grimes, 2001]. A fourth method of classification is based on the type of problem that each model typically is used to address. These classifications would include models for allocation, distribution, activity scheduling, decision and risk analysis, demand and resource forecasting, and process management and control [Davis, 1988]. Within each of these model classifications one finds a variety of quantitative techniques, including mathematical programming, network optimization, network analysis, stochastic methods, and forecasting procedures.

The features of the decision support model must correlate to the characteristics of the problem being analyzed and the needs of the particular decision maker. The key characteristics of the construction crew reassignment problem include:

(1) Uncertainty – Uncertainty is associated with the factors that influence the potential outcomes and the alternative courses of action that can be taken. For example, when the change is precipitated by a conflict between two elements, there may be more than one potential resolution to the conflict. Although the contractor can assess the likelihood for any particular resolution, it can not be known with certainty which resolution will be chosen by the designer.

(2) Subjective Input – The information available for consideration in making the crew reassignment decision is subject to the perspective of the particular decision maker. The decision maker's experience on other projects or a lack of experience may affect the way an issue is viewed and evaluated.

(3) Multi-stage Events – The complex choices that must be considered are dependent on a previous chain of events. As time progresses, the choices and decisions vary, depending on the stage of the project, the status of the work, and previous choices and decisions.

(4) Choices and Decisions – The decision-maker is confronted with a series of choices and decisions. Each of the possible crew reassignment options represents an available choice and the necessity for a decision.

(5) Flexibility and Dynamic Conditions – The underlying conditions of the crew assignment decision are constantly changing. These conditions include the labor market, material availability, task status, and the stage of the project.

(6) High Frequency of Use and Responsiveness – The crew reassignment is an “operational” decision, requiring quick responses and simple access for frequent updating.

(7) Ease of Use – On many projects, crew reassignment decisions due to changes are contemplated almost daily. In order to be useful to field personnel, the model must contain both conceptual and application simplicity. In addition to the characteristics of the problem, the nature of the user and the intended application of the decision support model requires consideration of the mathematical orientation of the decision makers, who will be comprised of construction management and field personnel, and the anticipated circumstances of use.

(8) Transparency – All analytical assumptions should be apparent to the user. This feature is critical to the use of the model as a record of the decision process, especially in the justification of productivity losses to the owner and for the development of a productivity database that can be used for future bid and estimate preparation.

(9) Evaluability – The internal criteria and the outcomes recommended by the model should be able to be tested with scenarios for which the "right" answers have been determined.

Of all the quantitative techniques previously listed, only network analysis and stochastic methods can accommodate the uncertainty that is inherent in the crew reassignment decision. Table 1 is a summary matrix of the frameworks available in both network analysis and stochastic methods and their ability to accommodate the characteristics and desired attributes of the crew reassignment decision support model.

Table 1: Decision Model Framework Evaluation

Model	Characteristics of Crew Reassignment Decision						Desired Attributes of Model		
	Uncertainty	Subjective Input	Multi-Stage Events	Choices and Decisions	Flexibility and Dynamic Conditions	High Frequency of Use and Responsiveness	Ease of Use	Transparency	Evaluability
Network Analysis Models									
Decision Trees	◆	◆	◆	◆	◆	◆	◆	◆	◆
Flowgraphs	◆	◆	◆	◆	◆	◆	◆	◆	◆
Influence Diagram	◆	◆	◆	◆	◆	◆		◆	◆
CPM and PERT	◆				◆	◆			
Stochastic Methods									
Simulation	◆	◆	◆		◆				
Queuing	◆								
Markovian Chains	◆		◆						

As summarized in Table 1, an evaluation of the available models relative to the key characteristics of the crew reassignment decision problem revealed that the decision tree and flowgraph frameworks appear to contain the necessary characteristics and desired attributes.

A decision tree provides both a graphic depiction of the problem as well as a framework for quantitative evaluation [Jeljeli and Russell, 1995]. The typical decision tree solution algorithm is based on roll-forward and roll-back techniques. During the roll-forward a joint probability and an output value for each branch in the tree is determined. During the roll-back the optimal policy that maximizes the expected value of the decision problem is determined. One advantage of the decision tree framework is the explicit representation of the chronology of events and the state of information at each decision. This allows a large, complicated problem to be viewed as a series of smaller, simpler problems. Additional advantages include the recognition of the uncertainty of any estimates used in the analysis and the formation of a basis for the continuous evaluation of decisions that have distant time horizons. A disadvantage of the decision tree is that every added variable expands the tree combinatorially.

A flow analysis or flowgraph is a graphic depiction of the problem using geometric shapes and arrows [Davis, 1988]. The geometric shapes represent the uncertain variables that comprise the problem. The directed arrows represent the flow of information and probabilistic dependencies. An advantage of a flowgraph is the ability to depict complex relationships between the activities. For example, the occurrence of an event may result in a portion of the process being repeated.

Since the consideration of repeating a part of the process is not a necessary requirement of the crew reassignment decision problem, there appears to be no reason to chose the flowgraph format. Therefore, the decision tree format appears to provide the best choice of the available models.

2.4. Sources of Uncertainty

There are two general sources of uncertainty: variability and incomplete knowledge [Hoffman and Hammonds, 1994]. Variability can occur due to the randomness of nature; human behavior; economic, cultural, and societal dynamics; subjective judgement; and technological surprise. Incomplete knowledge can be present due to unreliability and structural or systemic uncertainty [Morgan and Henrion, 1990; Rowe, 1994]. Unreliability is comprised of inexactness and the lack of available or practically immeasurable data, while structural or systemic uncertainty is comprised of indeterminacy, conflicting evidence, and reducible and irreducible ignorance [Morgan and Henrion,1990; Rowe, 1994]. Since there are both theoretical and practical limitations to the reduction of uncertainty it is necessary to develop means to accommodate and address uncertainty in the decision process.

The potential sources of uncertainty in the crew reassignment decision process are listed in Table 2.

Table 2: Potential Sources of Uncertainty

Variability	
Category	Example
Human Behavior	Performance of workers under change circumstances
Natural Randomness	N/A
Societal Randomness (social, economic, and cultural)	Labor and material markets
Technological Randomness	N/A
Value Diversity (disagreement)	Priorities of different parties involved in the change process

Lack of Knowledge		
	Category	Example
Unreliability	Inexactness	Amount of work that might be required to implement the change; Linguistic imprecision
	Lack of Measurements	No data or measurements available regarding the productivity rates
	Practically Immeasurable	Complete productivity data for each contractor not
Structural	Indeterminacy	Length of time to receive responses
	Conflicting Evidence	Inefficiencies attributable to unidentified causes
	Reducible Ignorance	Schedule analysis to accompany each potential change
	Irreducible Ignorance	Interactions between processes that can not be defined

2.5. Representation of Uncertain Information

One of the core problems in reasoning under conditions of uncertainty is that of combining pieces of uncertain information and inferring conclusions in a sound and consistent manner [Torsun, 1995]. Different theories have been developed to deal with different types of uncertainty. Smets [1995] identified three broad categories of analytical models for representing uncertainty in decision making: probability-based (Bayesian) models; non-standard probability models; and non-probabilistic models.

Probability theory, with over a one-hundred-year history, is best at representing uncertainty that often is described as randomness. When only partial information about the uncertainty of a variable is available a Bayesian probability model may not be appropriate, as exact probability distributions may be difficult or impossible to obtain. As discussed by Casman, Morgan, and Dowlatabadi [1999, p34]:

> However, as the quality of scientific understanding becomes poorer, developing meaningful probability judgments to combine alternative models of the world becomes increasingly more difficult. In such circumstances, many Bayesian theorists would advise the analyst to specify the (perhaps infinite) set of all priors and models which fit the constraints imposed by whatever limited knowledge one has. Probability weights (which might all be equal) should then be applied across this set, and the problem should be solved for all cases. While we have no basic theoretical disagreement with such an approach, we also know from experience that a prescription that one's analytical formulation should grow in complexity and computational intensity as one knows less and less about the problem, will not pass the laugh test in real-world policy circles.

Non-standard probability models have been developed to address vagueness or a lack of clarity [Bouchon-Meunier, Yager, and Zadeh, 2000; Chen, 1999]. Fuzzy sets, possibility theory, and other non-standard probability models allow the representation of concepts used in human reasoning and perceptions. In this group of models, the Dempster-Shafer theory and certainty factors are particularly well suited for the representation of information that is both random and granular. The following are brief descriptions of fuzzy sets, Dempster-Shafer theory, and certainty factors.

Unlike probability theory, fuzzy set theory has nothing to do with the frequency or repetition of an event. Instead, fuzzy set theory deals with the graduality of concepts and their boundaries, allowing reasoning with vague or ambiguous terms [Zadeh, 1965 and 1978]. A fuzzy set may be regarded as a class in which an object may have a grade of membership between unity (full membership) and zero (non-membership). For this reason, fuzzy set theory is well-suited for group decision making.

The Dempster-Shafer theory introduces the notion of non-belief or ignorance, which is not addressed in classical probability theory [Shafer, 1976]. The Dempster-Shafer theory assumes that the values of prior probabilities are not always known. Thus, any particular choice of the probability, P(x), may not be justified. Belief functions are introduced to distinguish between uncertainty and ignorance. Belief functions allow the decision maker to use his knowledge to bound the probabilities to events without designating exact probabilities. The difficulties in utilization of the Dempster-Shafer theory stem from the requirement that all subsets must be considered and probabilities assigned.

Certainty factors, which are based on experts' estimates using qualitative verbal assessments, are used to indicate a judgmental degree of confirmation in a hypothesis [Shortliff and Buchanan, 1975; Heckerman and Shortliffe, 1992; Fu and Shortliffe, 2000]. First used in the MYCIN expert system, developed at Stanford University in the mid-1970s, certainty factors were intended to address the problem of reasoning under uncertainty or with incomplete information [Buchanan and Shortliffe, 1984]. Although the certainty factor model has some basis in probability theory, it is considered more of an *ad hoc* approach that is meant to simulate inexact human reasoning. As such, it is computationally simple, but is generally considered to defy interpretation of the certainty factors as strict probabilities. However, Heckerman [1986] has described transformations of certainty-factor models to probability theory; Adams [1984] showed that certainty factor theory was an approximation of standard probability theory; and Lucas [2001] has investigated and mapped the relationship between Bayesian belief networks and fragments of the certainty-factor model.

As noted, certainty factors usually are obtained using linguistic terms. Table 3 provides the correlation between the verbal response and the numerical values of the certainty factors. Generally, certainty factors range from -1.0 to +1.0; 0 to +1; 0 to 10; or 0 to 100.

Based on the scale of 0 to +1, a zero indicates complete disbelief or the lowest possible belief, while a one indicates complete belief or the greatest possible belief. A certainty factor near 0.5 indicates little or no evidence either for or against.

Table 3: Certainty Factor Value Interpretation

Uncertain Term	Range of Values	
	-1 to +1 Scale	0 to +1 Scale
Definitely Not	-1.0	0
Almost Certainly Not	-0.8	0.1
Probably Not	-0.6	0.2
Maybe Not	-0.4	0.3
Unknown	-0.2 to +0.2	0.4 to 0.6
Maybe	+0.4	0.7
Probably	+0.6	0.8
Almost Certainly	+0.8	0.9
Definitely	+1.0	1.0

The mathematical method used to compute a new certainty factor from existing certainty factors is referred to as the certainty factor algebra. In the original certainty factor model, the evidence for similarly concluded rules was divided into confirming evidence and disconfirming evidence. The confirming evidence was combined together, in an asymptotic and commutative fashion, into a measure of belief. Similarly, the disconfirming evidence was combined into a measure of disbelief. The net belief was calculated as the difference between the measure of belief and the measure of disbelief using the formula:

$$CF[H,E+ \text{ and } E-] = MB[H,E+] - MD[H,E-] \quad (1)$$

Where

CF = combined certainty factor
H = hypothesis
E+ = Evidence for
E- = Evidence against
MB = Measure of Belief
MD = Measure of Disbelief

Using Equation 1, a single piece of disconfirming evidence could offset many confirming pieces of evidence. To desensitize this effect, the combining rules for multiple pieces of evidence for a single hypothesis were revised as shown in Equation 2.

$$CF_{combine}(CF_1, CF_2) = \begin{cases} CF_1 + CF_2(1 - CF_1) & CF_1 \text{ and } CF_2 > 0 \\ \dfrac{CF_1 + CF_2}{1 - \min\{|CF_1|, |CF_2|\}} & (CF_1)(CF_2) < 0 \\ CF_1 + CF_2(1 + CF_1) & CF_1 \text{ and } CF_2 < 0 \end{cases} \quad (2)$$

Where

$CF_{combine}$ = combined certainty factor
CF_1 = confidence in the hypothesis established by rule 1
CF_2 = confidence in the hypothesis established by a rule 2

These combination equations exhibit the desired properties of being both commutative and asymptotic. The commutative property allows $CF_{combine}$ to be independent of the order in which the evidence is considered. The asymptotic property allows multiple pieces of confirming evidence to incrementally add to $CF_{combine}$. In addition, the asymptotic property allows $CF_{combine}$ to converge toward 1 without ever reaching this value without absolute 'proof' from at least one piece of evidence.

The combining methods for multiple premise rules fall into two classes: joint methods and confirmative methods. Joint certainty-combining methods (conjunctive rules) are used for expressions involving 'and', while confirmative certainty-combining methods (disjunctive rules) are used for expressions involving 'or'. The following is a description of the most common joint and confirmative methods, using a scale of 0 to 1 for the certainty factor values.

Joint Methods – The most-widely used joint certainty-combining methods are the minimum method, the product method, and the joint average method. The following is a brief description of each of these three methods.

The minimum method is the lower of the two levels of confidence being considered. For example, if we have certainty factors of 0.6 and 0.8, the minimum method would yield a joint certainty factor = min {0.6, 0.8} = 0.6. Essentially, the minimum method is analogous to the 'weakest link' argument.

The product method, which is the mathematical product of the two levels of confidence, will yield a certainty factor that is less than or equal to the result from the minimum method.

Using the same two certainty factor values of 0.6 and 0.8, the product method yields a joint certainty factor = (0.6 * 0.8) = 0.48. Therefore, the product method is more conservative than the minimum method.

The joint average method is a compromise between the minimum and product methods. Using our example, this method yields a joint certainty factor = (min {0.6, 0.8} + (0.6 * 0.8))/2 = 0.54.

Figure 1 is a graphic comparison of the joint certainty-combining methods.

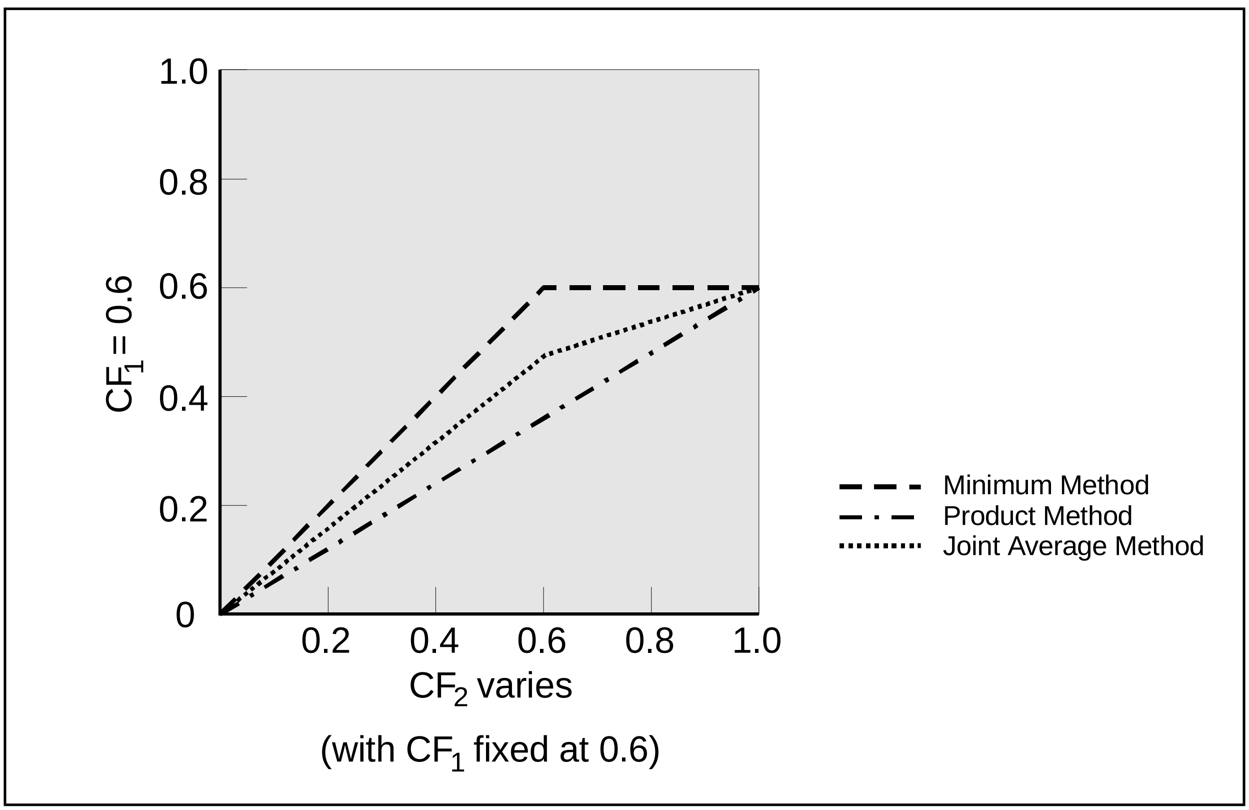


Figure 1: Comparison of Joint Certainty-Combining Methods

Confirmative Methods – The most-widely used confirmative certainty-combining methods are the maximum method, the probability sum method, and the confirmative average method. The following is a brief description of each of these three methods.

The maximum method is simply the higher of the two levels of confidence being considered. For example, if we have certainty factors of 0.4 and 0.7, the maximum method would yield a joint certainty factor = max {0.4, 0.7} = 0.7. This method provides the most cautious result of the three confirmative methods, as it does not consider any contribution from the confirming evidence.

The probability sum method calculates the sum of the two certainty factors minus the product of the two certainty factors, yielding a higher value than the maximum method. Since the expressions are combined with an 'or', the argument is that one reinforces or confirms the other. For the example of certainty factors of 0.4 and 0.7, the probability sum method returns a certainty factor = ((0.4 + 0.7) - (0.4 * 0.7)) = 0.82.

The confirmative average method is a compromise between the maximum and probability sum methods. Using our example, this method yields a confirmative certainty factor = (max {0.4, 0.7} + ((0.4 + 0.7) - (0.4 * 0.7))/2 = 0.76.

Figure 2 is a graphic comparison of the three confirmative certainty-combining methods discussed.

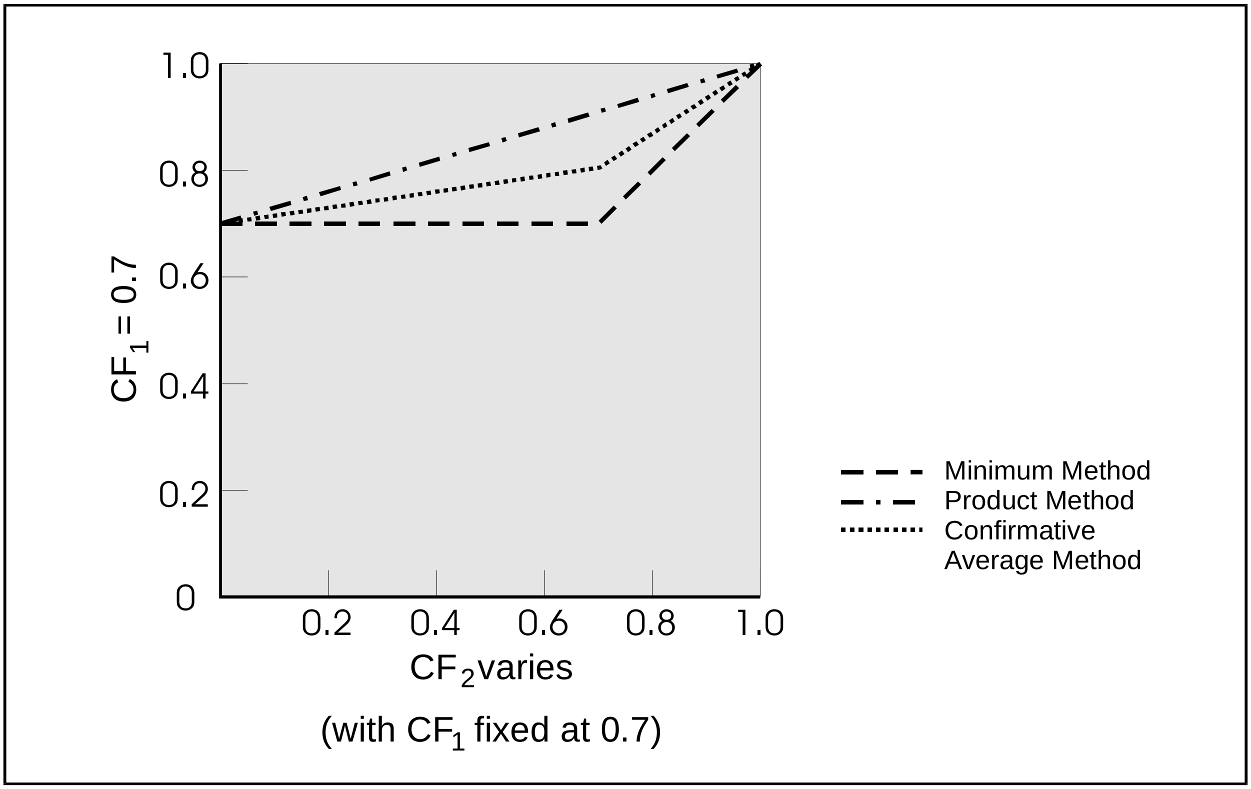


Figure 2: Comparison of Confirmative Certainty-Combining Methods

The combining method(s) employed should emulate the way in which the human expert combines the uncertainties for the particular situation (Holsapple and Whinston, 1996). This can be determined by asking the expert to provide joint or confirmative certainty factors for particular circumstances and then determining which method(s) provides the certainty factors closest to those provided by the expert. Alternatively, the joint or confirmative certainty factors calculated by each method can be evaluated by the expert to determine which appears to provide the most reasonable assessment. A summary of the joint and confirmative certainty factor algebras is shown in Table 4.

Table 4: Summary of Joint and Confirmative Certainty Factor Algebras

Summary of Certainty Factor Algebras for Combining Evidence (CF Scale of 0 to 1)	
Joint Certainty – evidence linked by 'and' –	Confirmative Certainty – evidence linked by 'or' –
Minimum Method: $CF_{New} = \min \{CF_1, CF_2\}$	Maximum Method: $CF_{New} = \max \{CF_1, CF_2\}$
Product Method: $CF_{New} = CF_1 * CF_2$	Probability Sum Method: $CF_{New} = (CF_1 + CF_2) - (CF_1 * CF_2)$
Joint Average Method: $CF_{New} = (\min \{CF_1, CF_2\} + (CF_1 * CF_2))/2$	Confirmative Average Method: $CF_{New} = (\max \{CF_1, CF_2\} + (CF_1 + CF_2) - (CF_1 * CF_2))/2$

Since certainty factors are not strict probabilities, there can be inconsistencies. One of the concerns is the overcounting of evidence, since the estimation of certainty factors is based on the assumption of independence among evidence. This concern can be address through careful model construction.

The final category of analytic methods, non-probabilistic models, attempts to match human judgmental reasoning, which is more qualitative than quantitative. One of the most-frequently used method in this category is scenario analysis. Robustness analysis is another non-probabilistic, non-quantitative model that can be applied to problems with a high degree of uncertainty where decisions are staged sequentially [Rosenhead and Mingers, 2001; Rosenhead, 2002].

Studies have shown that most people prefer to use linguistic phrases when communicating their opinions to others, while the preference is to receive opinions in numerical format. [Brun and Tiegen, 1988; Olson and Budescu, 1997]. During initial interviews to gain insight into the crew reassignment decision process, the decision makers used qualitative phrases such as “the change most likely would be . . .” or “the designer probably would issue a response . . .” in the description of the likelihood of an event occurring. This type of verbal rather than numerical assessment was consistent with the certainty factor approach to inexact reasoning. Although there are differing views on the quantifiability of probability phrases and the transformation of vague and incomplete preferences into numerical estimates, this research proceeded on the basis that such quantifiability was possible and meaningful [Bodescu, Karelitz, and Wallsten, 2003; Mosteller and Youtz, 1990; Moxey and Sanford, 2000; and Teigen and Brun, 1999; Wong and Lingras, 1994; Ngwenyama and Bryson, 1998; Yager, 1999]. This position is supported by a number of studies that have been performed on the transformation of verbal responses to numerical values, showing that the mapping of an individual’s verbal expressions to numbers is reasonably consistent and stable over time [Reagan, Mosteller, and Youtz, 1989].

Due to the planned frequency of application of the model, the need for a quick response, and the lack of probability distributions from repetitive occurrences, the decision support model must employ a simple-to-use, non-standard or non-probabilistic quantitative technique. Coupling the need for a non-probabilistic analytic method with the user preference to use verbal assessments results in a recommendation to use certainty factors as the quantitative method for the crew reassignment decision support model.

In summary, based on the problem definition, the model framework that appears to be most suitable is the decision tree, while the quantitative method that appears to be most suitable is certainty factors.

CHAPTER 3: DEVELOPMENT OF CREW REASSIGNMENT DECISION SUPPORT MODEL

3.1. Introduction

This section contains a discussion of the development and evolution of the crew reassignment decision model, including the methods of elicitation of information from potential model users and a presentation of the proposed models.

3.2. Model Development

In addressing the need for both an accurate representation of the crew reassignment decision problem and the issue of user-friendliness, the development of the proposed model was an evolutionary process. During the early phases of the research, the tasks that comprise the functional essence of the decision support model were identified and assessed. First, influence diagrams, shown as Figures 3 and 4, were created to depict the crew reassignment decision, which frequently occurs prior to the full definition of a potential change.

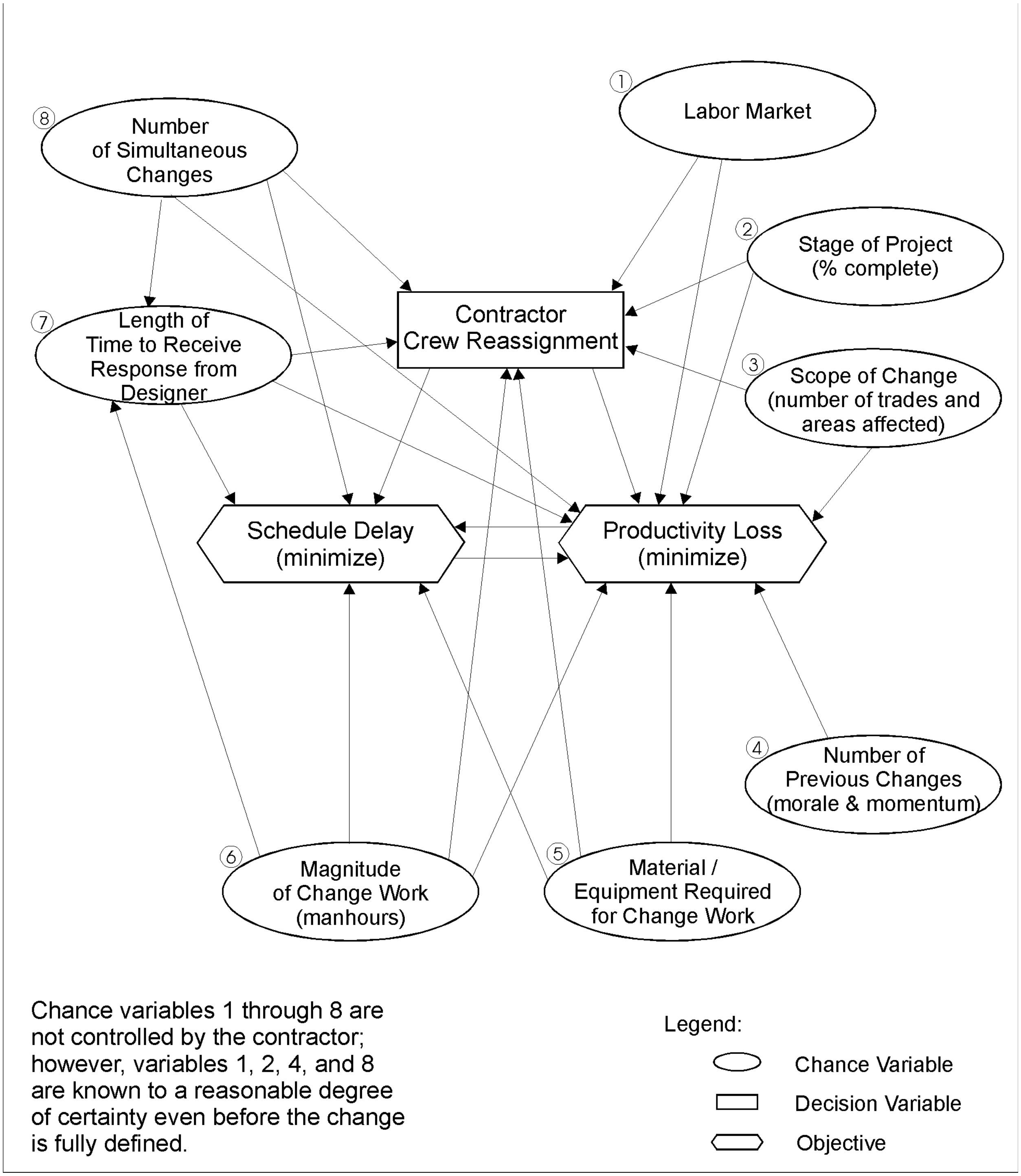
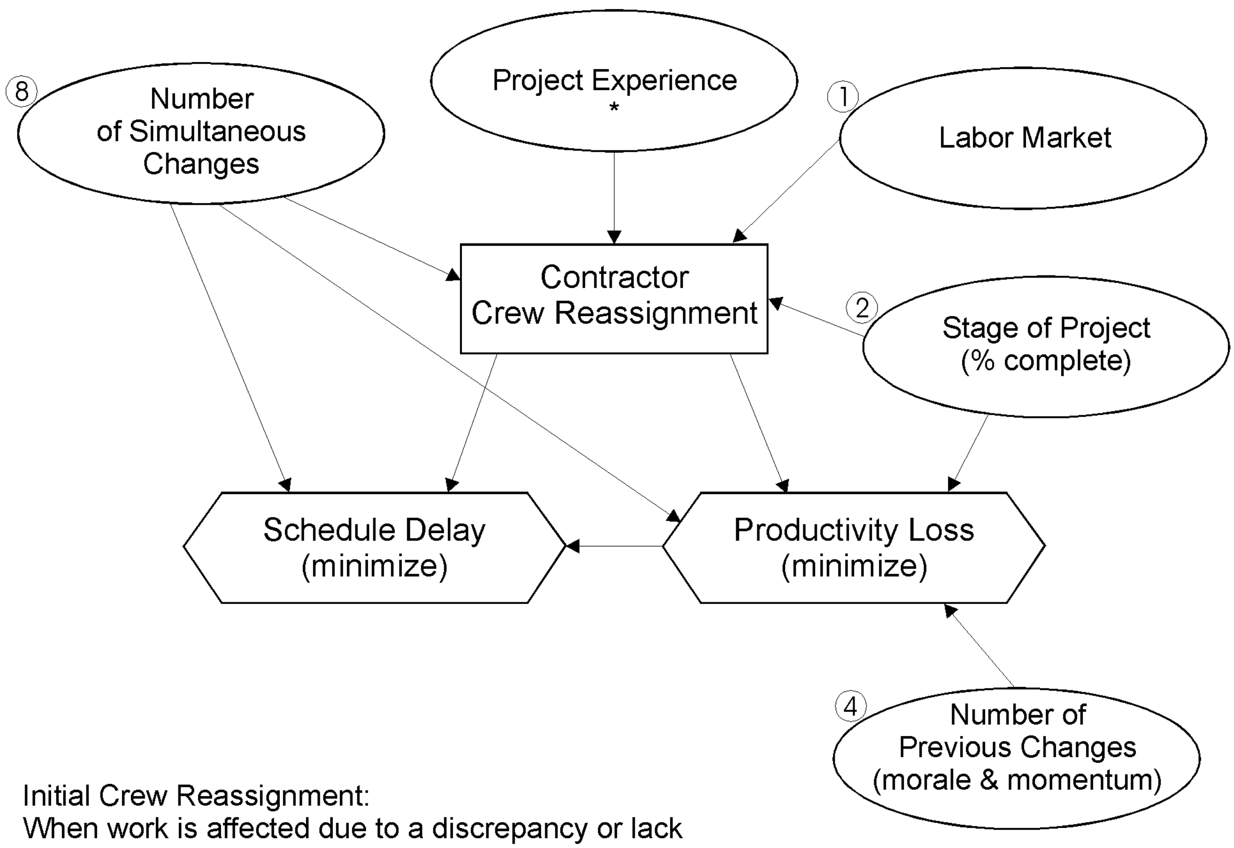


Figure 3: Influence Diagram for Crew Reassignment Decision



Initial Crew Reassignment:
When work is affected due to a discrepancy or lack of information in the drawings or specifications the contractor does not know with certainty:
-the length of time it will take to receive a response from the designer;
- the scope of the change work that will be required;
- whether material or special equipment will be required;
- the magnitude of the change work (number of manhours).
Therefore, the contractor must make assumptions based on project experience in determining the initial crew reassignment response.
* Project Experience includes historical knowledge about the current project as well as other projects. This includes responsiveness of the designer on this particular project; the likely response from the designer (i.e., of the possible resolutions, which is most likely to be chosen).

Legend:
Chance Variable
Decision Variable
Objective

Figure 4: Refined Influence Diagram for Crew Reassignment Decision

Next, descriptions of the possible circumstances under which changes occur were created. A table was developed for each of these potential change scenarios, based on the state of the affected work when the change was identified: (1) prior to the project starting (after signing of contract); (2) after the start of the project (or mobilization of affected trade), but before start of affected work activity; (3) after the start of the affected work activity; and (4) after completion of the affected work activity. The tables listed the cause of the change, potential subsequent actions, scope of the subsequent actions, contractor response options, and potential schedule and productivity effects. In addition, the links between each of the states were identified. A sample of the tables is included as Table 5.

The complete definition and analysis of the tables resulted in a series of ten flow charts based on the type of change as well as the stage of the project. The ten types of changes and project stages included: (1) lack of design information or discrepancy in the drawings or specifications prior to starting work in an area; (2) lack of design information during on-going construction in an area; (3) change work after signing the contract, but prior to work starting; (4) change work prior to work starting in an area; (5) change work after work is underway in an area; (6) change work after work is complete in an area (i.e., change that requires rework); (7) differing site conditions prior to starting work in an area; (8) differing site conditions after work is underway in an area; (9) stop work order prior to work starting in an area; and (10) stop work order after work is underway in an area. A sample of the flow charts is included as Figure 5.

Table 5: Crew Reassignment Considerations and Links

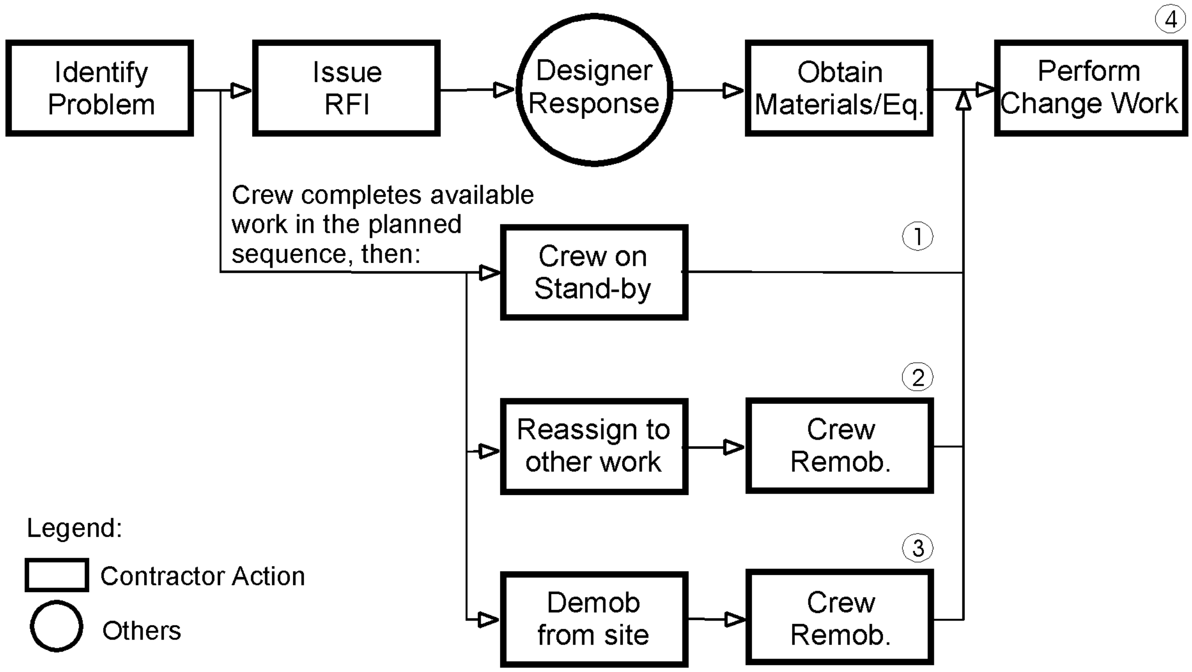
Time of Occurrence: Prior to Project starting (after contract is signed)					
(1) Cause of Change	Link	(2) Subsequent Action(s)	Link	(3) Scope of Subsequent Action	Link
Lack of design information or permits	11 12 13 15 16	11. *Owner or Regulatory Agency issues stop work order*	21 23	21. Entire project	31 35
Differing Site Conditions	11 12 13	12. Issue Request for Information -> *Issue Response to RFI* -> Issue Request for Proposal -> Issue Proposal -> *Issue Change Order or Construction Change Directive*	21 22 23	22. Specific trade	32 33 34 35
Owner-directed changes	14	13. Issue Request for Information -> *Issue Response to RFI* -> No change order required	21 22 23	23. Specific work activity(ies)	32 33 34 35
Weather	15	14. *Issue Request for Proposal* -> Issue Proposal -> *Issue Change Order or Construction Directive*	21 22 23		
Force Majeure	15	15. Issue notice of delay	21 23		
Contractor Coordination	11 15 16	16. Issue notice of breach	21		
Cash Flow Restrictions	11 15 16				
Instructions: Begin with column (1) and follow links to the numbered entries in subsequent columns.					

Change for which the Contractor is not responsible —
Time of Occurrence: Prior to Project starting (after contract is signed)

(4) Contractor Response Options	Link	(5) Potential Productivity Effects	(6) Potential Schedule Effects*
31. Do not mobilize	41 42 43 44 45 46	41. None	None
32. Mobilize as planned and work-around as necessary	42 44 45 46	42. Over-manning or congestion due to reassignment of manpower	Day-for-day delay to project completion
33. Mobilize for specific work activity and assign planned crew(s) to other work on project	42 44 45	43. Under-manning	Shift in critical path once float has elapsed for affected activity
34. Mobilize smaller crews than planned	43 44 45 46	44. Dilution of supervision (working in distant areas)	
35. Mobilize as planned and stand-by	42 44 45 46 47	45. Out-of sequence or Re-sequence	
		46. Shift work or Overtime	** Links to Potential Schedule Effects not shown*
		47. Stand-by time	

Instructions: Begin with column (1) and follow links to the numbered entries in subsequent columns.

Design conflict discovered after mobilization of crew



Potential causes of inefficiency:

① Crew completes all available work in the planned sequence, then is on stand-by pending receipt of the missing design information.
- stand-by

② Crew is reassigned to other available tasks on the project, then performs change work when information and/or material is available.
- de-mobilization from current task; mobilization for new task
- learning curve, dilution of supervision, congestion and/or trade stacking at new task
- re-mobilization for change work

③ Crew is demobilized from the site. When information and/or material is available, the crew (or a new crew) is re-mobilized.
- de-mobilization and re-mobilization
- orientation and learning curve if new crew is mobilized
- different base productivity if new crew is mobilized (may represent a productivity gain or loss)

④ Crew performs the affected work. (Note: these potential productivity losses are related to the change work, not the crew reassignment decision.)
- learning curve - if change work differs from original work
- congestion / trade stacking
- dilution of supervision
- overtime / shift work
- different base productivity - if different crew is re-mobilized

Figure 5: Flow Diagram for Design Conflict After Mobilization

3.2.1. Model Elements

The compilation of the information depicted in the influence diagrams, tables, and flow charts showed that each crew reassignment decision is comprised of five main elements: (1) possible responses or resolutions to the identified problem; (2) response time, which is the time between the identification of the problem and receipt of the response; (3) implementation preparation time, which is any additional time after receipt of the response and the time when implementation of the resolution can begin; (4) crew reassignment options and related costs; and (5) model recommendation. Each of the elements is discussed below.

(1) Possible responses or resolutions to the identified problem – The possible responses that may be received are comprised of the universe of potential resolutions for the issue at hand. The potential responses are as varied as the problems that arise on a construction project. For example, the potential resolutions to a conflict between the designed routing of ductwork and an existing structural beam could include (a) re-size the duct work to fit in the available space; (b) modify the structural element to accommodate the duct; (c) lower the ceiling to allow the duct to fit under the beam; or (d) re-route the duct to another area where adequate clearance exists. The likelihood of any particular response depends on the particular circumstances of the change and the general circumstances of the project, including how each potential resolution might affect the project schedule,

the aesthetics of each potential resolution, and the costs and ease of implementing each potential resolution.

(2) Response time – The response time for each potential response represents the amount of time expected to elapse between the identification of the problem and the receipt of direction for that particular resolution. Each potential resolution will have its own expected response time. For example, if the potential resolution requires revised drawings or revised engineering calculations, the expected response time for this particular resolution will probably be longer than for resolutions that do not require revised drawings or calculations. Additional factors that may affect the response time include the work load of the designer; whether or not coordination with outside agencies is required; and the criticality or priority of the issue.

(3) Implementation preparation time – The implementation preparation time is the amount of time between receipt of the required resolution to the point when the work can begin. Typically, the implementation preparation time is comprised of the time required to order and receive any materials, tools, and/or equipment that are not readily available on the project site. Thus, resolutions that can be implemented with materials, tools, and equipment that are readily available will have no implementation preparation time. Consideration of each potential resolution will reveal whether or not special materials, tools, and/or equipment will be required. Once it is determined that a potential resolution will require special materials, tools,

or equipment, it is necessary to assess the amount of time expected to obtain the material, tools and/or equipment.

(4) Crew reassignment options and related costs – The crew reassignment options and costs represent all the possible options and the costs related to each option. The available crew reassignment options depend on the circumstances on the project at the time of the crew reassignment decision. The costs may include one-time costs plus average hourly or daily crew costs. The possible options and costs are:

A. Do Not Mobilize – Delay the planned mobilization until the affected work is available. Then, perform the work in the originally-planned sequence, starting at a later date than originally planned. The costs for this option may range from zero dollars to increased hourly crew costs for wage escalation.

In the event that the decision not to mobilize is not a project-wide decision but pertains only to certain trades, there are possible productivity losses after mobilization due to changed work conditions. The sources of productivity losses may include more concurrent work than originally planned (congestion), more confined working conditions, and limited access to work areas. Additional costs may be incurred due to escalation of costs for materials and increased costs for equipment at the time the work is performed. For example, a contractor may plan on using owned equipment to perform the work. However, when the work is rescheduled, conflicting demands for the equipment may require the contractor to use rented equipment instead of owned equipment. Typically, the costs for rental equipment exceed those for owned equipment. These incremental additional costs would be part of the costs to be considered in the crew reassignment decision.

B. Standby – Mobilize the crew as planned (or retain the existing crew if already mobilized) and place on standby. Then, perform the change work as soon as the work is available, followed by the balance of the contract work in the planned sequence. The costs will be the hourly crew costs times the number of hours of standby. Note that standby crew costs include both labor and idle equipment.

If other work is planned to follow immediately after the work delayed by the change, the planned progress of additional trades may be affected if the standby time exceeds the lag between the activities. In that event, standby costs may be incurred for additional trades and/or equipment.

C. Reassign the Crew and Re-Sequence the Work – Mobilize the crew as planned (or maintain the existing crew if already mobilized), but assign the crew to work in an area or on a task other than what was originally planned, resulting in re-sequencing of the work. At some time in the future, the crew would perform the change work. Reassignment and re-sequencing is possible only if another work area exists. This option allows and/or requires the follow-on trades to perform re-sequenced work as well.

The costs would be comprised of demobilization and re-mobilization costs to move the crew from one area to another or one task to another (if already mobilized) plus any inefficiency costs associated with the performance of the out-of-sequence work. Typically, the inefficiency will be estimated as a range of productivity loss that would be applied to all or part of the hours planned for the out-of-sequence work.

D. Mobilize Smaller Crew – This is the same as option C. Reassign the Crew and Re-Sequence the Work except that a smaller-than-planned crew would be mobilized (or a smaller crew would be retained if already mobilized) and assigned to work in an area or on a task other than what was originally planned, resulting in re-sequencing of the work. Then, when the as-planned work is available, additional forces could be mobilized to achieve the planned crew size. Mobilization of a smaller crew with reassignment and re-sequencing is possible only if another work area exists. This option allows or requires the follow-on trades to perform re-sequenced work as well.

As with option C, the costs would be comprised of demobilization and re-mobilization costs to move the crew from one area to another or one task to another (if already mobilized) plus any inefficiency costs associated with the performance of the out-of-sequence work, including any inefficiency resulting from the performance of the work with a smaller-than-planned crew size. Typically, the inefficiency will be estimated as a range of productivity loss that would be applied to all or part of the hours planned for the out-of-sequence work. Note that since a smaller-than-planned crew is utilized the work is expected to be performed over a longer-than-planned duration. Therefore, possible wage escalation costs may be incurred.

E. Demobilize the Crew from the Site – The crew would be demobilized from the site. At some time in the future, a crew (not necessarily the same crew) would be re-mobilized to perform the change work and any remaining original work scope. The costs would be comprised of demobilization and re-mobilization costs for the crew plus inefficiencies for ‘learning curve and orientation’ effects after re-mobilization. In addition, since a different crew may have a lower productivity rate, there may be inefficiency costs associated with all remaining manhours.

(5) Model recommendation – The final element is the model recommendation. The goal of the next phase of the research was to develop a model that would address each of the four previous elements in a manner that would provide the decision maker with information to make the crew reassignment decision from a more informed position than was achieved previously without the model.

3.2.2. Proposed Model Framework

The results of the investigation into the available decision support model frameworks coupled with an analysis of the elements that comprise the crew reassignment decision problem led to the development of three preliminary proposed decision trees. These models represent the three possible change work scenarios and the crew reassignment decisions that must be made when a change is identified on a construction project.

The three possible change work scenarios are: (1) a change that is identified before the work starts on the project or in the particular area affected by the change; (2) a change that is identified during on-going work in the area affected by the change; and (3) a change that is identified after work is complete in an area, resulting in rework. The differences in the three scenarios manifest themselves in the choices available for the crew reassignment.

Since the decision tree model representing the scenario when a change is identified during on-going work in an area encompasses all possible crew reassignment options, the proposed decision tree model for this scenario was used as the basis for further research. A summary of this decision tree model is included as Figure 6. As shown, the crew reassignment decision options under this scenario include “standby,” “reassignment on site,” and “demobilization off site.”

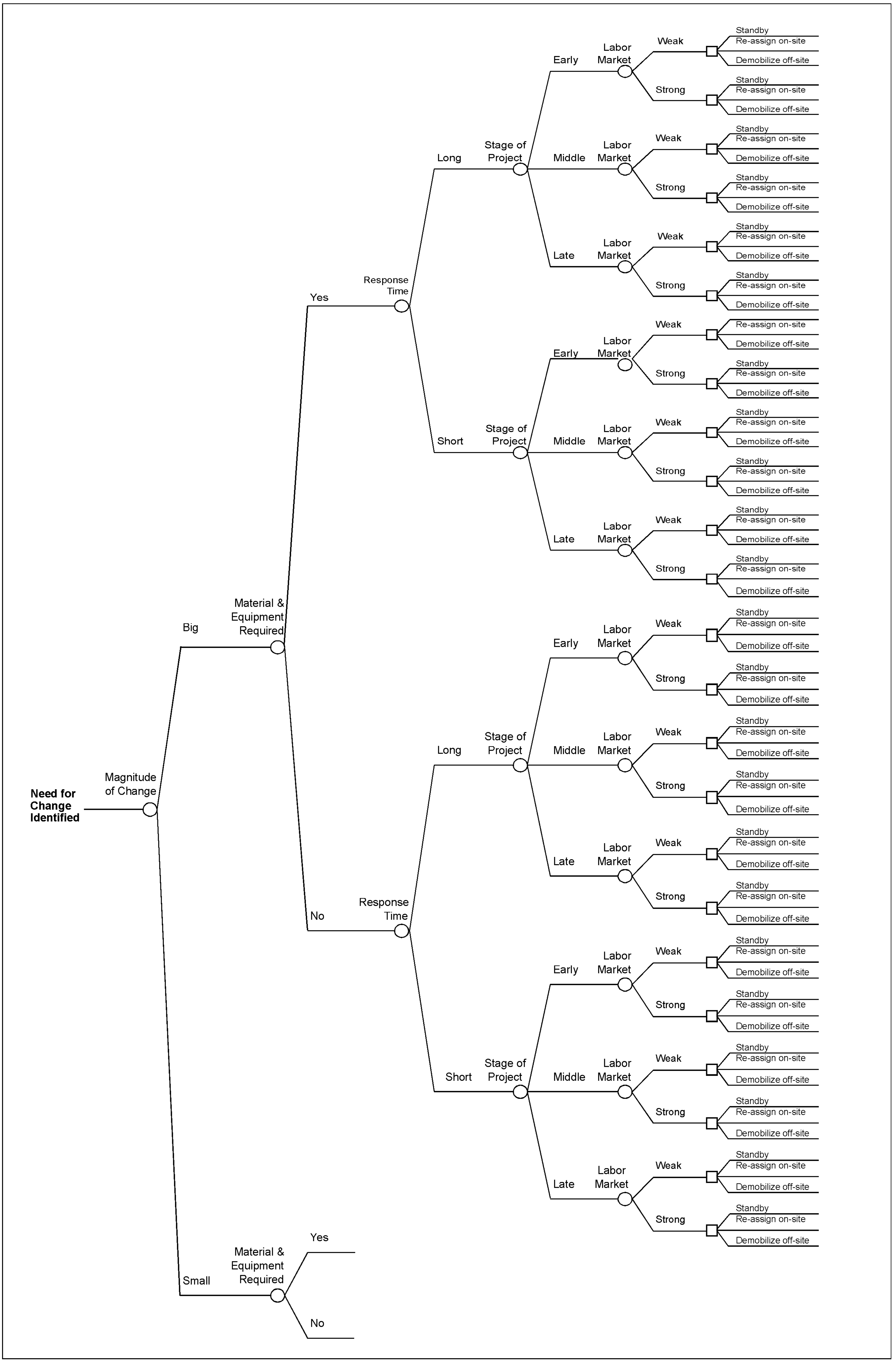


Figure 6: Initial Crew Reassignment Decision Model

3.2.3. Refinement of Proposed Model Framework

This section describes the process used to obtain information from members of the construction industry who are responsible for crew reassignment decisions in order to refine the proposed model framework. The following steps were used in this process:

(1) Solicitation of information from crew reassignment decision makers via questionnaires regarding the key factors in the crew reassignment decision process.

(2) Gathering of information from the crew reassignment decision makers via group meetings regarding the process of the crew reassignment decision.

(3) Refinement of the model based on information received.

Potential participants were selected for inclusion in the study by invitation of the author. The consideration of potential participants was limited to those involved in either commercial or institutional construction. All potential participants were considered to represent respected members of the construction community in the state of Florida. The potential participants were informed that the study would entail the completion of a survey and attendance at a group meeting. The estimated time to complete the survey was 20 minutes, while the estimated duration of the group meeting was 3 to 4 hours. All potential participants that were invited to be included in the study agreed to take part, except one.

The declining potential participant cited an out-of-state assignment as the reason for not being available.

Due to scheduling conflicts, that precluded assembling all the volunteer participants at a single time, two group meetings were scheduled. The first meeting was scheduled for Friday, December 19, 2003, in Daytona Beach, Florida, and the second meeting was scheduled for Friday, January 30, 2004, in Jacksonville Beach, Florida. There were six participants in the first meeting and eight participants in the second meeting for a total of fourteen participants in this phase of the research.

3.2.3.a. Initial Survey

One week prior to the group meetings, the participants were provided with a brief background on the crew reassignment decision problem and a survey questionnaire. The information and survey, which is shown as Figure 7, included definitions of the crew reassignment problem, descriptions of the typical crew reassignment options, and identification and definition of several of the key factors that may affect the crew reassignment decision.

Crew Reassignment Decision Support Model

Name: ____

Address: ______________________________________

____

Phone: ____

Education: Check the highest level of education completed –

High School ___ Some College ___
College Degree ___ Graduate Degree ___

Number of years in construction or construction-related field: _____

Briefly explain your construction experience:

____

____

____

____

____

____

Initial Survey Page 1

Figure 7a: Initial Survey

Crew Reassignment Decision Support Model

Changes occur on almost every construction project. The nature and circumstances of some changes require the reassignment of personnel. The purpose of this study is to identify and compile the considerations and options available to project management and supervision in making crew reassignment decisions when changes occur. The findings will be incorporated into a Crew Reassignment Decision Support Model that will assist in the prospective identification of the crew reassignment alternative expected to minimize productivity loss and/or costs.

Definition of Crew Reassignment – Crew reassignment means that the crew does not perform the work as planned. The crew reassignment can take several forms, including standby, re-sequencing, smaller crew size (partial demobilization), and/or demobilization.

Do Not Mobilize – delay the planned mobilization until a later date.

Standby – crew is completely non-productive awaiting resolution of the change.

Re-Sequencing – crew performs work in a sequence other than originally planned.

Smaller Crew Size – a portion of the crew is demobilized, leaving a smaller-than-planned crew.

Demobilization – the entire crew is demobilized from the site. This may include reassignment to another site. Once the change work is available to be performed, a crew is remobilized.

The crew reassignment decision can arise whenever a change occurs. Failure to address the issue or a decision to "do nothing" inevitably results in a loss of productivity. These productivity losses typically are not captured in the pricing of change orders, as the losses occur not from the actual performance of the change work but from the circumstances surrounding the identification of the change work.

Initial Survey Page 2

Figure 7b: Initial Survey

Initial research has identified several factors that appear to be key elements in the crew reassignment decision. These factors are:

> Stage of the Work – this represents the identification of where in the work process the change occurs. The stages are the beginning, middle, or end of the planned work for either a particular crew, trade, or the project as a whole. Typically, the stage of the project affects the available crew assignment options. For example, at the early stage of a project, there may not be other available work areas to allow crew re-sequencing.
>
> Labor Market – this represents the availability of manpower. In a strong labor market, it is relatively difficult to obtain additional, qualified manpower. Whereas, in a weak labor market, additional, qualified workers are readily available.
>
> Time Horizon for Implementation of the Change – this factor is composed of several elements: (1) response time from the designer; (2) necessity for additional material to implement the change; and (3) necessity for additional equipment to implement the change. Each of these elements is defined in the following paragraphs.
>
> > (1) Response time from the designer – this is the length of time from when the problem is identified until direction in received that will allow resolution of the issue.
> >
> > (2) Necessity for additional material – this is whether or not materials that are not readily available will be required to implement the change.
> >
> > (3) Necessity for additional equipment – this is whether or not equipment that is not readily available will be required to implement the change.

Since there usually is more than one way to resolve an issue, the contractor does not know which of the potential resolutions the designer will choose. Therefore, the contractor first must identify the possible resolutions and evaluate the likelihood that the designer will choose each particular resolution. Finally, the contractor must evaluate the elements of each potential resolution in order to establish the likely time horizon for the implementation of that resolution. That is, once a resolution is identified, how long will it be before the work can be performed.

Initial Survey Page 3

Figure 7c: Initial Survey

The following questions are intended to help identify the key considerations by construction management / supervisory personnel when evaluating a crew reassignment situation. Please answer each question as thoroughly as possible.

The following is a list of factors that appear to be key elements in the crew reassignment decision. In column 1, please add any additional factors that you consider important. In column 2, rank the factors from most important to least important, with 1 representing the most important factor(s). Add any comments or explanations in column 3.

1 Factors	2 Rank Order (1 = most important)	3 Comments
Stage of the Work		
Labor Market		
Response Time		
Additional Material Required		
Additional Equipment Required		
Other:		

Describe any additional considerations in making a crew reassignment decision.

____

____

____

____

____

____

____

Initial Survey Page 4

Figure 7d: Initial Survey

The first part of the survey, shown in Figure 7, collected education and work history of each of the participants. The responses were collected from the participants either by telephone or in person three to four days prior to the scheduled group meeting. The responses to the questionnaire are shown in Table 6.

Table 6: Summary of Participants' Education and Work History

Participant	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Method of Contact	T	P	T	T	P	T	P	P	P	P	P	T	T	T
Education	C	C	H	C	S	S	C	G	H	S	H	C	S	C
Current Position	P	P	S	P	AS	AS	P	AP	S	AP	S	P	AS	S
Years in Construction	15	32	35	27	19	10	28	12	42	16	12	36	21	18
Current Project Type	I	C	C	I	C	C	C	C	C	C	C	I	I	I
Current Project Value (millions)	$40	$25	$18	$39	$26	$32	$24	$24	$16	$10	$20	$32	$28	$37
	Group 1						Group 2							

Legend:

Method of Contact:
T = Telephone
P = In Person

Education:
H = High School
S = Some College
C = College
G = Graduate School

Current Position:
P = Project Manager
AP = Assistant Project Manager
S = Superintendent
AS = Assistant Superintendent

Current Project Type:
C = Commercial
I = Institutional

As shown in Table 6, the fourteen participants were project managers, assistant project managers, superintendents, and assistant superintendents. All participants were male. These personnel currently had the responsibility for resource planning and the assigning and reassigning of construction labor and equipment on their respective projects. The experience of the participants ranged from 10 to 42 years in the construction industry. The maximum education level achieved by the participants ranged from high school through graduate school. Although several participants had experience on other types of construction, at the current time all participants were involved in the areas of commercial or institutional construction, including mid-and high-rise condominium buildings, apartment complexes, retail shopping and entertainment complexes, hotels, schools, and health care facilities. All the participants currently were employed on medium-sized projects, ranging in value from $10 to $40 million. The study specifically excluded those with construction experience solely outside of the commercial and institutional arena, such as transportation, manufacturing, or process facility construction.

The participants also completed a questionnaire that requested the identification and assessment of key factors in the crew reassignment decision. A summary of the rankings of the factors included in the questionnaire is shown in Table 7. Note that none of the participants identified any “Other” factors as playing a key role in the crew reassignment decision.

Table 7: Summary of Factor Rankings in Initial Survey

Factors	Rank Order (1 = most important)														Median Rank	Mode
Participant	A	B	C	D	E	F	G	H	I	J	K	L	M	N		
Stage of the Work	4	5	3	3	2	2	4	2	4	5	3	5	5	5	4	5
Labor Market	5	5	4	3	4	5	5	5	5	4	5	4	4	2	4.5	5
Response Time	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Additional Material Required	3	3	2	5	3	3	2	3	2	3	2	3	2	4	3	3
Additional Equipment Required	3	3	5	5	5	4	3	4	3	3	4	3	3	4	3.5	3
	Group 1						Group 2									

As shown in Table 7, all participants ranked Response Time as the most important factor in the crew reassignment decision.

The participants were asked if there were any additional possible crew reassignment options not included in the Initial Survey. All participants agreed that the listing and descriptions of the possible crew reassignment options included in the Initial Survey, as shown in Figure 7, encompassed all available choices for crew reassignment. These options were: Do Not Mobilize (delay mobilization); Standby; Re-Sequencing (reassignment of crew elsewhere on the project); Partial Mobilization or De-Mobilization (smaller crew size); and Demobilization. Although demobilization was identified by all participants as a potential crew reassignment option, the participants expressed an aversion to demobilization, regardless of the stage of the project, the strength of the labor market, and/or the time horizon of the response and implementation. The general assessment was that once a crew is mobilized on the site, it is desirable to maintain that crew on site until the work is complete. The participants also indicated that the opposition to demobilization stemmed from that fact that there was no guarantee that the same crew would return or that any crew would be immediately available at the time that the work could resume.

The survey also provided space for the description of “additional considerations in making the crew reassignment decision.” The responses from participants B and I and L noted that the likelihood of receiving prompt payment for the change work was a consideration. When asked to provide further explanation, all three participants indicated that this consideration affected whether or not the performance of the change work would be undertaken prior to the receipt of a executed change order or directive from the designer and was not related to the decision of what to do with the crew upon initial identification of a problem. Therefore, this was not a concern that had to be addressed by the proposed model.

In addition to the questions on the survey, each participant was asked, “What is the current method used to determine the crew reassignment when a change is identified on the project?” Every participant responded that there was no specific process or standard of considerations. The methods currently used were characterized as “trying to find some other work to fill in the time until the planned work could resume." This was in keeping with the previously-noted reluctance to demobilize a crew.

3.2.3.b. Group Meetings

The group meetings, which followed the initial surveys, were for the purpose of identifying any additional considerations in the crew reassignment decision, to ascertain the methods used by the decision makers to combine the various factors, and to perform a preliminary test of the proposed model.

The first group meeting was held on Friday, December 19, 2003, from 1:00 PM to 4:25 PM. The meeting was held in the conference room of a contractor's home office in Daytona Beach, Florida. The second meeting was held on Friday, January 30, 2004, from 12:15 PM to 4 PM. The meeting was held in the conference room at a construction site in Jacksonville Beach, Florida. There were six participants in the first meeting and eight participants in the second meeting for a total of fourteen participants in this phase of the research. These were the same participants that completed the Initial Survey discussed in the previous section.

The start of the group meetings was in the format of directed discussions. The opening introduction included a review of the definition of the crew reassignment problem and a summary of the results of the initial surveys regarding the key elements of the crew reassignment decision. In addition, a general overview of management decisions made under risk and ambiguity was presented as background information [Blondel, 2002; Ho, Keller, and Keltyka, 2002; Neilson, 2002]. The introduction lasted 15 to 20 minutes. Following the introduction, the participants were encouraged to discuss any additional considerations in the crew reassignment decision that were not previously identified. The participants indicated that the previously-identified elements fully addressed the decision problem.

Next, the groups read a devised scenario and, through open-discussions, described the decision process used for the crew reassignment decision in response to the circumstances described. The scenario, which is included as Figure 8, involves a design discrepancy between the size of the mechanical duct and the ceiling space into which the duct is to be installed.

Scenario 1
While installing the HVAC trunk line in a corridor, the contractor discovers a conflict between the trunk line and the existing structure. The duct in question is located in the first area that duct is scheduled to be installed on the project. The contractor issues a Request for Information to the designer. Since the sheet metal tradesmen have mobilized, the potential choices available to the contractor are: (1) put the crew(s) on standby until a resolution is received from the designer and any necessary materials are available; (2) re-sequence the work and reassign the crew(s) to another area on the project, i.e., develop a "work-around" schedule; (3) partial de-mobilization of the crew(s), resulting in smaller-than-planned crew(s); (4) de-mobilize the crew(s) from the project. The HVAC trunk lines typically are installed first, followed by the branch lines. In addition, since the trunk lines are the largest items installed in the ceiling space, the trunk lines are installed prior to all other Mechanical, Electrical, and Plumbing commodities. All other trades (with the exception of architectural finishes) have mobilized. The structure has been dried-in and interior metal stud framing in underway. In addition, electrical rough and fire pipe installation is starting. The potential resolutions are: (A) re-design and re-fabricate the duct to fit in the available space and (B) lower the ceiling to accommodate the as-fabricated duct.

Figure 8: Crew Reassignment Scenario 1

The ensuing discussions of both groups identified the expected time from the identification of the problem to the point when implementation of the resolution could begin as the major factor in consideration of the crew reassignment decision. This total time period was comprised of the sum of the "Response Time" plus the "Implementation Preparation Time." The participants were asked to describe how the duration of this time period was estimated. The process used to estimate the duration was described as being based on previous experience on other projects on which a similar problem occurred combined with experience specific to the current project regarding the performance and responsiveness of the designer. When asked what action would be taken when presented with a problem for which there was no prior experience, the participants indicated they would rely on “instinct” or ask someone who had experience with a similar situation.

The participants were asked to describe the factors or considerations used to estimate the duration of the Response Time and the Implementation Preparation Time. The participants identified three main factors as the determinants of the expected duration of the Response Time for any particular resolution: (1) complexity of the potential response, i.e., whether or not drawing revisions, engineering calculations, and/or coordination with outside agencies were required prior to the issuance and implementation of the resolution; (2) work load of the designer at the time the issue is identified; and (3) criticality or priority of the issue. Neither group indicated that any one of these factors was more important than the others in the effect on the Response Time.

Both groups indicated that, although any single factor had the ability to affect the expected Response Time, all three factors had to be considered in concert for a proper assessment of the Response Time. For example, if a particular resolution was considered to be very complex and the designer work load was high, then it would be expected that the response time would be relatively long. However, if the criticality or priority of the response also was high, then the Response Time was likely to be shorter than it would be in the absence of this factor. The combination of the factors is discussed in detail in section 3.2.4.

The time between receipt of the resolution and the time the work could begin was identified as the “Implementation Preparation Time.” This time period was defined as consisting of the time required to obtain any materials, tools, and/or equipment required to perform the change work. In the event that all required materials, tools, and equipment are readily available or if no materials, tools, or equipment are required for implementation, then the Implementation Preparation Time would be equal to zero.

Note that the results of the initial survey showed that “Additional Material Required” and “Additional Equipment Required” were ranked second and third in importance in the crew reassignment decision. The identification of the Implementation Preparation Time as being a critical element of equal importance to the Response Time Horizon was recognition that the combined duration of these two elements represented the total time from identification of the problem to the earliest possible start of the change work. Thus, it was this total duration that had the greatest effect on the crew reassignment decision.

In the first group meeting the previously described discussion took approximately 45 minutes. During the second meeting this discussion took approximately 1 hour and 5 minutes. A ten minute break was taken prior to the start of the next portion of the group meetings.

Upon reconvening after the break, each participant was provided a copy of the Proposed Crew Reassignment Model, which was previously shown as Figure 6. The information depicted on the Proposed Crew Reassignment Model was presented by “walking through” several branches of the decision tree and describing each of the events nodes and decision nodes.

In addition, the groups were introduced to certainty factors. Although all the participants expressed at least some familiarity with the basics of probability theory, only one of the participants had previous exposure to the application of certainty factors. That experience was during a college graduate-level course. The introduction to certainty factors included a description of certainty factors as judgmental measures of belief that can be used for inexact reasoning. The participants were provided with a copy of Table 8, which lists the uncertain linguistic terms and corresponding certainty factors, based on a scale of 0 to +1.

Following the presentation of the model and the introduction to certainty factors, which took approximately 20 minutes, the participants were asked to work individually and apply the circumstances described in Scenario 1 to the proposed decision tree model. The participants were directed to use the Uncertain Terms listed in Table 8 in the application of the model and evaluation of the crew reassignment options. Calculators and additional copies of the proposed model were available for the use of the participants.

Table 8: Linguistic Terms and Certainty Factors

CF Value Interpretation	
Uncertain Term	Range of Values 0 to +1 Scale
Definitely Not	0
Almost Certainly Not	0.1
Probably Not	0.2
Maybe Not	0.3
Unknown	0.4 to 0.6
Maybe	0.7
Probably	0.8
Almost Certainly	0.9
Definitely	1.0

Since all participants currently were involved on active construction projects, they were directed to use the circumstances from their individual projects in evaluating the scenario. Thus, each application could result in varying costs and inefficiencies for each crew reassignment option and different certainty factors for each of the elements and factors. Finally, each application could result in a different recommendation. The main purpose of this exercise was to obtain additional information regarding the participants' decision process as it related to the identification and evaluation of each of the crew reassignment options; the identification and evaluation of the key factors affecting the response time; the identification and evaluation of the key factors affecting the implementation time; the establishment of certainty factors; and the combining methods applied to the certainty factors. Thus, the process was of greater interest than any specific factors used or results obtained.

No time limit was set for the participants to perform the application of Scenario 1 to the proposed model. The Group 1 members were complete and ready for the ensuing discussion in 30 minutes. Group 2 completed the task in 35 minutes. A five minute break was held prior to the start of the discussion of the results of the model application.

Immediately after the break, discussions began on each element of the model, as well as a general critique of the model, including the validity of the model as an appropriate representation of the crew reassignment decision process, the perceived utility of the model, and ease of use. Note that during the application of the model by both groups it was apparent that additional research would be needed to ascertain the combining methods used to determine the model recommendation. Thus, the following discussion focused mainly on the individual elements of the model and the general structure of the model rather than the determination of the model recommendation.

Model Elements – As noted, the main focus was an evaluation each element of the proposed model to discern the general method(s) used to combine the available information to reach a decision.

The participants agreed that the potential crew reassignment options of “standby,” “re-sequence,” “partial demobilization,” and “demobilization” provided a list of all available options for the scenario.

All participants indicated that the key elements of the proposed model, including the potential resolutions, response times, and implementation preparation time identified the main considerations in the crew reassignment decision. Both groups indicated that the "Stage of the Project" could be eliminated from the model since it was reflected in the possible crew reassignment options. In addition, the groups stated that the status of the "Labor Market" could be addressed within the potential costs for each crew reassignment. Therefore, the consensus was that the proposed model could be simplified into two main elements: Response Time and Implementation Preparation Time.

The members of both groups indicated that the factors of complexity of the potential resolution, workload of the designer, and priority of the issue were the determining factors for the Response Time. A member of Group 1 suggested the addition of a fourth factor: "general attitude and responsiveness of the designer." The suggestion was opened to group discussion. Another member of the group indicated that he believed that the "general attitude and responsiveness of the designer" was inherent in the expected response time for all three of the factors already in the proposed model. The member who made the initial suggestion agreed, as did the remaining members of Group 1. Therefore, the group concluded that the three factors of complexity of the potential resolution, workload of the designer, and priority of the issue provided complete definition of the factors that determine the expected response time. Group 2 did not suggest any changes to the factors. The suggestion made by the member of Group 1 to consider the additional factor of "general attitude and responsiveness of the designer" was presented to Group 2.

As with Group 1, the members of Group 2 concluded that this factor was included within each of the other three factors and should not be added as a separate factor.

Although Group 1 did not voice any reservations about the use of fuzzy terms such as "long," "medium," and "short" in the description of the potential time frames for response and implementation, participant H of Group 2 suggested the use of specific ranges of time. A discussion with Group 2 resulted in a unanimous support for the use of discrete time frames rather than fuzzy terms. For example, instead of identifying the Implementation Preparation Time as either "short" or "long," the revised model would replace "short" with a range of "0 to 3 days" and replace "long" with a duration of "4 to 5 days." The durations would be identified by the decision maker during the application of the model. The model was revised to include the recommended specific time durations, and a copy of the revised model was provided to and discussed with each of the members of Group 1. All members of Group 1 agreed that the revised model, which identified specific time durations for Response Time and Implementation Preparation Time, was superior to the earlier model using fuzzy terms to describe the time ranges. Thus, the revised model was used for the remainder of the research.

In summary, the consensus of the groups was that the model elements, revised as discussed above and shown in Figure 9, captured the critical elements of the crew reassignment decision process. These elements were comprised of the Crew

Reassignment Options, Potential Resolutions, Response Time, and Implementation Preparation Time.

Combination of Model Elements – The next segment of the discussion addressed the methods used to combine the certainty factors for each of the model elements.

The first portion of the model discussed was the Response Time. The participants were asked to describe how they combined the expected durations for each of the three factors of complexity, designer workload, and issue priority to arrive at the likelihood that the Response Time would fall into any one of the identified durations. The participants in both groups described the combination of individual durations and likelihoods assigned to each factor as a "worst case scenario." That is, the lowest level of belief for any one of the factors was expected to represent the overall level of belief for the duration. Table 9 provides an example of the method using the information provided by participant B.

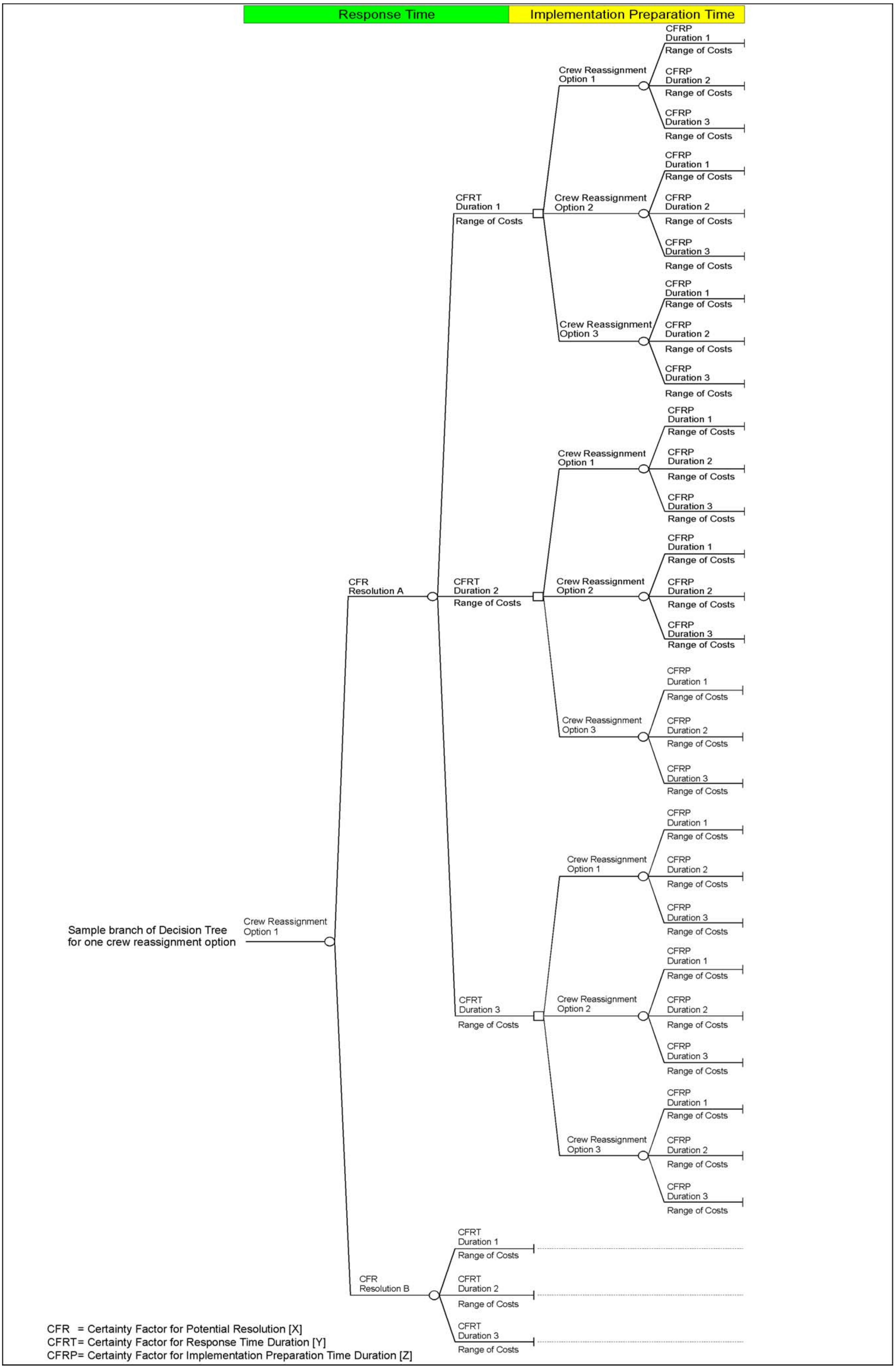


Figure 9: Sample of Revised Model

Table 9: Example of Certainty Factors for Response Time

Resolution: Revise Duct Size	Time Increment		
	"short"	"medium"	"long"
Complexity	Definitely not CF= 0	Almost certainly CF = 0.9	Maybe CF = 0.7
Workload	Maybe not CF = 0.3	Almost certainly CF = 0.9	Maybe CF = 0.7
Criticality or Priority	Maybe not CF = 0.3	Almost certainly CF = 0.9	Probably not CF = 0.2
Resolution "A" (single response)	Definitely not CF = 0	Almost certainly CF = 0.9	Probably not CF = 0.2

Note that the remaining participants did not prepare notes that could be translated into tabular information as shown above.

The combination of the likelihood of any particular response with the likelihood of any particular duration was discussed next. The participants indicated that the method used was represented by a multiplication of the certainty factors for each element. For example, if potential Resolution A was "almost certainly" (certainty factor = 0.9) to be selected by the designer and the Response Time duration of 0 to 3 days was "almost certainly not" (certainty factor = 0.1) expected to occur, then the likelihood of receiving Response A in 0 to 3 days was described as the product of the two certainty factors or 0.9 * 0.1 = 0.09 or "almost definitely not."

The discussion regarding the element Implementation Preparation Time indicated that for the potential resolutions of Scenario 1 it could be determined with certainty whether or not materials, tools, and/or equipment that were not readily available would be necessary. Thus, the certainty factor would be either 0 or 1. Note: this was represented on the Initial Proposed Model as either a “Yes” or “No” option. Therefore, only those options for which it was determined that materials, tools, and/or equipment would be necessary had to have durations identified and likelihoods assigned.

The combination of the likelihood of a particular time duration for the circumstance where materials, tools, and/or equipment would be required with the overall likelihood for a particular Response Time was also described as the product of the two factors. For example, using the results of 0.09 or “almost definitely not” for the Response Time noted above and the likelihood of “probably” (certainty factor = 0.8) for an Implementation Preparation Time duration of 4 to 5 days would provide the result of 0.09 x 0.8 = 0.072 or “almost definitely not. Thus the likelihood of receiving Response A in 0 to 3 days and the necessary material, tools, and/or equipment to implement Response A in 4 to 5 days would result in a combined certainty of 0.072 or “almost definitely not.”

Model Utility – The groups indicated that the model offered the following advantages over the current methods of crew reassignment:

(1) The model forced consideration of the change in a global perspective of how the change might affect the overall manpower and work plan, rather than the usual concern of keeping each crew busy. This would provide information that could support improved management of the entire project.

(2) The model provided a map and record of how and why the crew reassignment decision was undertaken. This would support future planning efforts as well as provide documentation for inefficiencies and delays that might be incurred.

The disadvantage cited by the group was the time required to address each of the elements and factors. For example, assigning costs for the crew options, determining appropriate time increments, and establishing certainty factors. However, it was noted that this disadvantage was diametrically opposed to the advantages noted.

The Group 1 discussion of the application of the proposed model was 80 minutes in duration, while the Group 2 discussion was 70 minutes. A summary of the time and topics during each of the group meetings is included in Table 10.

Table 10: Summary of Time for Group Meetings

Topic	Group 1 Duration	Group 2 Duration
Introduction	15 minutes	20 minutes
Open discussion of Scenario 1	45 minutes	65 minutes
Break	10 minutes	10 minutes
Presentation of Proposed Model and Introduction to Certainty Factors	20 minutes	20 minutes
Individual Evaluation of Scenario 1 Using Proposed Model	30 minutes	35 minutes
Break	5 minutes	5 minutes
Discussion of Application of Proposed Model	80 minutes	70 minutes
Total	205 minutes	225 minutes

As noted, it was determined that individual interviews were necessary to collect additional information regarding the methods used to assign and combine the certainty factors in the model. As discussed in the following section, the results of the group sessions coupled with the detailed information gathered during the individual interviews formed the basis for the certainty factor combining methods employed by the model.

3.2.4. Model Quantification

During the time period of February, March, and April 2004, a series of in-depth interviews with six individual experts in the construction industry was undertaken in order to gain a fuller understanding of the analytical method(s) used in the crew reassignment decision and to determine the appropriate representation of this process within the model. The experts were chosen based on the variety of experience in addressing crew reassignment decisions as well as an expressed interest in the process of developing the crew reassignment model.

Four of the experts in this phase had been participants in the group sessions. These experts were denoted as B, C, G, and H in Table 6. Experts O and P had not participated in the group sessions. The experts had the same general backgrounds and experience levels as the group participants with specific years of construction-related experience ranging from 12 years to 35 years. As with the group members, all the experts were employed in the construction industry in the areas of commercial and institutional construction. Table 11 is a summary of the six experts' education and work history.

Table 11: Summary of Experts' Education and Work History

Expert	B	C	G	H	O	P
Education	C	H	C	G	C	S
Current Position	P	S	P	AP	S	AS
Years in Construction	32	35	28	12	17	23
Current Project Type	C	C	C	C	I	C
Current Project Value	$25	$18	$24	$24	$33	$14
	Group 1		Group 2			

Legend:

Education:
H = High School
S = Some College
C = College
G = Graduate School

Current Position:
AP = Assistant Project Manager
P = Project Manager
AS = Assistant Superintendent
S = Superintendent

Current Project Type:
C = Commercial
I = Institutional

Three interviews were scheduled with each expert. During each interview one of each of three crew reassignment scenarios was discussed. The experts were informed that the expected duration for each interview was one to two hours.

The first of each of the individual meetings started with a review of the crew reassignment decision problem and certainty factors in general. This encompassed a summary of the previously-issued definitions that were presented in Figures 5 and 6. This review lasted between 10 and 15 minutes. In the cases of the two experts that did not participate in the group meetings, approximately one week prior to the individual meetings, each was provided a copy of the Initial Survey that was shown in Figure 7. Each expert completed the survey and the responses were discussed via telephone. These responses, in addition to the responses previously presented for the four experts from the group sessions, are presented in Table 12.

Since the group discussions established support for the theory that the revised model was a reasonable framework for the decision process of the crew reassignment problem, the individual meetings focused on the analytical method used by the decision makers in the assessment of the crew reassignment decision, including the assignment and propagation of the certainty factors for the various model elements. In order to determine the certainty factor algebra that should be employed in the model, each expert ‘walked through’ the analysis of three different change scenarios, including the scenario used during the group sessions. The three scenarios are described in Figure 10.

Table 12: Summary of Factor Rankings in Experts' Survey

Factors	Rank Order						Median Rank	Mode
Expert	B	C	G	H	O	P		
Stage of the Work	5	3	4	2	4	5	4	4, 5
Labor Market	5	4	5	5	3	5	5	5
Response Time	1	1	1	1	1	1	1	1
Additional Material Required	3	2	2	3	2	2	2	2
Additional Equipment Required	3	5	3	4	3	5	3.5	3
	Group 1		Group 2					

Scenario 1

While installing the HVAC trunk line in a corridor, the contractor discovers a conflict between the trunk line and the existing structure. The duct in question is located in the first area that duct is scheduled to be installed on the project. The contractor issues a Request for Information to the designer. Since the sheet metal tradesmen have mobilized, the potential choices available to the contractor are: (1) put the crew(s) on standby until a resolution is received from the designer and any necessary materials are available; (2) re-sequence the work and reassign the crew(s) to another area on the project, i.e., develop a "work-around" schedule; (3) partial de-mobilization of the crew(s), resulting in smaller-than-planned crew(s); (4) de-mobilize the crew(s) from the project. The HVAC trunk lines typically are installed first, followed by the branch lines. In addition, since the trunk lines are the largest items installed in the ceiling space, the trunk lines are installed prior to all other Mechanical, Electrical, and Plumbing commodities.

All other trades (with the exception of architectural finishes) have mobilized. The structure has been dried-in and interior metal stud framing in underway. In addition, electrical rough and fire pipe installation is starting.

The potential resolutions are: (A) re-design and re-fabricate the duct to fit in the available space and (B) lower the ceiling to accommodate the as-fabricated duct.

Figure 10a: Change Scenario 1 Evaluated by Experts

Scenario 2
During the installation of 6" ceiling moulding in a high-rise condominium building, it is discovered that the fire sprinkler heads are mounted 4" below the ceiling, resulting in the heads being in conflict with the decorative wood moulding. The sprinkler heads are mounted on only the north-south walls. Therefore, the conflict occurs on approximately half the walls, with no conflict on the east-west walls. The sprinklers are installed as per the approved shop drawings and the moulding is as per the architectural drawings. Thus, the conflict is the result of the designers failure to coordinate the drawings. The drywall is taped, finished, primed, and the first coat of final paint is applied. The ceiling moulding is stained and delivered to each unit. The trim carpenters are mobilized and ready to begin installation of the moulding. The options available to the contractor are: (1) maintain the existing trim carpenter crews and perform the available work, returning to each unit at a later time to install the remaining trim; (2) partially demobilize the trim carpenters and perform the available work at a slower pace; (3) completely demobilize. Potential resolutions are: (A) relocate the sprinkler heads (cut wallboard, sprinkler pipe, patch wallboard, paint); (B) notch wood moulding to accommodate sprinkler heads; (C) revise the specifications for the wood trim to a smaller height (less than 4").

Figure 10b: Change Scenario 2 Evaluated by Experts

Scenario 3
Shortly after the start of foundation work for a multi-story hospital complex, a stop-pump order is issued due to arsenic-contaminated groundwater. The structural concrete crews are mobilized and electrical and mechanical crews for underslab utilities are ready to be mobilized. The options available to the contractor are (1) maintain existing crews, performing limited available work (roughly equivalent to standby) until resolution is received; (2) demobilize a portion of the existing crews, performing the limited available work until resolution with a smaller crew; or (3) stop all work and completely demobilize until resolution of the stop-pump order. Note that due to the high water table at the site, dewatering is necessary to complete the foundations. Therefore, re-sequencing is not an option. The potential resolutions are: (A) install monitoring wells then resume dewatering and (B) construct holding ponds and restrict daily dewatering quantities.

Figure 10c: Change Scenario 3 Evaluated by Experts

In order to allow time to evaluate the information received from the experts' analysis of each scenario, the scenarios were reviewed in three separate sessions with each expert. The sessions, which were held at the jobsite office of each expert, were scheduled at the expert's convenience. The dates and durations of each session are shown in Table 13.

Table 13: Dates and Durations of Expert Interviews

Scenario	Expert	Date	Duration
1	O	February 5, 2004	135 minutes, including 30 minute introduction
	H	February 12, 2004	65 minutes
	P	February 13, 2004	105 minutes, including 30 minute introduction
	B	February 18, 2004	90 minutes
	C	February 18, 2004	65 minutes
	G	February 19, 2004	85 minutes
2	H	February 26, 2004	60 minutes
	G	February 26, 2004	65 minutes
	B	March 4, 2004	55 minutes
	C	March 4, 2004	60 minutes
	P	March 5, 2004	70 minutes
	O	March 12, 2004	65 minutes
3	O	March 18, 2004	65 minutes
	B	March 19, 2004	65 minutes
	C	March 26, 2004	80 minutes
	P	March 27, 2004	70 minutes
	G	March 30, 2004	65 minutes
	H	April 2, 2004	70 minutes

Note that the durations listed in Table 13 do not include approximately 15 minutes of time used to compile the expert-provided information into the decision tree format prior to the discussion of the analytical method.

The method of obtaining information from the experts and the results of the analysis of the information obtained are discussed in the following sections.

3.2.4.a. Potential Responses

At the start of each session, the expert was provided a printed copy of the scenario to be reviewed during that session. After reading a scenario, the first issue discussed with each expert was the likelihood of each of the identified potential responses being received from the designer. Table 14 contains a listing of the potential responses and the experts' assessments of the likelihood of each potential response.

Table 14: Likelihood of Potential Responses for Test Scenarios

Scenario 1 Potential Responses	Expert					
	B	C	G	H	O	P
A – resize and refabricate the duct	0.8	0.9	0.9	0.8	0.95	0.9
B – lower the ceiling	0.1	0.2	0.1	0.2	0.1	0.1
Scenario 2 Potential Responses	**Expert**					
	B	C	G	H	O	P
A – relocate the sprinkler heads	0.8	0.95	0.8	0.75	0.9	0.9
B – notch wood molding to accommodate sprinkler heads	0.0	0.0	0.1	0.1	0.0	0.1
C – revise the specifications for the wood trim to a smaller height	0.2	0.1	0.1	0.3	0.2	0.1
Scenario 3 Potential Responses	**Expert**					
	B	C	G	H	O	P
A – monitoring wells, resume dewatering	0.8	0.6	0.7	0.5	0.5	0.5
B – holding ponds with restricted dewatering	0.4	0.5	0.4	0.5	0.6	0.5

As shown in Table 14, for Scenarios 1 and 2, the experts tended to indicate that one of the potential resolutions was much more likely than any other. Scenario 3 was specifically chosen for inclusion in this phase of the research, as it was anticipated that there would not be as clear a “favorite” resolution. This would allow analysis of the way the experts considered the crew reassignment decision under circumstances where all potential resolutions were considered almost equally likely.

3.2.4.b. Response Time

The Response Time is the time from the identification of the problem to the receipt of the resolution. The experts identified the time increments for the Response Time for each of the potential resolutions for each scenario. For example, for Scenario 1, Expert B identified three time increments for Resolution A: (1) less than one day; (2) one day through five days; and (3) six days through ten days. The time increments identified by the experts for each potential resolution of each scenario are shown in Table 15.

Table 15: Experts' Time Increments for Potential Resolutions

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
Scenario 1	Resolution A	B	< 1 day	1 day - 5 days	6 days - 10 days
		C	1 day - 2 days	3 days - 5 days	6 days - 8 days
		G	1 day - 3 days	4 days - 6 days	7 days - 9 days
		H	1 day - 2 days	3 days - 7 days	8 days - 10 days
		O	1 day - 2 days	3 days - 5 days	6 days - 10 days
		P	1 day - 5 days	6 days - 10 days	N/A
Scenario 1	Resolution B	B	< 1 day	1 day - 5 days	6 days - 10 days
		C	1 day - 2 days	3 days - 5 days	6 days - 8 days
		G	1 day	2 days - 3 days	4 days - 5 days
		H	1 day - 2 days	3 days - 5 days	6 days - 8 days
		O	1 day - 2 days	3 days - 5 days	6 days - 10 days
		P	1 day - 5 days	6 days - 10 days	N/A

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
Scenario 2	Resolution A	B	1 day - 2 days	3 days - 5 days	N/A
		C	1 day	2 days - 3 days	4 days - 5 days
		G	1 day - 3 days	4 days - 5 days	6 days - 8 days
		H	1 day	2 days - 5 days	6 days - 10 days
		O	1 day	2 days - 4 days	5 days - 7 days
		P	1 day - 3 days	4 days - 6 days	7 days - 10 days
Scenario 2	Resolution B	B	1 day - 2 days	3 days - 5 days	N/A
		C	1 day	2 days - 3 days	4 days - 5 days
		G	1 day - 3 days	4 days - 5 days	6 days - 8 days
		H	1 day	2 days - 5 days	6 days - 10 days
		O	1 day	2 days - 4 days	5 days - 7 days
		P	1 day - 3 days	4 days - 6 days	7 days - 10 days
Scenario 2	Resolution C	B	1 day - 2 days	3 days - 5 days	N/A
		C	1 day - 3 days	4 days - 7 days	8 days - 10 days
		G	1 day - 3 days	4 days - 5 days	6 days - 8 days
		H	1 day	2 days - 5 days	6 days - 10 days
		O	1 day	2 days - 4 days	5 days - 7 days
		P	1 day - 3 days	4 days - 6 days	7 days - 10 days
Scenario 3	Resolution A	B	1 day - 5 days	6 days - 10 days	11 days - 15 days
		C	1 day - 5 days	6 days - 10 days	11 days - 15 days
		G	1 day - 3 days	4 days - 8 days	9 days - 12 days
		H	1 day - 5 days	6 days - 10 days	11 days - 15 days
		O	1 day - 5 days	6 days - 10 days	11 days - 15 days
		P	1 day - 3 days	4 days - 6 days	7 days - 10 days

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
Scenario 3	Resolution B	B	1 day - 5 days	6 days - 10 days	11 days - 15 days
		C	1 day - 5 days	6 days - 10 days	11 days - 15 days
		G	1 day - 3 days	4 days - 8 days	9 days - 12 days
		H	1 day - 2 days	3 days - 7 days	8 days - 10 days
		O	1 day - 3 days	4 days - 6 days	7 days - 10 days
		P	1 day - 3 days	4 days - 6 days	7 days - 10 days

The experts were not limited in the number of time increments that could be identified for each potential resolution. However, as shown in Table 15, the experts usually identified three discrete time increments. The experts were queried regarding the likelihood of any one duration within each individual time increment being more likely than any other value. Although Expert H indicated that the longest time increment for Scenario 2, Resolution C, had a distribution that was approximately triangular in shape, in all other instances each of the experts indicated that the values within a single time increment were equally likely. That is, the values within each range followed a uniform distribution.

For each time increment a certainty factor was identified for each of the three main factors that have been identified as the determinants of the expected duration of the response time for any particular resolution. The three factors are (1) complexity of the potential response; (2) work load of the designer at the time the issue is identified; and (3) criticality or priority of the issue. The experts were asked a series of three questions for each combination of potential resolution and time increment. For example, for Scenario 1, potential Resolution A – re-size and re-fabricate the duct, each expert was asked:

(1) Based on the complexity of Resolution A, how likely is it that the response will be received in less than one day? One day through five days? Six days through ten days?

(2) Based on the current workload of the designer, how likely is it that Resolution A will be received in less than one day? One day through five days? Six days through ten days?

(3) Based on the criticality or priority of the affected work, how likely is it that Resolution A will be received in less than one day? One day through five days? Six days through ten days?”

Using the terminology and format developed for certainty factors, the preceding questions could be stated as follows:

(1) *Rule 1. Complexity*

IF Coordination with outside agencies (e.g., review by building department, new permits, etc.) or re-design and/or re-submittals are (are not) required.

THEN The response time will be (1) less than or equal to1 day; (2) greater than one day and less than or equal to five days; and (3) greater than five days and less than 10 days.

CF_1 = (a separate CF is given for each of the three time increments)

(2) *Rule 2. Designer Work Load*

IF There are (are not) a number of outstanding questions awaiting responses from the designer.

THEN The response time will be (1) less than or equal to1 day; (2) greater than one day and less than or equal to five days; and (3) greater than five days and less than 10 days.

CF_2 = (a separate CF is given for each of the three time frames)

(3) *Rule 3. Criticality or priority of the Affected Activity*

IF The activity is (is not) on or near the critical path or is (is not) a controlling item of work for the affected crew.

THEN The response time will be (1) less than or equal to1 day; (2) greater than one day and less than or equal to five days; and (3) greater than five days and less than 10 days.

CF_3 = (a separate CF is given for each of the three time frames)

As previously discussed, the combining method(s) employed in a model should emulate the way in which the human expert combines the uncertainties for the particular situation. This can be ascertained in one of two ways (1) by asking the expert to provide joint and/or confirmative certainty factors for particular circumstances and then determining which method(s) provides the certainty factors closest to those provided by the expert or (2) the joint and/or confirmative certainty factors calculated by each method can be evaluated by the expert to determine which appears to provide the most reasonable assessment.

Due to the lack of familiarity of the experts with the mechanics of certainty factors, it was determined to follow the first procedure. That is, the experts were requested to provide responses to general, all-encompassing questions such as, "*For Scenario 1, Resolution A, how likely is it that the response will be received in less than one day? One day through five days? Six days through ten days?*" The responses were translated into certainty factors, using a scale of 0 to 1. Table 16 is a sample listing of the resulting certainty factors for the responses received for Scenario 1, Resolution A. Tables 17 through 19 are summaries of all responses received for all three scenarios.

Table 16: Sample of Experts' Certainty Factors for Response Time

Scenario 1, Resolution A – Response Time				
Expert	Resolution A Factor	Time Increment		
		< 1 day	1 day - 5 days	6 days - 10 days
B	Complexity	0.0	0.9	0.7
	Workload	0.3	0.9	0.7
	Criticality or Priority	0.3	0.9	0.2
	Resolution "A" (single response)	0.0	0.9	0.2
Expert	Resolution A Factor	1 day - 2 days	3 days - 5 days	6 days - 8 days
C	Complexity	0.2	0.8	0.8
	Workload	0.5	0.8	0.8
	Criticality or Priority	0.7	0.9	0.3
	Resolution "A" (single response)	0.2	0.8	0.3
Expert	Resolution A Factor	1 day - 3 days	4 days - 6 days	7 days - 9 days
G	Complexity	0.2	0.8	0.7
	Workload	0.4	0.8	0.3
	Criticality or Priority	0.5	0.9	0.1
	Resolution "A" (single response)	0.2	0.8	0.2
Expert	Resolution A Factor	1 day - 2 days	3 days - 7 days	8 days - 10 days
H	Complexity	0.1	0.7	0.7
	Workload	0.2	0.9	0.7
	Criticality or Priority	0.2	0.8	0.7
	Resolution "A" (single response)	0.1	0.7	0.7

Expert	Resolution A Factor	1 day - 2 days	3 days - 5 days	6 days - 10 days
O	Complexity	0.1	0.7	0.9
	Workload	0.3	0.6	0.3
	Criticality or Priority	0.3	0.7	0.3
	Resolution "A" (single response)	0.1	0.6	0.3
Expert	**Resolution A Factor**	**1 day - 5 days**	**6 days -10 days**	**N/A**
P	Complexity	0.2	0.9	---
	Workload	0.4	0.9	---
	Criticality or Priority	0.7	0.9	---
	Resolution "A" (single response)	0.2	0.9	---

Table 17: Scenario 1 – Experts' Response Time Certainty Factors

		Resolution A			Resolution B		
		Time Increment					
Expert	Factor	(1)	(2)	(3)	(1)	(2)	(3)
B	Complexity	0.0	0.9	0.7	0.6	0.9	0.1
	Workload	0.3	0.9	0.7	0.5	0.9	0.1
	Criticality or Priority	0.3	0.9	0.2	0.7	0.9	0.1
	Resolution "X" (single response)	0.0	0.9	0.2	0.5	0.9	0.1
C	Complexity	0.2	0.8	0.8	0.8	0.7	0.2
	Workload	0.5	0.8	0.8	0.5	0.7	0.1
	Criticality or Priority	0.7	0.9	0.3	0.8	0.7	0.1
	Resolution "X"	0.2	0.8	0.3	0.5	0.7	0.1

Expert	Factor	Resolution A			Resolution B		
		Time Increment					
		(1)	(2)	(3)	(1)	(2)	(3)
G	Complexity	0.2	0.8	0.7	0.7	0.8	0.4
	Workload	0.4	0.8	0.3	0.3	0.8	0.4
	Criticality or Priority	0.5	0.9	0.1	0.4	0.9	0.2
	Resolution "X" (single response)	0.2	0.8	0.2	0.3	0.8	0.2
H	Complexity	0.1	0.9	0.5	0.2	0.9	0.3
	Workload	0.2	0.9	0.7	0.2	0.9	0.5
	Criticality or Priority	0.2	0.8	0.3	0.2	0.9	0.2
	Resolution "X" (single response)	0.1	0.85	0.3	0.2	0.9	0.2
O	Complexity	0.1	0.7	0.9	0.8	0.9	0.2
	Workload	0.3	0.6	0.3	0.3	0.8	0.3
	Criticality or Priority	0.3	0.7	0.3	0.6	0.9	0.1
	Resolution "X" (single response)	0.1	0.6	0.3	0.3	0.8	0.15
P	Complexity	0.2	0.9	---	0.2	0.9	--
	Workload	0.4	0.9	---	0.4	0.8	--
	Criticality or Priority	0.7	0.9	---	0.5	0.9	--
	Resolution "X" (single response)	0.2	0.9	---	0.2	0.8	--

Table 18: Scenario 2 – Experts' Response Time Certainty Factors

Expert	Factor	Resolution A			Resolution B			Resolution C		
		Time Increment								
		(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
B	Complexity	0.3	0.8	--	0.3	0.8	--	0.3	0.8	--
	Workload	0.3	0.9	--	0.3	0.9	--	0.3	0.9	--
	Criticality or Priority	0.6	0.9	--	0.6	0.9	--	0.6	0.9	--
	Resolution "X" (single response)	0.3	0.8	--	0.3	0.8	--	0.3	0.8	--
C	Complexity	0.2	0.9	0.2	0.2	0.9	0.2	0.2	0.9	0.2
	Workload	0.2	0.9	0.2	0.2	0.9	0.2	0.2	0.9	0.2
	Criticality or Priority	0.3	0.9	0.1	0.3	0.9	0.1	0.3	0.9	0.1
	Resolution "X" (single response)	0.2	0.9	0.1	0.2	0.9	0.1	0.2	0.9	0.1
G	Complexity	0.4	0.9	0.2	0.4	0.9	0.2	0.4	0.6	0.8
	Workload	0.4	0.9	0.2	0.4	0.9	0.2	0.2	0.9	0.2
	Criticality or Priority	0.7	0.9	0.2	0.7	0.9	0.2	0.4	0.6	0.7
	Resolution "X" (single response)	0.4	0.9	0.2	0.4	0.9	0.2	0.4	0.6	0.2
H	Complexity	0.3	0.8	0.3	0.3	0.8	0.3	0.3	0.8	0.3
	Workload	0.3	0.8	0.2	0.3	0.8	0.2	0.3	0.8	0.2
	Criticality or Priority	0.7	0.9	0.2	0.7	0.9	0.2	0.7	0.9	0.2
	Resolution "X" (single response)	0.3	0.8	0.2	0.3	0.8	0.2	0.3	0.8	0.2
O	Complexity	0.1	0.7	0.7	0.1	0.7	0.7	0.1	0.7	0.7
	Workload	0.2	0.7	0.2	0.2	0.7	0.2	0.2	0.7	0.2
	Criticality or Priority	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9	0.3
	Resolution "X" (single response)	0.1	0.7	0.3	0.1	0.7	0.3	0.1	0.7	0.3

Expert	Factor	Resolution A			Resolution B			Resolution C		
		Time Increment								
		(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
P	Complexity	0.2	0.9	0.3	0.2	0.9	0.3	0.2	0.9	0.3
	Workload	0.2	0.8	0.1	0.2	0.8	0.1	0.2	0.8	0.1
	Criticality or Priority	0.5	0.9	0.1	0.5	0.9	0.1	0.5	0.9	0.1
	Resolution "X" (single response)	0.2	0.8	0.1	0.2	0.8	0.1	0.2	0.8	0.1

Table 19: Scenario 3 – Experts' Response Time Certainty Factors

Expert	Factor	Resolution A			Resolution B		
		Time Increment					
		(1)	(2)	(3)	(1)	(2)	(3)
B	Complexity	0.1	0.7	0.4	0.2	0.8	0.3
	Workload	0.2	0.8	0.3	0.2	0.8	0.3
	Criticality or Priority	0.2	0.9	0.3	0.3	0.9	0.3
	Resolution "X" (single response)	0.1	0.7	0.3	0.2	0.8	0.3
C	Complexity	0.0	0.8	0.3	0.1	0.8	0.3
	Workload	0.1	0.8	0.2	0.1	0.8	0.2
	Criticality or Priority	0.1	0.9	0.2	0.1	0.9	0.2
	Resolution "X" (single response)	0.0	0.8	0.2	0.1	0.8	0.2
G	Complexity	0.1	0.7	0.3	0.1	0.9	0.1
	Workload	0.1	0.8	0.2	0.1	0.9	0.1
	Criticality or Priority	0.2	0.8	0.2	0.2	0.9	0.1
	Resolution "X"	0.1	0.7	0.2	0.1	0.9	0.1

Expert	Factor	Resolution A			Resolution B		
		Time Increment					
		(1)	(2)	(3)	(1)	(2)	(3)
H	Complexity	0.0	0.5	0.5	0.2	0.8	0.3
	Workload	0.1	0.5	0.5	0.2	0.8	0.2
	Criticality or Priority	0.1	0.5	0.5	0.2	0.9	0.2
	Resolution "X" (single response)	0.0	0.5	0.5	0.1	0.8	0.2
O	Complexity	0.1	0.8	0.2	0.1	0.8	0.2
	Workload	0.2	0.8	0.2	0.2	0.8	0.2
	Criticality or Priority	0.2	0.8	0.2	0.2	0.8	0.2
	Resolution "X" (single response)	0.1	0.8	0.2	0.1	0.8	0.2
P	Complexity	0.0	0.7	0.5	0.1	0.8	0.3
	Workload	0.1	0.8	0.4	0.1	0.8	0.2
	Criticality or Priority	0.1	0.8	0.3	0.1	0.8	0.2
	Resolution "X" (single response)	0.0	0.7	0.3	0.1	0.8	0.2

Using the responses provided for each factor and time increment, the combined certainty factor was calculated using three combination algebras: minimum method, product method, and joint average method. These combination algebras were discussed in Chapter 2 and are summarized in Table 20.

Table 20: Summary of Certainty Factor Algebras

Certainty Factor Algebras for Combining Evidence (CF Scale of 0 to 1)	
Joint Certainty – evidence linked by 'and' –	Confirmative Certainty – evidence linked by 'or' –
Minimum Method: $CF_{New} = \min \{CF_i, CF_j\}$	Maximum Method: $CF_{New} = \max \{CF_i, CF_j\}$
Product Method: $CF_{New} = CF_i * CF_j$	Probability Sum Method: $CF_{New} = (CF_i + CF_j) - (CF_i * CF_j)$
Joint Average Method: $CF_{New} = (\min \{CF_i, CF_j\} + (CF_i * CF_j))/2$	Confirmative Average Method: $CF_{New} = (\max \{CF_i, CF_j\} + (CF_i + CF_j) - (CF_i * CF_j))/2$

Where

CF_i and CF_j represent the certainty factors for individual factors.

CF_{New} represents the new certainty factor resulting from the combination of individual certainty factors.

An analysis of the experts' responses for the individual factors indicated that the joint-conjunctive minimum rule provided the certainty factor that was most-closely correlated to the single response certainty factor. Using the durations identified for Scenario 1, Resolution A in Table 16, the questions, "*For Resolution A, how likely is it that the response will be received in less than one day? One day through five days? Six days through ten days?*" resulted in responses that correlated to the minimum value of the certainty factors for each of the three factors.

Although the responses from all the experts were not all as precise a match as the example, the minimum method consistently provided the closest match between the three factors and the single factor provided by the expert. Thus, although the group discussions established that none of the three factors was more important than the others in the effect on the Response Time Horizon, it appeared that any one factor could override or dominate the effects of the other two factors on the expected response time.

Next, information was gathered to determine the method used by the experts to identify the likelihood that any one particular combination of Response and Time Increment might occur. The experts were asked to describe the process used in arriving at the answer. The experts indicated that the process involved an adjustment of the certainty factor for each time increment through consideration of the certainty factor for the particular resolution. That is, the certainty factor for the time increment was adjusted downward by combining it with how likely the expert thought it was that a particular resolution received.

In addition, the experts were asked the question "*How likely is it that the response will be 'Resolution [A]'* <u>*and*</u> *that the response will be received in less than one day? One day through five days? Six days through ten days?*" The verbal responses, which were translated into certainty factors on a scale of 0 to 1, are shown in Table 21. Note that in several cases the experts indicated a confidence or likelihood of being "almost certain that it definitely won't happen." This was translated to a Certainty Factor of 0.01.

The responses provided by the experts, as shown in Table 21, were compared to the combined certainty factors calculated using a variety of joint combination methods. A sample of the calculations is shown in Table 22. The sample calculations represent the responses received from Expert C for Scenario 1. The joint product method of calculating the combined certainty factors provided the certainty factor that most-closely simulated the responses provided by the experts. In addition, this combination method was consistent with the process described by the experts for combining the confidence levels for the potential responses and the time increments.

Table 21: Experts' Combination of Certainty Factors for Potential Resolutions and Time Increments

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
1	A	B	0.0	0.7	0.15
	B		0.05	0.1	0.01
	A	C	0.15	0.7	0.25
	B		0.1	0.15	0.01
	A	G	0.2	0.7	0.2
	B		0.02	0.1	0.01
1	A	H	0.1	0.7	0.2
	B		0.01	0.1	0.01
	A	O	0.1	0.6	0.3
	B		0.01	0.1	0.01
	A	P	0.2	0.8	--
	B		0.01	0.1	--

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
2	A	B	0.25	0.65	--
	B		0.0	0.0	--
	C		0.05	0.15	--
	A	C	0.2	0.85	0.1
	B		0.0	0.0	0.0
	C		0.05	0.2	0.01
	A	G	0.3	0.7	0.15
	B		0.05	0.1	0.01
	C		0.05	0.05	0.0
	A	H	0.2	0.6	0.15
	B		0.05	0.1	0.01
	C		0.1	0.25	0.05
	A	O	0.1	0.65	0.25
	B		0.0	0.0	0.0
	C		0.01	0.15	0.05
	A	P	0.2	0.7	0.1
	B		0.01	0.15	0.01
	C		0.01	0.1	0.01

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
3	A	B	0.1	0.55	0.25
	B		0.1	0.3	0.1
	A	C	0.0	0.5	0.1
	B		0.05	0.4	0.1
	A	G	0.05	0.5	0.1
	B		0.05	0.4	0.05
	A	H	0.0	0.25	0.25
	B		0.05	0.4	0.1
	A	O	0.05	0.4	0.1
	B		0.05	0.5	0.1
	A	P	0.0	0.4	0.1
	B		0.05	0.4	0.1

Table 22: Example Calculations of Combination of Certainty Factors for Potential Resolution and Response Time

Certainty Factor for Element	Time Increment		
	1 day - 2 days	3 days - 5 days	6 days - 8 days
Resolution A	0.2	0.8	0.3
CF for Resolution A		0.9	
Combined CF provided by expert	0.15	0.7	0.25
Combined CF calculated by joint product method	0.18	0.72	0.27
Combined CF calculated by joint minimum method	0.2	0.8	0.3
Combined CF calculated by joint average method	0.19	0.76	0.285

3.2.4.c. Implementation Preparation Time

The Implementation Preparation Time is time between the receipt of the resolution and the start of the work. This time period is comprised of the duration necessary to acquire any materials, tools, and/or equipment required to construct the change work. Generally, the decision maker will be able to predict with certainty whether or not materials, tools, and/or equipment that are not readily available will be necessary to implement any particular potential resolution. For any potential resolution where no special materials, tools, and/or equipment are necessary, the Implementation Preparation Time will be zero days. For those resolutions that will require materials, tools, and/or equipment, the decision maker will identify appropriate time increments.

For each scenario and potential resolution the experts identified time increments for the Implementation Preparation Time. As with the time increments for the resolution time, the experts were not limited in the number of time increments that could be identified for the implementation preparation time for each potential resolution. The time increments designated by the experts are shown in Table 23. As noted, the Implementation Preparation Time was zero days for any potential resolution that was determined to require only materials, tools, or equipment that were readily available. For example, Scenario 1, Resolution B was determined not to require any special materials, tools, or equipment. Thus, the Implementation Preparation Time increment for Resolution B was zero days.

For each combination of scenario and potential resolution for which the experts indicated materials, tools, and/or equipment would be necessary, the experts were asked to identify the likelihood that the particular resolution would be received during each time increment. The question posed was in the same form used for the Resolution Response Time. For example, for Scenario 1, Resolution A, the question to Expert B was: “*For Scenario 1, Resolution A, how likely is it that the necessary materials, tools, and/or equipment will be received in one day to three days? Four days through five days? Six days through ten days?*” The responses were translated into certainty factors, using a scale of 0 to 1. Tables 24 through 26 is a listing of the responses received for all three scenarios.

Table 23: Experts' Time Increments for Implementation Preparation Time

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
1	A	B	1 day - 3 days	4 days - 5 days	6 days - 10 days
		C	1 day - 5 days	6 days - 10 days	N/A
		G	1 day - 5 days	6 days - 10 days	11 days - 15 days
		H	1 day - 2 days	3 days - 7 days	8 days - 10 days
		O	1 day - 2 days	3 days - 5 days	6 days - 10 days
		P	1 day - 5 days	6 days - 10 days	N/A
	B	B	0	0	0
		C	0	0	0
		G	0	0	0
		H	0	0	0
		O	0	0	0
		P	0	0	0

Scenario and Resolution		Expert	Time Increments		
			(1)	(2)	(3)
2	A	B	0	0	0
		C	0	0	0
		G	0	0	0
		H	0	0	0
		O	0	0	0
		P	0	0	0
	B	B	0	0	0
		C	0	0	0
		G	0	0	0
		H	0	0	0
		O	0	0	0
		P	0	0	0
	C	B	1 day - 5 days	6 days - 10 days	N/A
		C	1 day - 4 days	5 days - 7 days	8 days - 10 days
		G	1 day - 3 days	4 days - 5 days	6 days - 10 days
		H	1 day	2 days - 5 days	6 days - 10 days
		O	1 day	2 days - 5 days	N/A
		P	1 day - 3 days	4 days - 6 days	7 days - 10 days
3	A	B	1 day - 5 days	6 days - 10 days	11 days - 15 days
		C	1 day - 5 days	6 days - 10 days	11 days - 15 days
		G	1 day - 5 days	6 days - 10 days	11 days - 15 days
		H	1 day - 5 days	6 days - 10 days	11 days - 15 days
		O	1 day - 5 days	6 days - 10 days	11 days - 15 days
		P	1 day - 10 days	11 days - 15 days	16 days - 20 days
	B	B	0	0	0
		C	0	0	0
		G	0	0	0
		H	0	0	0
		O	0	0	0
		P	0	0	0

Table 24: Scenario 1 – Experts' Implementation Preparation Time Certainty Factors

Expert	Resolution A			Resolution B		
	Time Increment					
	(1)	(2)	(3)	(1)	(2)	(3)
B	0.2	0.8	0.1	--	--	--
C	0.3	0.8	N/A	--	--	--
G	0.1	0.9	0.1	--	--	--
H	0.1	0.8	0.1	--	--	--
O	0.1	0.9	0.1	--	--	--
P	0.3	0.8	N/A	--	--	--

Table 25: Scenario 2 – Experts' Implementation Preparation Time Certainty Factors

Expert	Resolution A			Resolution B					
	Time Increment								
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
B	--	--	--	--	--	--	0.3	0.8	N/A
C	--	--	--	--	--	--	0.1	08	0.1
G	--	--	--	--	--	--	0.1	0.75	0.2
H	--	--	--	--	--	--	0.0	0.8	0.2
O	--	--	--	--	--	--	0.1	0.9	N/A
P	--	--	--	--	--	--	0.1	0.9	0.1

Table 26: Scenario 3 – Experts' Implementation Preparation Time Certainty Factors

Expert	Resolution A			Resolution B		
	Time Increment					
	(1)	(2)	(3)	(1)	(2)	(3)
B	0.1	0.7	0.3	--	--	--
C	0.1	0.9	0.1	--	--	--
G	0.0	0.9	0.1	--	--	--
H	0.0	0.8	0.2	--	--	--
O	0.1	0.9	0.1	--	--	--
P	0.1	0.8	0.2	--	--	--

All experts indicated that the values within a single time increment had a uniform distribution. That is, any single duration within a time increment was equally likely to represent the expected Implementation Preparation Time.

3.2.4.d. Crew Reassignment Option Costs

The last element of the model was comprised of the potential costs associated with each of the crew reassignment options. Using the conditions on their individual projects, the experts identified the expected daily crew costs and productivity losses associated with each of the available crew reassignment options for each scenario.

Since the crew reassignment option of “standby” represents a 100% productivity loss, the costs for this option were represented by 100% of the hourly or daily crew costs. Regardless of the expected duration of the standby time, none of the experts identified any productivity loss associated with the “standby” option. However, the model does not preclude the identification of productivity loss associated with this crew reassignment option. For the crew reassignment option of “re-sequence,” the experts identified the potential productivity losses as being comprised of a certain number of hours to demobilize from the existing task plus time to mobilize at the next task. In addition, the experts designated additional inefficiencies that were expected to be incurred for a period of time while performing the new task as a result of learning curve, dilution of supervision, and so forth. The potential productivity losses assigned for “demobilize from site” included time for complete demobilization and subsequent re-mobilization. Additionally, upon re-mobilization inefficiencies were expected to be incurred for a period of time due to learning curve, re-orientation, different levels of skills between the crew prior to demobilization and the crew after re-mobilization. The crew reassignment options of “partial mobilization” or “partial de-mobilization” were expected to result in costs for the staged mobilization or de-mobilization of the crew rather than a single mobilization or demobilization. Inefficiencies resulting from sub-optimal crew sizes also were anticipated.

Based on the hourly or daily crew costs and expected productivity losses provided by the experts, the costs were calculated for each crew reassignment option that was possible for each scenario. The calculated costs for the Scenario 1 Response Time Increments are shown in Table 27.

Table 27: Scenario 1 Costs for Crew Reassignment Options

Expert B – Resolution A or Resolution B		
Response Time Increment	Description	Range of Costs
Reassignment Option: Standby		
< 1 day	Daily crew cost multiplied by the duration of the standby time.	$1,120 - $1,120
1 - 5 days		$1,120 - $5,600
6 - 10 days		$6,720 - $11,200
Reassignment Option: Re-Sequence		
< 1 day	4 hours for demobilization from existing task and remobilization at new task on jobsite plus 20% - 40% loss of efficiency for 5 days.	$1,680 - $1,680
1 - 5 days		$1,680 - $2,800
6 - 10 days		$1,680 - $2,800
Reassignment Option: Demobilization		
< 1 day	8 hours for demobilization from site and remobilization to site plus a 10% - 20% loss of efficiency for the number of days equal to the duration of the demobilization.	$1,232 - $1,232
1 - 5 days		$1,232 - $2,240
6 - 10 days		$1,792 - $3,360
Expert C – Resolution A or Resolution B		
Response Time Increment	Description	Range of Costs
Reassignment Option: Standby		
1 - 2 days	Hourly or daily crew cost multiplied by the duration of the standby time.	$1,000 - $2,000
3 - 5 days		$3,000 - $5,000
6 - 8 days		$6,000 - $8,000

Reassignment Option: Re-Sequence		
1 - 2 days	1 day for demobilization from existing task and remobilization at new task on jobsite plus 30% - 40% loss of efficiency for total number of days of reassignment.	$1,300 - $1,800
3 - 5 days		$1,900 - $3,000
6 - 8 days		$2,800 - $4,200
Reassignment Option: Demobilization		
1 - 2 days	1 day for demobilization from site and remobilization to site plus a 20% - 30% loss of efficiency for 10 days.	$3,000 - $4,000
3 - 5 days		$3,000 - $4,000
6 - 8 days		$3,000 - $4,000

Expert G – Resolution A

Response Time Increment	Description	Range of Costs
Reassignment Option: Standby		
1 - 3 days	Daily crew cost multiplied by the duration of the standby time.	$1,000 - $3,000
4 - 6 days		$4,000 - $6,000
7 - 9 days		$7,000 - $9,000
Reassignment Option: Re-Sequence		
1 - 3 days	8 hours demobilization from existing task and remobilization at new task on jobsite plus 20% - 30% loss of efficiency for each day.	$1,200 - $1,900
4 - 6 days		$1,800 - $2,800
7 - 9 days		$2,400 - $3,700
Reassignment Option: Demobilization		
1 - 3 days	8 hours for demobilization from site and 8 hours remobilization to site plus a 10% - 20% loss of efficiency for each day.	$2,100 - 2,600
4 - 6 days		$2,400 - $3,200
7 - 9 days		$2,700 - $3,800

Expert H – Resolution A		
Response Time Increment	Description	Range of Costs
Reassignment Option: Standby		
1 - 2 days	Daily crew cost multiplied by the duration of the standby time.	$1,600 - $3,200
3 - 7 days		$4,800 - $11,200
8 - 10 days		$12,800 - $16,000
Reassignment Option: Re-Sequence		
1 - 2 days	1 day for demobilization from existing task and remobilization at new task on jobsite plus 30% - 40% loss of efficiency for each day.	$2,080 - $2,880
3 - 7 days		$3,040 - $6,080
8 - 10 days		$5,440 - $8,000
Reassignment Option: Demobilization		
1 - 2 days	1 day for demobilization from site and 1 day for remobilization to site plus a 20% - 40% loss of efficiency for each day.	$3,520 - $4,480
3 - 7 days		$4,160 - $7,680
8 - 10 days		$5,760 - $9,600

Expert O – Resolution A or Resolution B		
Response Time Increment	Description	Range of Costs
Reassignment Option: Standby		
1 - 2 days	Daily crew cost multiplied by the duration of the standby time.	$2,000 - $4,000
3 - 5 days		$6,000 - $10,000
6 - 10 days		$12,000 - $20,000
Reassignment Option: Re-Sequence		
1 - 2 days	1/2 day for demobilization from existing task and remobilization at new task on jobsite plus 20% - 40% loss of efficiency for each day.	$1,400 - $2,600
3 - 5 days		$2,200 - $5,000
6 - 10 days		$3,400 - $9,000

Reassignment Option: Demobilization		
1 - 2 days 3 - 5 days 6 - 10 days	1 day for demobilization from site and remobilization to site plus a 20% - 40% loss of efficiency for each day.	$2,400 - $3,600 $3,200 - $6,000 $4,400 - 10,000

Expert P – Resolution A or Resolution B

Response Time Increment	Description	Range of Costs
Reassignment Option: Standby		
1 - 5 days 6 - 10 days	Daily crew cost multiplied by the duration of the standby time.	$1,000 - $5,000 $6,000 - $10,000
Reassignment Option: Re-Sequence		
1 - 5 days 6 - 10 days	1/2 day for demobilization from existing task and remobilization at new task on jobsite plus 30% - 40% loss of efficiency for each day.	$800 - $2,500 $2,300 - $4,500
Reassignment Option: Demobilization		
1 - 5 days 6 - 10 days	1 day for demobilization from site and remobilization to site plus a 30% - 40% loss of efficiency for each day.	$1,300 - $3,000 $2,800 - $5,000

Note that the crew reassignment costs do not include any productivity losses associated with the performance of the change work. These costs are captured in the pricing of the change order. The crew reassignment costs address only those costs emanating from the change that generally are not included in the change order. This includes any costs incurred during the time preceding the performance of the change work, which is comprised of the time between the identification of the problem and the start of implementation, and costs incurred after the start of implementation that are a result of the change but are not captured in the change order, such as inefficiencies due to ramping-up of manpower after a re-mobilization.

3.2.4.e. Model Analytical Method

The first task was to determine how the experts combined the certainty factors for each element with the range of costs for each crew reassignment option. This was achieved through discussions of each scenario and the previously established certainty factors for the potential resolution, response time increments, and implementation preparation time increments, and the estimated crew costs for each of the reassignment options.

The experts evaluated the time horizons for the Response Time and the Implementation Preparation Time as separate elements. The potential costs associated with each time horizon and reassignment option were calculated by the experts by applying the certainty factor for a particular time increment to the costs for that time increment. Table 28 shows an example of the calculations using the data for Scenario 1 provided by Expert P.

Table 28: Sample of Experts' Combination of Certainty Factors and Costs

Resolution A Implementation Preparation Time				
Implementation Time Increment	CF	Estimated Costs		
		Standby	Re-sequence	Demobilize
1 - 5 days	0.2	$1000 - $5,000	$800 - $2,500	$1,300 - $3,000
6 - 10 days	0.9	$6,000 - $10,000	$2,300 - $4,500	$2,800 - $5,000
Expert P Assessment		The range of costs for each potential crew reassignment option was calculated by multiplying the Certainty Factor times the dollar amounts that comprised each range of costs. The low amounts were summed and the high amounts were summed to arrive at a range of costs for each crew reassignment option.		
Calculations	Low	0.2 * $1,000 + 0.9 * $6,000 = $5,600	0.2 * $800 + 0.9 * $2,300 = $2,230	0.2 * $1,300 + 0.9 * $2,800 = $2,780
	High	0.2 * $5,000 + 0.9 * $10,000 = $10,000	0.2 * $2,500 + 0.9 * $4,500 = $4,550	0.2 * $3,000 + 0.9 * $5,000 = $5,100

The calculated costs for each crew reassignment option were evaluated to determine if there was an option that represented a more attractive range of potential costs than all other options. In the example shown in Table 28, the "Re-Sequence" crew reassignment option has a range of costs that is lower than any other range of costs. Expert P identified the "Re-sequence" crew reassignment option as the most attractive option for the Implementation Preparation Time.

Thus, the method used to combine the certainty factors and potential costs appeared to emulate the same process used in a typical decision tree. That is the certainty factors were applied to the potential costs as if the factors were probabilities. The resulting costs for each element were evaluated to determine which crew reassignment option appeared to provide the most favorable range of costs based on the individual decision maker's preferences. By starting with an evaluation of the crew reassignment options for the Implementation Preparation Time, selecting the best alternative, then "rolling back" to an evaluation of the Response Time, the experts were able to ascertain the crew reassignment decision that provided the most attractive range of potential costs.

These discussions also revealed that some experts always tended to favor a decision that had the potential to result in the minimum costs possible, while others favored decisions that had the potential to minimize the maximum costs that might be incurred. Additional discussions regarding the terms of the contracts for each expert's current projects did not provide any insight into the reason for the consistency of preference for each expert. Instead, based on the limited information gathered, it appeared that the inclination to favor one decision rule over another was a matter of personnel preference.

Following the evaluation of the scenarios via discussions, the experts were provided a copy of the decision tree model with the previously established certainty factors and crew costs shown on each branch. An example decision tree model is shown in Figure 11.

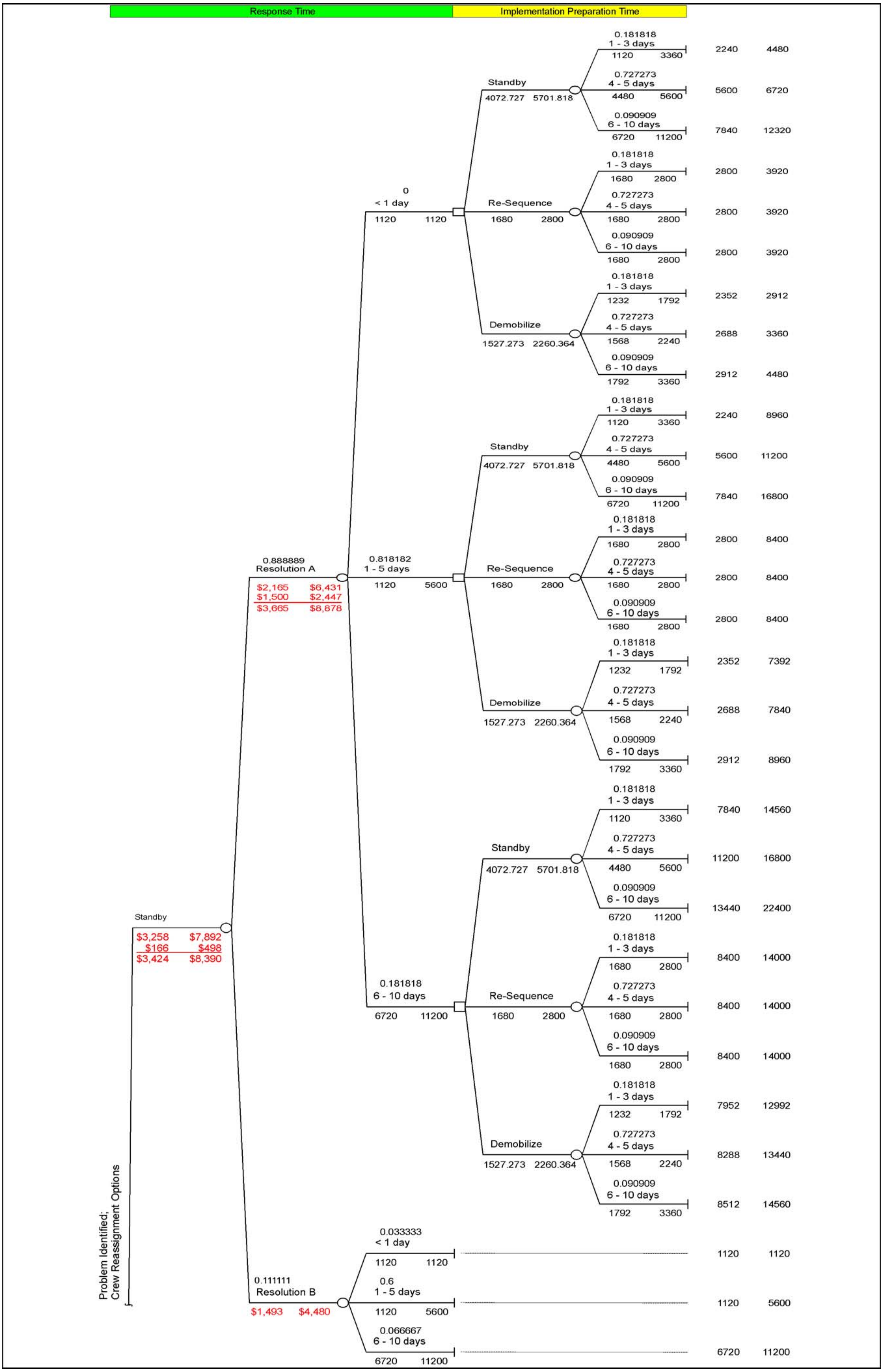


Figure 11a: Example of Model Application

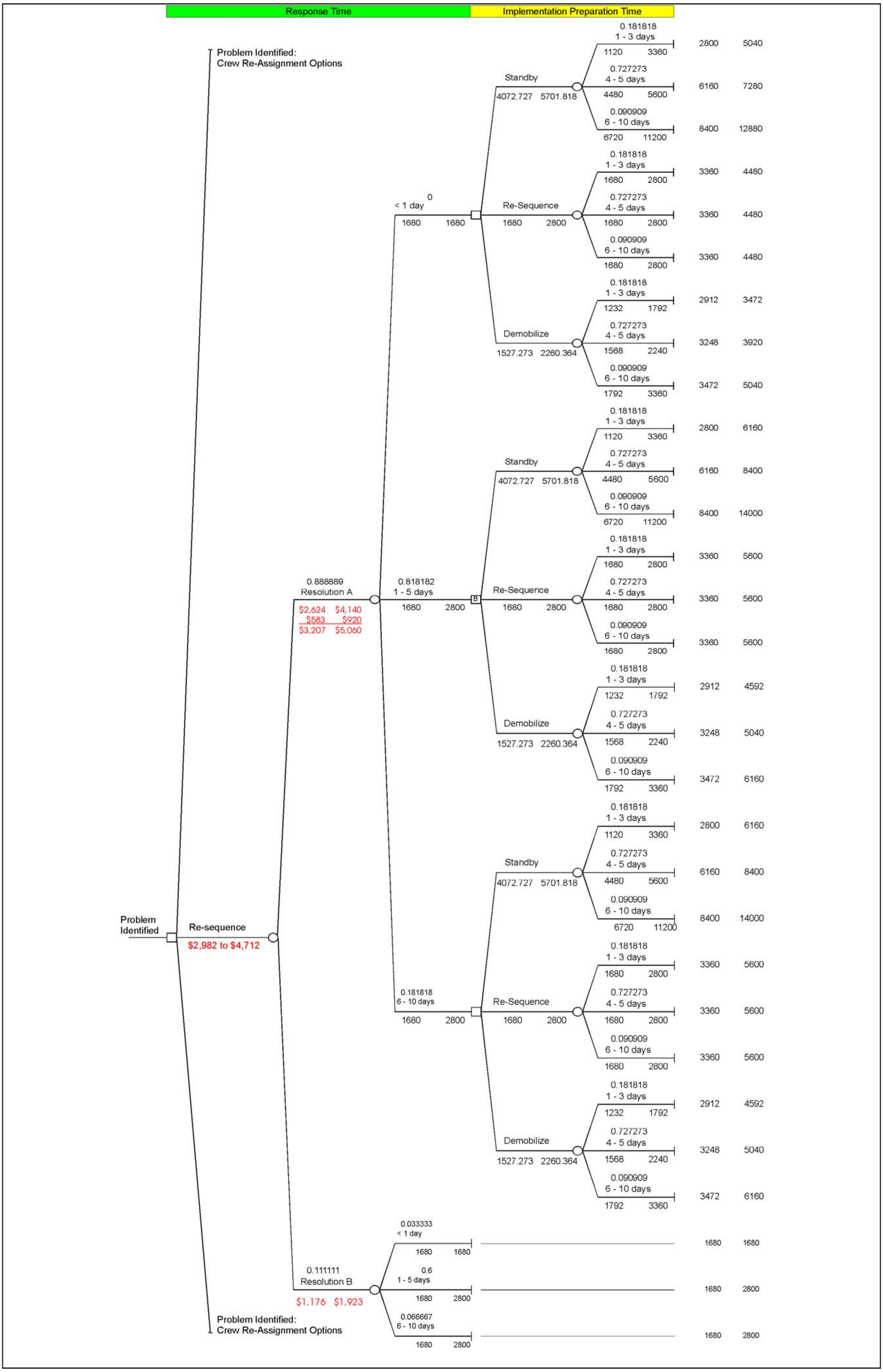


Figure 11b: Example of Model Application

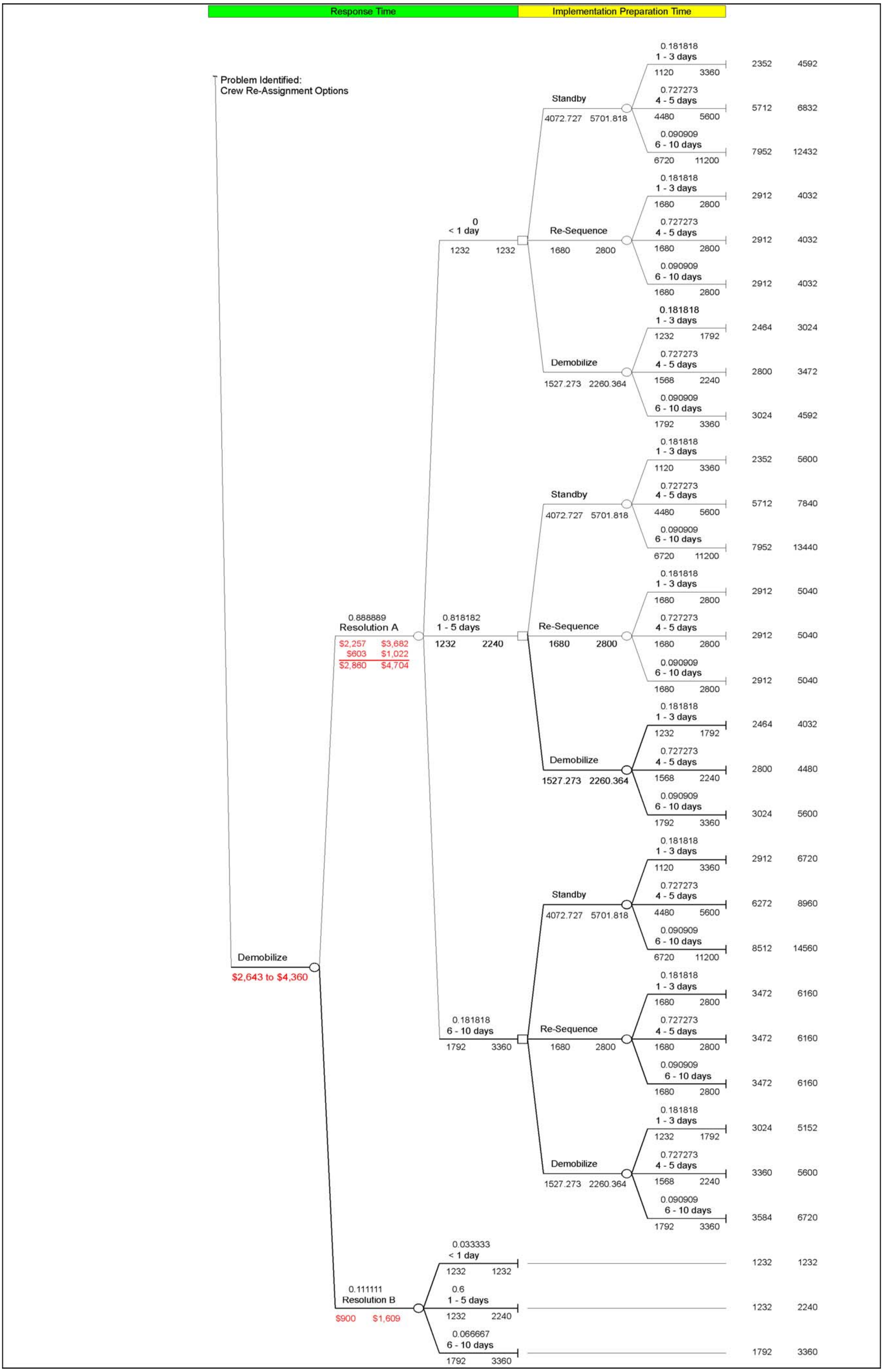


Figure 11c: Example of Model Application

Using the decision tree, the experts then walked through the previously-discussed rationale for determining the ‘best’ crew reassignment option. This procedure provided consistent results with the process described by experts.

Note that the experts did not attempt to normalize the certainty factors that did not sum to a total of 1.0. However, without normalization of the factors, for any case where the certainty factors did not sum to 1.0 the estimated costs provided as the outcomes of the model would either overestimate or underestimate the expected costs.

Potential normalizing procedures include (1) dividing each factor to be normalized by the sum of all factors to be normalized and (2) dividing each factor to be normalized by the maximum value the factors to be normalized [Saaty, 2000]. The following examples illustrate the results obtained without normalization and the results obtained by applying the two normalization methods.

Each example is comprised of two alternatives, X and Y. Example (a) has $CF_X = 0.9$ and $CF_Y = 0.6$, resulting in a sum of 1.5 for the certainty factors, which is greater than 1.0. Example (b) has $CF_X = 0.6$ and $CF_Y = 0.1$, resulting in a sum of 0.7 for the certainty factors, which is less than 1.0. The expected cost for each alternative is $100. Figure 12 depicts Examples (a) and (b) in a decision tree format.

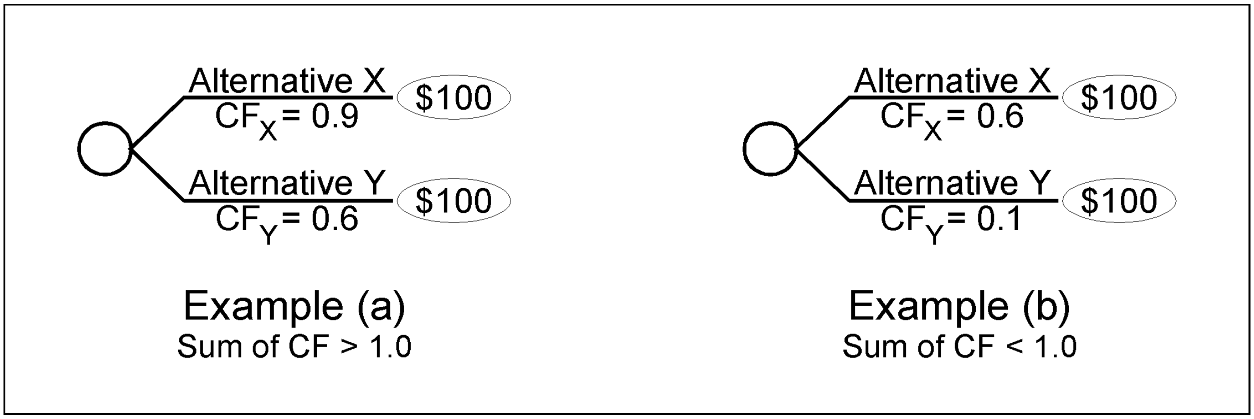


Figure 12: Depiction of Examples (a) and (b) for Normalization Procedures

For the given examples, the desired characteristics of a normalizing procedure include maintaining the relationship between the certainty factors for each alternative while resulting in an expected outcome of $100.

Without normalization, the expected outcome for Example (a) is calculated as:

$$0.9 * \$100 + 0.6 * \$100 = \$150$$

While the expected outcome for Example (b) is calculated as:

$$0.6 * \$100 + 0.1 * \$100 = \$70$$

Thus, the outcomes for Examples (a) and (b) are overestimated and underestimated, respectively, corresponding to (a) certainty factors whose sum is greater than 1.0 and (b) certainty factors whose sum is less than 1.0.

Example (a) – Applying normalizing procedure (1), which divides each certainty factor by the sum of the factors, results in the following:

0.9 / (0.9 + 0.6) * $100 + 0.6 / (0.9 + 0.6) * $100 = 0.6 * $100 + 0.4 * $100 = $100

The non-normalized factors of 0.9 and 0.6 and the normalized factors of 0.6 and 0.4 maintain the same relationship to each other, satisfying the first of the desired characteristics. The resulting outcome after normalization is $100, which is the expected outcome when both alternatives have expected costs of $100. Thus, the second desired characteristic also is fulfilled.

The application of normalizing procedure (2), which divides each certainty factor by the value of the maximum factor, provides the following result:

(0.9 / 0.9) * $100 + (0.6 / 0.9) * $100 = 1.0 * $100 + 0.67 * $100 = $167

Although the normalized factors of 1.0 and 0.67 maintain the same relative proportions, the outcome of $167 is an overestimate of the expected costs for the given data. Thus, dividing by the value of the maximum certainty factor does not exhibit both of the desired characteristics.

Example (b) – Applying normalizing procedure (1), which divides each certainty factor by the sum of the factors, results in the following:

0.6 / (0.6 + 0.1) * $100 + 0.1 / (0.6 + 0.1) * $100 = 0.857 * $100 + 0.143 * $100 = $100

The non-normalized factors of 0.6 and 0.1 and the normalized factors of 0.857 and 0.143 maintain the same relationship to each other, satisfying the first of the desired characteristics. The resulting outcome after normalization is $100, which corresponds to the expected outcome when both alternatives have expected costs of $100.

The application of normalizing procedure (2), which divides each certainty factor by the value of the maximum factor, provides the following result:

(0.6 / 0.6) * $100 + (0.1 / 0.6) * $100 = 1.0 * $100 + 0.167 * $100 = $117

Although the normalized factors of 1.0 and 0.167 maintain the same relative proportions, the outcome of $117 is an overestimate of the expected costs for the given data. Thus, dividing by the value of the maximum certainty factor does not exhibit both of the desired characteristics.

In summary, normalization procedure (1) dividing each factor to be normalized by the sum of all factors to be normalized, meets both of the desired characteristics of maintaining the relationship between the values and providing an accurate measure of the expected costs whether the non-normalized sum of the factors is greater than or less than 1.0. Thus, the application of this normalizing procedure to data of the crew reassignment decision provides the desired properties of maintaining the relationship between the certainty

As with the previous process, the experts combined the certainty factor for each element with the costs through simple multiplication. The resulting range of costs were evaluated to determine the range that best suited the decision maker's preference for either maximizing the minimum potential costs or minimizing the maximum potential costs. The path that provided the costs in line with the decision maker's preference was deemed to represent the 'best' crew reassignment option.

3.3. Summary

The following is a summary outline of the crew reassignment decision model. Steps 1 and 2 are an evaluation of the problem and the potential resolutions. Steps 3 and 4 represent the factors to be considered in order to identify the expected Response Time. Steps 5 and 6 represent the Implementation Preparation Time considerations. Steps 7 and 8 are the identification of potential crew reassignment options and costs. Step 9 represents the quantification of the options. Step 10 is the evaluation of the model results and selection of the crew reassignment option.

Once a potential change is identified:

Step 1 – Identify the possible resolutions to the problem, R_i, for i = 1, . . ., n possible resolutions.

List and describe each of the possible resolutions that might be issued by the designer in response to the problem.

Step 2 – Define the Certainty Factor associated with each potential resolution, CFR_i, where i = 1, . . ., n possible resolutions.

Establish the certainty factor for each potential resolution that represents the decision maker's belief that a particular resolution will be selected by the designer.

Step 3 – Identify the time increments for each possible response, RT_{ij}, where i = 1, . . ., n possible resolutions and j = 1, . . ., m time increments.

For a scenario with two possible responses and three time increments for each possible response, the time increments would be as shown in Table 29.

Table 29: Matrix of Response Time Increments

	Time Increment (1)	Time Increment (2)	Time Increment (3)
Response 1	RT_{11}	RT_{12}	RT_{13}
Response 2	RT_{21}	RT_{22}	RT_{23}

Step 4 – Identify the Certainty Factor for each Response Time increment associated with each possible response, $CFRT_{ij}$, where $i = 1, \ldots, n$ possible resolutions and $j = 1, \ldots, m$ time increments.

For each possible resolution, the decision maker would consider the key factors that might affect the time increments for that particular resolution. The key factors that have been identified are:

1. Complexity

Is coordination with outside agencies (e.g., review by building department, new permits, etc.), re-design, or re-submittals required?

2. Designer Work Load

Are there a significant number of outstanding questions awaiting responses from the designer?

3. Criticality or Priority of the Affected Activity

Is the affected activity on or near the critical path or a controlling item of work for the affected crew(s)?

For example, in the terminology of certainty factors, the rules would be stated as:

Rule 1. Complexity

IF Coordination with outside agencies (e.g., review by building department, new permits, etc.), re-design, or re-submittals are (are not) required.

THEN The response time will be (1) 1 day to 2 days; (2) 3 days to 5 days; and (3) 6 days to 8 days.

CRT_{ij} = Certainty factor for each identified Response Time Increment, RT_{ij} associated with each possible response.

Rule 2. Designer Work Load

IF There are (are not) a significant number of outstanding questions are awaiting responses from the designer.

THEN The response time will be (1) 1 day to 2 days; (2) 3 days to 5 days; and (3) 6 days to 8 days.

WRT_{ij} = Certainty factor for each identified Response Time Increment, RT_{ij} associated with each possible response.

Rule 3. Criticality or Priority of the Affected Activity

IF The activity is (is not) on or near the critical path or is (is not) a controlling item of work for the affected crew.

THEN The response time will be (1) 1 day to 2 days; (2) 3 days to 5 days; and (3) 6 days to 8 days.

PRT_{ij} = Certainty factor for each identified Response Time Increment, RT_{ij} associated with each possible response.

Use the joint-conjunctive minimum rule to calculate the certainty factor for each combination of Response and Time Increment. Thus, the certainty factors, $CFRT_{ij}$, are calculated as min $\{CRT_{ij}, WRT_{ij}, PRT_{ij}\}$ for each i = 1, . . ., n possible resolutions and j = 1, . . ., m time increments.

For a scenario with two possible responses and three time increments for each possible response, the certainty factors for each combination of possible resolution and time increment would be as shown in Table 30.

Table 30: Matrix of Certainty Factors for Potential Resolutions and Response Times

	Resolution R_1			Resolution R_2		
	Time Increment					
Factor	(1)	(2)	(3)	(1)	(2)	(3)
Complexity	CRT_{11}	CRT_{12}	CRT_{13}	CRT_{21}	CRT_{22}	CRT_{23}
Workload	WRT_{11}	WRT_{12}	WRT_{13}	WRT_{21}	WRT_{22}	WRT_{23}
Priority	PRT_{11}	PRT_{12}	PRT_{13}	PRT_{21}	PRT_{22}	PRT_{23}
$CFRT_{ij}$	min $\{CRT_{11}, WRT_{11}, PRT_{11}\}$	min $\{CRT_{12}, WRT_{12}, PRT_{12}\}$	min $\{CRT_{13}, WRT_{13}, PRT_{13}\}$	min $\{CRT_{21}, WRT_{21}, PRT_{21}\}$	min $\{CRT_{22}, WRT_{22}, PRT_{22}\}$	min $\{CRT_{23}, WRT_{23}, PRT_{23}\}$

Step 5 – Identify the time increments for the Implementation Preparation Time, RP_{ik}, where i = 1, . . ., n possible resolutions and k = 1, . . ., p time increments.

The Implementation Preparation Time is the time between the receipt of the resolution and the start of the work. This time period is comprised of the duration necessary to acquire any materials, tools, and/or equipment required to construct the change work.

For each possible resolution, determine if material, tools, or equipment that is not readily available will be required to implement the resolution. In the event that material, tools, or equipment that is not readily available will be required prior to the start of implementation of the resolution, determine the appropriate time increments for consideration.

Note that for any potential resolution where no special materials, tools, and/or equipment are necessary, the Implementation Preparation Time will be zero days.

For example, a scenario with two possible responses where the implementation of Response 1 requires material, tools, or equipment that is not readily available and three time increments of 1 - 3 days, 4 - 7 days, and 8 - 10 days were identified for the implementation preparation time, and the implementation of Response 2 requires no materials, tools, or equipment, the time increments for the Implementation Preparation would be summarized as follows:

Table 31: Matrix of Implementation Preparation Time Increments

	Time Increment (1)	Time Increment (2)	Time Increment (3)
Response 1	RP_{11} = 1 day to 3 days	RP_{12} = 4 days to 7 days	RP_{13} = 8 days to 10 days
Response 2	$RP_{21} = 0$	$RP_{22} = 0$	$RP_{23} = 0$

Step 6 – Identify the CF for the Implementation Preparation Time Increments, $CFRP_{ik}$, where i = 1, . . ., n possible resolutions and k = 1, . . ., p time increments.

Using the time increments identified in Step 5, the certainty factors would be determined by responding to the question, "*Based on Resolution [X], how likely is it that the materials, tools, and/or equipment will be available in one day to three days? Four days through seven days? Eight days through ten days?*" For any resolution for which no materials, tools, and/or equipment are required, $CFRP_{ik}$ = 1.

Step 7 – Identify the Crew Reassignment Options, A_h, for h = 1, . . ., q, for q available options.

The most common crew reassignment options include:

A. Do Not Mobilize – Delay the planned mobilization until the affected work is available. Then, perform the work in the originally-planned sequence, starting at a later date than originally planned.

B. Standby – Place the existing crew on standby or mobilize the crew as planned and place on standby. Then, perform the change work as soon as the work is available, followed by the balance of the contract work in the planned sequence.

C. Reassign the Crew and Re-Sequence the Work – Mobilize the crew as planned or maintain the already mobilized crew, but assign the crew to work in an area or on a task other than what was originally planned, resulting in re-sequencing of the work. At some time in the future, the crew would perform the change work. The reassignment and re-sequencing option is available only if another work area exists. This option allows the follow-on trades to perform re-sequenced work as well.

D. Mobilize Smaller Crew – This is the same as option C. Reassign the Crew and Re-Sequence the Work except that a smaller-than-planned crew would be mobilized or maintained and assigned to work in an area or on a task other than what was originally planned, resulting in re-sequencing of the work. Then, when the as-planned work is available, additional forces would be mobilized or re-mobilized to achieve the planned crew size. Mobilization of a smaller crew with reassignment and re-sequencing is an available option only if another work area exists. This option allows the follow-on trades to perform re-sequenced work as well. However, since a smaller-than-planned crew is utilized the work is expected to be performed over a longer-than-planned duration.

E. Demobilize the Crew from the Site – The crew would be demobilized from the site. At some time in the future, a crew (not necessary the same crew) would be re-mobilized to perform the change work and any remaining original work scope.

Step 8 – Identify the costs corresponding to each combination of Crew Reassignment Option and Response Time Increment, ART_{hij}, and the costs corresponding to each combination of Crew Reassignment Option and Implementation Time Increment, ARP_{hik}. For time increments where the costs vary with the length of time, there will be a range of costs. The ranges can be bracketed by the lower costs, ART_{hijL}, and ARP_{hikL}, and upper costs, ART_{hijU} and ARP_{hikU}.

Based on the crews and equipment, the user establishes the related daily costs for each crew reassignment option. In the event that the potential costs include inefficiencies, a range of inefficiencies or a Certainty Factor for the potential inefficiencies should be identified.

The potential daily costs associated with each option include the costs for demobilization and remobilization plus any inefficiency costs. For example, for Option B, Standby, there are no demobilization or remobilization costs. However, the inefficiency is 100% for the duration of the standby time. Thus, the daily inefficiency costs are 100% of the crew cost, including both labor and idle equipment. For Option E, Demobilize the Crew from the Site, there are both demobilization and remobilization costs and potential inefficiency costs, such as 'learning curve' inefficiencies, that might be experienced when a crew is remobilized at some future date. In the case that a different crew is mobilized in the future, that new crew may not perform at the same level of productivity as the current crew. As a result, there is the possibility that all remaining hours on the project will incur a loss or gain of efficiency. Note that not all crew reassignment options will be available for all change occurrences.

Step 9 – Apply the model to calculate the range of costs for each combination of options.

The model combines the certainty factors and ranges of costs for each branch of the decision tree and calculates the costs associated with the options represented by that branch.

A. In order to calculate meaningful dollar values, the certainty factors for Potential Resolutions, Response Time Increments, and Implementation Preparation Time Increments are re-scaled to a sum of 1 when necessary, as shown in Equations 3, 4, and 5.

$$CFR_{iNORM} = \frac{CFR_i}{\sum_{i=1}^{n} CFR_i} \qquad (3)$$

$$CFRT_{ijNORM} = \frac{CFRT_{ij}}{\sum_{j=1}^{m} CFRT_{ij}} \qquad (4)$$

$$CFRP_{ikNORM} = \frac{CFRP_{ik}}{\sum_{k=1}^{p} CFRP_{ik}} \qquad (5)$$

B. The range of costs for each Potential Resolution and Crew Reassignment Option associated with the Implementation Preparation Time is calculated as shown in Equations 6 and 7.

$$PRANGE_{hiL} = \sum_{k=1}^{p} CFRP_{ikNORM} * ARP_{hikL} \qquad (6)$$

$$PRANGE_{hiU} = \sum_{k=1}^{p} CFRP_{ikNORM} * ARP_{hikU} \qquad (7)$$

For each Potential Response, R_i, select the PRANGE for Crew Reassignment Option *h* that represents the lowest expected costs, $\{VP_L, VP_U\}$, as shown in Equation 8.

$$\{VP_L, VP_U\} = \min_h \{PRANGE_{hiL}, PRANGE_{hiU}\} \qquad (8)$$

In the event that there is no clear minimum range of costs, then the selection is based on the decision maker's criteria. For example, the decision maker may choose the option that minimizes the maximum expected costs or minimizes the minimum expected costs.

C. Calculate the range of costs for each combination of Crew Reassignment Option, Potential Response, and Response Time Increment as shown in Equations 9 and 10.

$$TRANGE_{hijL} = CFRT_{ijNORM} * ART_{hijL} \quad (9)$$

$$TRANGE_{hijU} = CFRT_{ijNORM} * ART_{hijU} \quad (10)$$

D. Combine the selected $\{VP_L, VP_U\}$ with each $\{TRANGE_{hijL}, TRANGE_{hijU}\}$ to arrive at the expected range of costs for each possible Crew Reassignment Option, Response, Response Time Increment, and the minimum or selected expected costs for Preparation Time, $\{VTP_{hijL}, VTP_{hijU}\}$.

E. For each available Crew Reassignment Option, multiply $\{VTP_{hijL}, VTP_{hijU}\}$ by the normalized Certainty Factor for each potential Response, CFR_{iNORM}, and sum the ranges of costs for each potential Response to obtain the expected range of costs for each available Crew Reassignment Option, $\{VA_{hL}, VA_{hU}\}$, as shown in Equations 11 and 12.

$$VA_{hL} = \sum_{i=1}^{n} \sum_{j=1}^{m} CFR_{iNORM} * VTP_{hijL} \quad (11)$$

$$VA_{hU} = \sum_{i=1}^{n} \sum_{j=1}^{m} CFR_{iNORM} * VTP_{hijU} \quad (12)$$

Step 10 – Identify the most-desirable crew reassignment option based on the calculated expected range of costs for each Crew Reassignment Option $\{VA_{hL}, VA_{hU}\}$.

The decision maker chooses the Crew Reassignment Option that provides the range of potential costs that are most suitable to the decision maker's preferences. As noted, during the model development research, the experts expressed preferences for either minimization of the maximum potential costs or maximizing the minimum potential costs.

In summary, the steps are:

Step 1 – Potential Resolutions –

Identify the possible resolutions to the problem, R_i, for i = 1, . . ., n possible resolutions.

Step 2 – Certainty Factors for Potential Resolutions –

Define the Certainty Factor associated with each potential resolution, CFR_i, for i = 1, . . ., n possible resolutions.

Step 3 – Response Time Increments –

Identify the time increments for each potential response, RT_{ij}, for i = 1, . . ., n possible resolutions and j = 1, . . ., m time increments.

Step 4 – Certainty Factors for Response Time Increments –

Identify the Certainty Factor for each Response Time factor CRT_{ij}, WRT_{ij}, PRT_{ij}, for i = 1, . . ., n possible resolutions and j = 1, . . ., m time increments, and calculate the Certainty Factor for each time increment, $CFRT_{ii}$, by the solving for the min {CRT_{ij}, WRT_{ij}, PRT_{ij}}.

Step 5 – Implementation Preparation Time Increments –

Identify the time increments for the Implementation Preparation Time, RP_{ik}, for i = 1, . . ., n possible resolutions and k = 1, . . ., p time increments.

Step 6 – Certainty Factors for Implementation Preparation Time Increments –

Identify the certainty factors for the Implementation Preparation Time increments, $CFRP_{ik}$, for i = 1, . . ., n possible resolutions and k = 1, . . ., p time increments.

Step 7 – Identify the Crew Reassignment Options, A_h, for h = 1, . . ., q number of available options.

Step 8 – Identify the range of costs for each combination of Crew Reassignment Option and Response Time Increment, ART_{hijL} to ART_{hijU}, and each combination of Crew Reassignment Option and Implementation Time Increment, ARP_{hikL} to ARP_{hikU}.

Step 9 – Apply the model to calculate the range of costs for each Crew Reassignment Option.

A. Normalize the certainty factors for Potential Resolutions, Response Time Increments, and Implementation Preparation Time Increments, if necessary, as shown in Equations 3, 4, and 5.

$$CFR_{iNORM} = \frac{CFR_i}{\sum_{i=1}^{n} CFR_i} \tag{3}$$

$$CFRT_{ijNORM} = \frac{CFRT_{ij}}{\sum_{j=1}^{m} CFRT_{ij}} \tag{4}$$

$$CFRP_{ikNORM} = \frac{CFRP_{ik}}{\sum_{k=1}^{p} CFRP_{ik}} \tag{5}$$

B. Calculate the range of costs for each combination of Crew Reassignment Option, Potential Response, and Implementation Preparation Time:

$$PRANGE_{hiL} = \sum_{k=1}^{p} CFRP_{ikNORM} * ARP_{hikL} \quad (6)$$

$$PRANGE_{hiU} = \sum_{k=1}^{p} CFRP_{ikNORM} * ARP_{hikU} \quad (7)$$

Select the PRANGE that represents the costs that fit the decision maker's preferences, where $\{VP_L, VP_U\}$ is calculated as per Equation 8.

$$\{VP_L, VP_U\} = \min_h \{PRANGE_{hiL}, PRANGE_{hiU}\} \quad (8)$$

C. Calculate the range of costs for each combination of Crew Reassignment Option, Potential Response, and Response Time Increment as shown in Equations 9 and 10.

$$TRANGE_{hijL} = CFRT_{ijNORM} * ART_{hijL} \quad (9)$$

$$TRANGE_{hijU} = CFRT_{ijNORM} * ART_{hijU} \quad (10)$$

D. Combine the selected $\{VP_L, VP_U\}$ with each $\{TRANGE_{hijL}, TRANGE_{hijU}\}$ to arrive at the expected range of costs for each possible Crew Reassignment Option, Potential Response, Response Time Increment, and the minimum or selected expected costs for Preparation Time, $\{VTP_{hijL}, VTP_{hijU}\}$.

E. For each available Crew Reassignment Option, multiply $\{VTP_{hijL}, VTP_{hijU}\}$ by the normalized Certainty Factor, CFR_{iNORM}, for each potential Response and sum the lower and upper ranges of costs for each potential Response to obtain the expected range of costs for each available Crew Reassignment Option, $\{VA_{hL}, VA_{hU}\}$, as shown in Equations 11 and 12.

$$VA_{hL} = \sum_{i=1}^{n} \sum_{j=1}^{m} CFR_{iNORM} * VTP_{hijL} \qquad (11)$$

$$VA_{hU} = \sum_{i=1}^{n} \sum_{j=1}^{m} CFR_{iNORM} * VTP_{hijU} \qquad (12)$$

Step 10 – Based on the calculated expected range of costs for each Crew Reassignment Option, $\{VA_{hL}, VA_{hU}\}$, choose the option that provides the range of costs most suitable to the decision maker's preferences.

CHAPTER 4: APPLICATION AND VALIDATION OF THE CREW REASSIGNMENT DECISION SUPPORT MODEL

4.1. Introduction

The purpose of a decision support model or system is to provide assistance to the decision maker in identifying the available options and the potential consequences of selecting an option. Thus, the test of a decision support model is whether or not it aides the decision maker in making more-informed decisions.

The following is a description of the projects and change circumstances to which the Crew Reassignment Decision Support Model was applied in order to test its ability to provide the decision makers with the information necessary to improve the crew reassignment decisions made in response to changes. The model was applied to contemporaneous issues to assist project management with the crew reassignment decision. Each of the model applications is described and discussed, including the comments by the project management on each of the projects.

4.2. Model Implementation

The model was applied prospectively to six actual change circumstances on three construction projects. All three projects were mid- to high-rise condominium complexes, with two of the projects located in Central Florida and one project in North Florida. Two of the projects were constructed under Guaranteed Maximum Price contracts and one project was a lump sum project. The projects were constructed by three different general contractors. All three projects involved architects that were responsible for the review and evaluation of change work, while final authorization of change work was the responsibility of the project owners. None of the contracts had a “no damages for delay” clause. The value of the projects ranged from $12 million to $26 million.

The model was applied to two different changes on each of the three projects. All three projects were in the structural erection stage when the first model application was undertaken on each project. The model was applied to the same projects during the later stages of construction, from rough-in of the mechanical systems through the start of interior finishes.

The following sections describe the circumstances for each change scenario, the data provided by the decision makers for use in the model, and the results of the model application. The actual crew reassignment decisions made by the management on each project also are discussed.

4.2.1. Model Application 1

During the forming and placement of reinforcing for the first elevated slab on Project A, the threshold inspector issued a stop work order due to questions regarding offset columns above and below the first elevated slab. When the stop work order was issued, the structural concrete was the only work underway on the project.

The potential responses from the designer were comprised of (A) additional analysis resulted in no changes to the existing design and (B) additional analysis resulted in additional reinforcing requirements. The likelihood of receiving Resolution A was identified as "*don't know, but maybe not,*" which was translated to a certainty factor of 0.4. The likelihood of receiving Resolution B was "*almost certainly*," which resulted in a certainty factor of 0.8.

Only two time increments were identified for each of the potential resolutions: (1) less than 1 day and (2) 1 day to 5 days. Table 32 contains the certainty factors for the three main factors that are considered as the determinants of the expected duration of the response time for a particular resolution and the combined certainty factors using the joint certainty minimum method.

Table 32: Application 1 – Certainty Factors for Response Time

Resolution A Factor	Response Time Increment: < 1 day	Response Time Increment: 1 day through 5 days
Complexity	0.4	0.8
Workload	0.5	0.8
Criticality or Priority	0.7	0.9
Combined CF	0.4	0.8

Resolution B Factor	Response Time Increment: < 1 day	Response Time Increment: 1 day through 5 days
Complexity	0.1	0.9
Workload	0.2	1.0
Criticality or Priority	0.2	1.0
Combined CF	0.1	0.9

Since Resolution A required no changes to the existing design, no tools, materials, or equipment would be needed to implement this resolution. Therefore, the Implementation Time for Resolution A was zero days with a certainty factor of 1. However, it was expected that specially-fabricated stud rails would be added if the existing engineering calculations were found to be deficient. Only two time increments were identified for the Implementation Time for Resolution B: (1) 1 to 3 days and (2) 4 to 5 days. The certainty factors for the Resolution B Implementation Preparation Time are shown in Table 33.

Table 33: Application 1 – Certainty Factors for Implementation Preparation Time

Resolution	Implementation Preparation Time Increment	
	1 - 3 days	4 - 5 days
Resolution B	0.4	0.8

Since the project was in such an early stage, only the structural concrete crew had mobilized. This early stage of the project resulted in only two available crew reassignment options: (1) Standby or (2) Demobilization from site.

The crew costs for the structural crew were comprised of $327 per hour for labor plus $65 per hour for equipment for a total of $392 per hour or $3,136 per eight-hour day. Note that the equipment costs were based on the hourly costs for idle equipment. Therefore, the costs for the crew reassignment option of Standby would be $392 per hour or $3,136 per day.

The costs for the crew Demobilization option were identified as four hours for demobilization plus four hours for re-mobilization when the work resumed. In addition, inefficiencies ranging from 10% to 20% for a time period equivalent to the duration of demobilization were expected. Table 34 shows the calculated costs for each of the possible crew reassignment options.

Table 34: Application 1 – Crew Reassignment Costs

Crew Reassignment Option	Time Increment			
	Response Time		Implementation Time	
	< 1 day	1 - 5 days	1 - 3 days	4 - 5 days
Standby	$392 - $3,136	$3,136 - $15,680	$3,136 - $9,408	$9,408 - $15,680
Demobilize	$3,450	$3,450 - $6,272	$314 - $1,882	$1,254 - $3,136
Standby - Demobilize	$392 - $3,136	$3,136 - $15,680	$3,450 - $5,018	$4,077 - $6,272

Note that in the event of demobilization at the onset of the problem, the costs for remaining demobilized throughout the Implementation Preparation Time represent only the incremental additional costs for productivity losses commensurate with the added duration of demobilization. These costs are represented by the entries in the row titled Demobilize. That is, during the Implementation Preparation Time there are no additional costs related to the initial four hours of crew and equipment costs for demobilization plus four hours for re-mobilization. However, in the event that the crew reassignment option throughout the Response Time was Standby and then changed to Demobilize for the Implementation Preparation Time, at the initiation of the crew demobilization the costs will include four hours of crew and equipment costs for demobilization and re-mobilization.

Table 35 provides a matrix of all possible states and the crew reassignment options. The Crew Reassignment Options titled Standby and Demobilize represent either placing the crew on standby or demobilizing for the entire duration of the Response Time plus the

Implementation Preparation Time, if any. The Crew Reassignment Option titled Standby - Demobilize represents placing the crew on standby during the Response Time then demobilizing the crew during the Implementation Preparation Time, if any. Similarly, the Crew Reassignment Option titled Demobilize - Standby represents demobilizing the crew during the Response Time then re-mobilizing the crew and placing it on standby during the Implementation Preparation Time.

A review of Table 35 reveals that the range of costs for the Demobilize - Standby option are the same or greater than the costs for the Demobilize option for every possible state. Since this option is dominated by the Demobilize option, no further consideration of the Demobilize - Standby option is merited. In addition, the range of costs for the Standby option are the same or greater than the costs for the Standby - Demobilize option for every possible state. Therefore, no further consideration of the Standby option is merited. Table 36 is the updated matrix of crew reassignment costs, with the dominated options eliminated.

Table 35: Application 1 – Matrix of Crew Reassignment Costs

	States					
Crew Reassignment Options	A < 1 day, Material 0 days	A 1 - 5 days, Material 0 days	B < 1 day, Material 1 - 3 days	B < 1 day, Material 4 - 5 days	B 1 - 5 days, Material 1 - 3 days	B 1 - 5 days, Material 4 - 5 days
Standby	\$392 - \$3,136	\$3,136 - \$15,680	\$3,528 - \$12,544	\$9,800 - \$18,816	\$6,272 - \$25,088	\$12,544 - \$31,360
Demobilize	\$3,450	\$3,450 - \$6,272	\$3,764 - \$5,332	\$4,704 - \$6,586	\$3,764 - \$8,154	\$4,704 - \$9,408
Standby - Demobilize	\$392 - \$3,136	\$3,136 - \$15,680	\$3,842 - \$8,154	\$4,469 - \$9,408	\$6,586 - \$20,698	\$7,213 - \$21,952
Demobilize - Standby	\$3,450	\$3,450 - \$6,272	\$6,586 - \$12,858	\$12,858 - \$19,130	\$6,586 - \$15,680	\$12,858 - \$21,952

Table 36: Application 1 – Non-Dominated Crew Reassignment Costs

	States					
Crew Reassignment Options	A < 1 day, Material 0 days	A 1 - 5 days, Material 0 days	B < 1 day, Material 1 - 3 days	B < 1 day, Material 4 - 5 days	B 1 - 5 days, Material 1 - 3 days	B 1 - 5 days, Material 4 - 5 days
Demobilize	\$3,450	\$3,450 - \$6,272	\$3,764 - \$5,332	\$4,704 - \$6,586	\$3,764 - \$8,154	\$4,704 - \$9,408
Standby - Demobilize	\$392 - \$3,136	\$3,136 - \$15,680	\$3,842 - \$8,154	\$4,469 - \$9,408	\$6,586 - \$20,698	\$7,213 - \$21,952

Figure 13 is a summary of the data for the offset column problem on Project A using the Crew Reassignment Model. The data in Figure 13 show the non-dominated options that were depicted in Table 36. The dollar ranges shown in italics were calculated by the application of the certainty factors using the methods discussed in Chapter 3.

As shown in Figure 13, the application of the model to the data provides the result that the crew reassignment option of Demobilize throughout both the Response Time and Implementation Preparation Time has an expected range of costs of $4,077 to $7,582, while the range of costs for the crew reassignment option of Standby - Demobilize is $5,227 to $17,353. A graphic depiction of the ranges of costs calculated by the model is shown as Figure 14.

The crew reassignment decision made on the project was to demobilize the structural concrete crew. In this instance, the contractor had another project that was able to utilize the additional manpower and equipment that was demobilized from Project A. Thus, the contractor’s costs for the demobilization were contained within the ranges originally estimated in the model. Further, when the change work on Project A was ready to be performed, the same crew was available for re-mobilization.

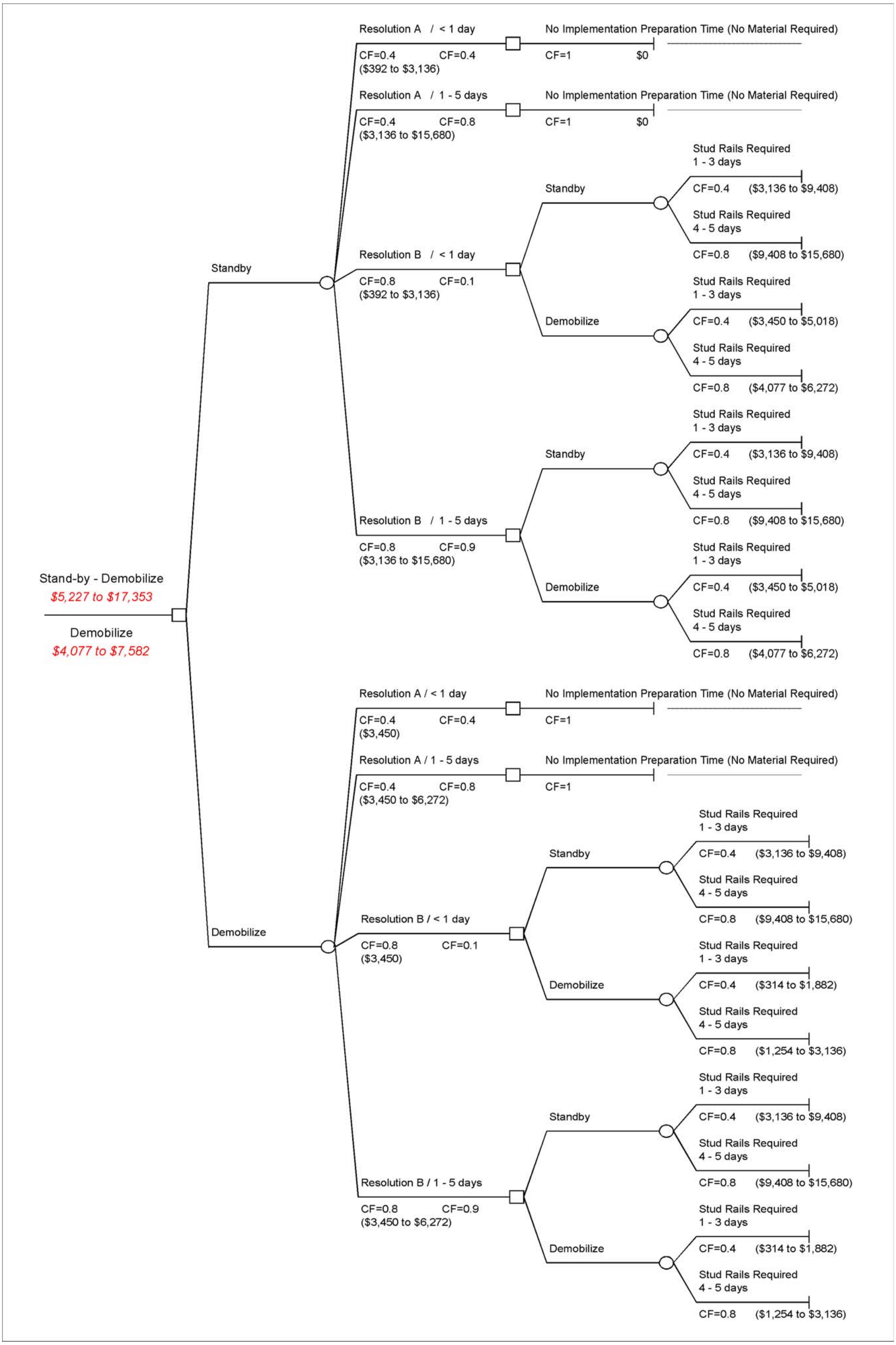


Figure 13: Crew Reassignment Model Applied to Application 1 Data

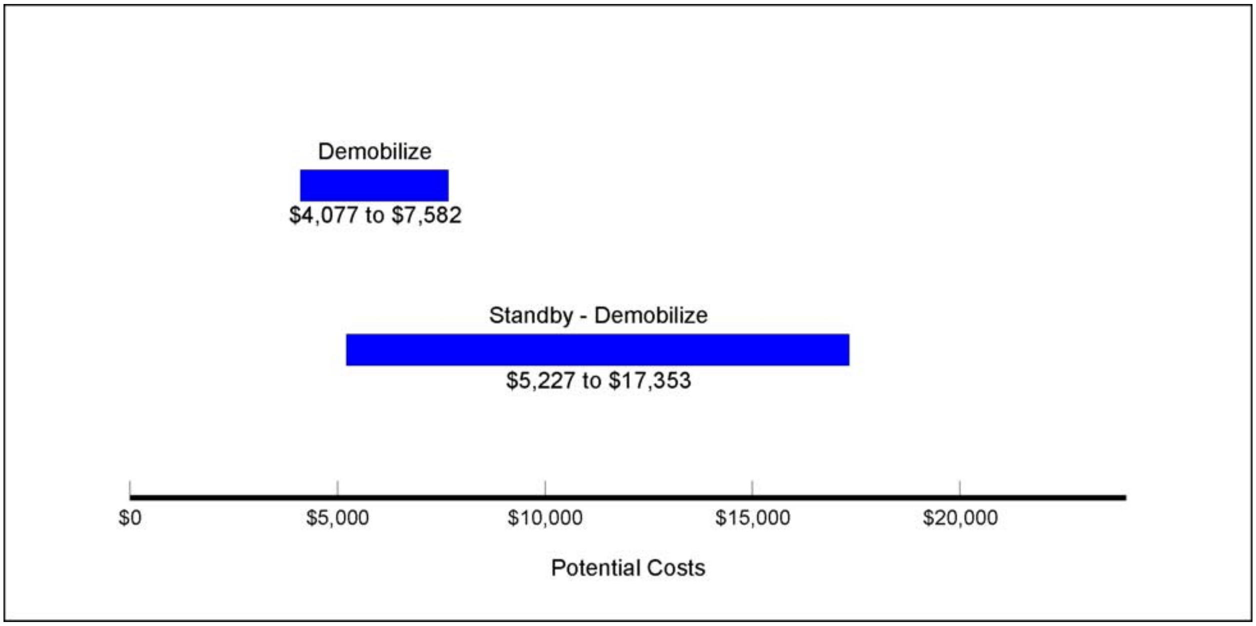


Figure 14: Ranges of Potential Costs for Application 1

The resolution that ultimately occurred included not only a review of the design by the original engineer, but also a peer review by an additional engineering firm. The initial review by the original engineer was completed within five workdays. However, the peer review took an additional two weeks. Following the completion of the peer review, a design change was issued that added stud rails at each offset column. The order and delivery of the added stud rails took an additional four days. Thus, the total duration was 19 workdays or 25 calendar days from the identification of the problem to the point when construction of the change work could begin. In consideration of the actual duration experienced, the decision to demobilize the structural concrete crew by far resulted in the lowest costs.

The Project A representatives' assessment of the model is contained at the end of Section 4.2.2.

4.2.2. Model Application 2

The eight-story structure was topped-out, the framing on the first three floors was complete, and the electrical rough-in was underway when it was determined that the vertical chases had inadequate space for all of the necessary conduit.

The potential responses from the designer were comprised of (A) revise the size of the existing chase, including enlargement of the penetrations at each slab and (B) add a second electrical chase at a separate location. The likelihood of receiving Resolution A was identified as "*almost certainly,*" which was translated to a certainty factor of 0.9. The likelihood of receiving Resolution B was "*probably not*," which resulted in a certainty factor of 0.2.

Three time increments were identified for each of the potential resolutions: (1) 1 day to 2 days; (2) 3 days to 5 days; and (3) 6 days to 10 days. Table 37 contains the certainty factors for the three main factors that are considered as the determinants of the expected duration of the response time for a particular resolution and the combined certainty factors using the joint certainty minimum method.

Table 37: Application 2 – Certainty Factors for Response Time

Resolution A Factor	Response Time Increment		
	1 day - 2 days	3 days - 5 days	6 days - 10 days
Complexity	0.2	0.9	0.2
Workload	0.3	0.8	0.3
Criticality or Priority	0.5	0.9	0.2
Combined CF	0.2	0.8	0.2
Resolution B Factor	**Response Time Increment**		
	1 day - 2 days	3 days - 5 days	6 days - 10 days
Complexity	0.1	0.7	0.7
Workload	0.1	0.8	0.5
Criticality or Priority	0.5	0.8	0.5
Combined CF	0.1	0.7	0.5

Neither Resolution A nor B required any special tools, materials, or equipment for implementation. However, both resolutions required core boring of the existing post-tensioned slabs. Therefore, the Implementation Preparation Time for both Resolution A and Resolution B was identified as two days with a certainty factor of 1. The certainty factors for the Resolution B Implementation Preparation Time are shown in Table 38.

Table 38: Application 2 – Certainty Factors for Implementation Time

Resolution	Implementation Preparation Time Increement 2 days
Resolution A	1.0
Resolution B	1.0

Based on the stage of the project, the crew reassignment options were: (1) Standby, (2) Partial Demobilization , i.e., smaller crew size, and (3) Demobilization. For option (2), it was noted that there was an estimated five days of work available if one-half of the crew was maintained on site.

The electrical crew costs were $211 per hour for supervision, labor, and equipment, which was a total of $1,688 per eight-hour day. The equipment was comprised of one pick-up truck. There was no difference in the hourly rate for standby or idle time.

The costs for the partial demobilization option included two hours of demobilization plus two hours for re-mobilization when the design change work was available. Inefficiencies for the smaller crew were estimated at 20% to 30% for the duration of the partial demobilization plus an additional 20% to 30% for the balance of the crew upon re-mobilization for a time period equal to the length of the demobilization.

The costs for complete demobilization were comprised of three hours for demobilization plus three hours for re-mobilization. Inefficiencies were estimated at 20% to 25% for a time period equivalent to the duration of demobilization. Table 39 shows the calculated costs for each of the possible crew reassignment options.

Table 39: Application 2 – Crew Reassignment Costs

Crew Reassignment Option	Time Increment			
	Response Time			Implementation Time
	1 day - 2 days	3 days - 5 days	6 days - 10 days	2 days
Standby	$1,688 - $3,376	$3,376 - $8,440	$8,440 - $16,880	$3,376
Partial Demobilization	$1,013 - $1,603	$1,350 - $3,123	$2,363 - $5,655	$675 - $1,013
Standby - Partial Demobilization	$1,688 - $3,376	$3,376 - $8,440	$8,440 - $16,880	$1,350 - $1,604
Complete Demobilization	$1,350 - $1,794	$2,026 - $3,060	$2,701 - $3,060	$675 - $844
Standby - Demobilization	$1,688 - $3,376	$3,376 - $8,440	$8,440 - $16,880	$1,688 - $1,794
Partial Demobilization - Complete Demobilization	$1,013 - $1,603	$1,350 - $3,123	$2,363 - $5,655	$971 - $1,055

Table 40 provides a matrix of all possible states and the crew reassignment options. The Crew Reassignment Options titled Standby, Partial Demobilization, and Complete Demobilize represent either placing the crew on standby, partially demobilizing, or completely demobilizing for the entire duration of the Response Time plus the

Implementation Preparation Time. The Crew Reassignment Options titled Standby - Partially Demobilize and Standby - Completely Demobilize represent placing the crew on standby during the Response Time then partially or completely demobilizing the crew during the Implementation Preparation Time. Similarly, the Crew Reassignment Option titled Partially Demobilize - Completely Demobilize represents partially demobilizing the crew during the Response Time then completely demobilizing the crew during the Implementation Preparation Time. Although other combinations of the Crew Reassignment Options existed, Project Management did not consider these as reasonable options. Thus, they were not included in the model application.

A review of the ranges of costs for each Crew Reassignment Option shown in Table 40 resulted in two non-dominated options. These non-dominated option are listed in Table 41.

Table 40: Application 2 – Matrix of Crew Reassignment Costs

	States		
Crew Reassignment Options	Resolution A or B 1 day - 2 days, Implementation Preparation 2 days	Resolution A or B 3 - 5 days, Implementation Preparation 2 days	Resolution A or B 6 days - 10 days, Implementation Preparation 2 days
Standby	$5,064 - $6,752	$6,752 - $11,816	$11,816 - $20,256
Partially Demobilize	$1,688 - $2,616	$2,025 - $4,136	$3,038 - $6,668
Completely Demobilize	$2,025 - $2,638	$2,701 - $3,904	$3,376 - $3,904
Standby - Partially Demobilize	$3,038 - $4,980	$4,726 - $10,044	$9,790 - $18,484
Standby - Completely Demobilize	$3,376 - $5,170	$5,064 - $10,234	$10,128 - $18,674
Partially Demobilize - Completely Demobilize	$1,984 - $2,658	$2,321 - $4,178	$3,334 - $6,710

Table 41: Application 2 – Non-Dominated Crew Reassignment Costs

	States		
Crew Reassignment Options	A or B 1 day - 2 days, Implementation Prep 2 days	A or B 3 - 5 days, Implementation Prep 2 days	A or B 6 days - 10 days, Implementation Prep 2 days
Partially Demobilize	$1,688 - $2,616	$2,025 - $4,136	$3,038 - $6,668
Completely Demobilize	$2,025 - $2,638	$2,701 - $3,904	$3,376 - $3,904

Figure 15 shows the application of the model to the data. The dominated option of Partially Demobilize - Completely Demobilize is included for illustrative purposes only.

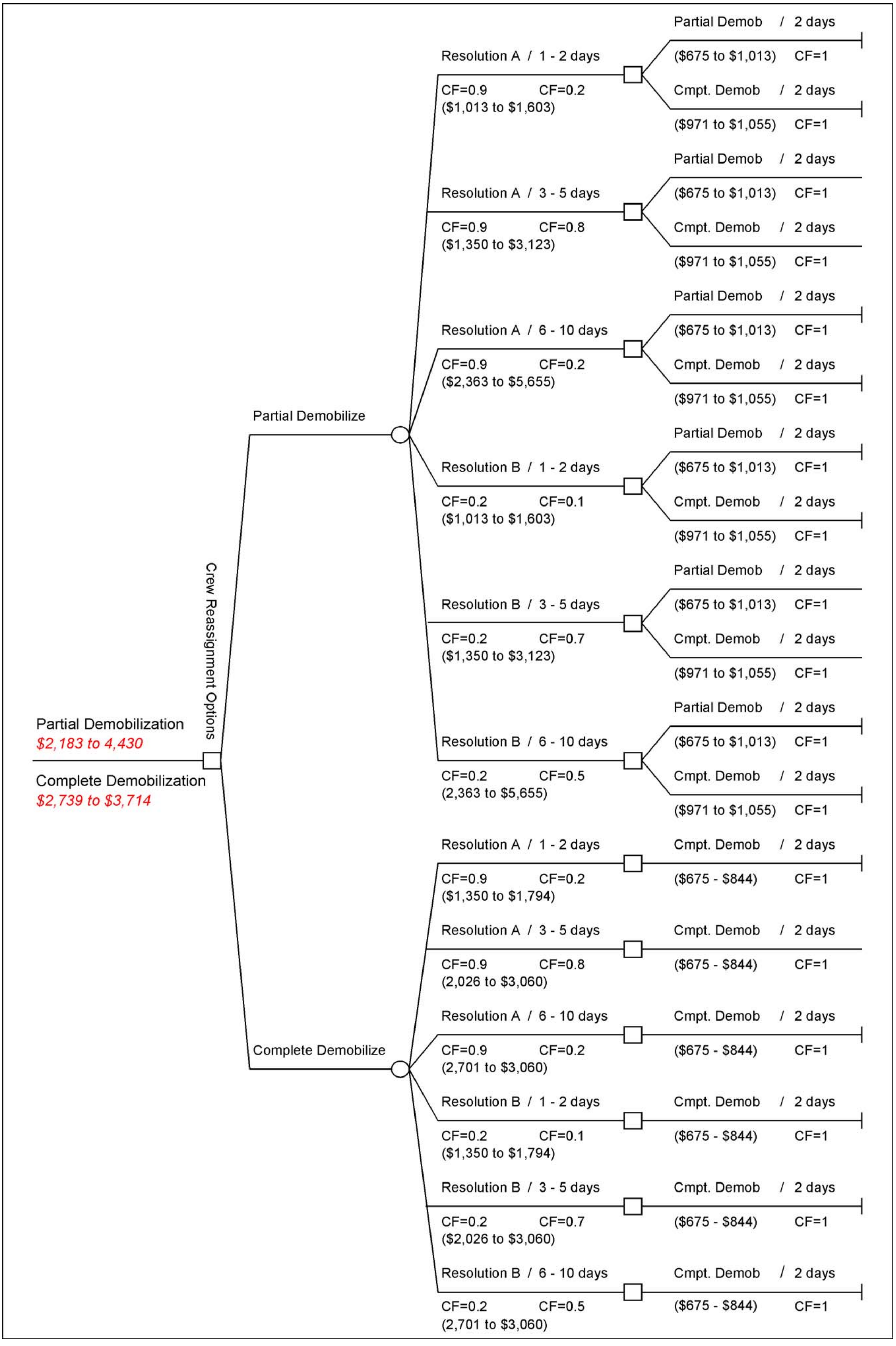


Figure 15: Crew Reassignment Model Applied to Application 2 Data

The application of the certainty factors shows that the crew reassignment option of Partial Demobilize throughout both the Response Time and Implementation Preparation Time has an expected range of costs of $2,183 to $4,430, while the range of costs for the crew reassignment option of Complete Demobilize is $2,739 to $3,714. Therefore, the crew reassignment option of Partial Demobilize has the potential for the lowest minimum costs, while the option of Complete Demobilize has the potential for the lowest maximum costs. Figure 16 is a graphic depiction of the potential ranges of the costs predicted by the model.

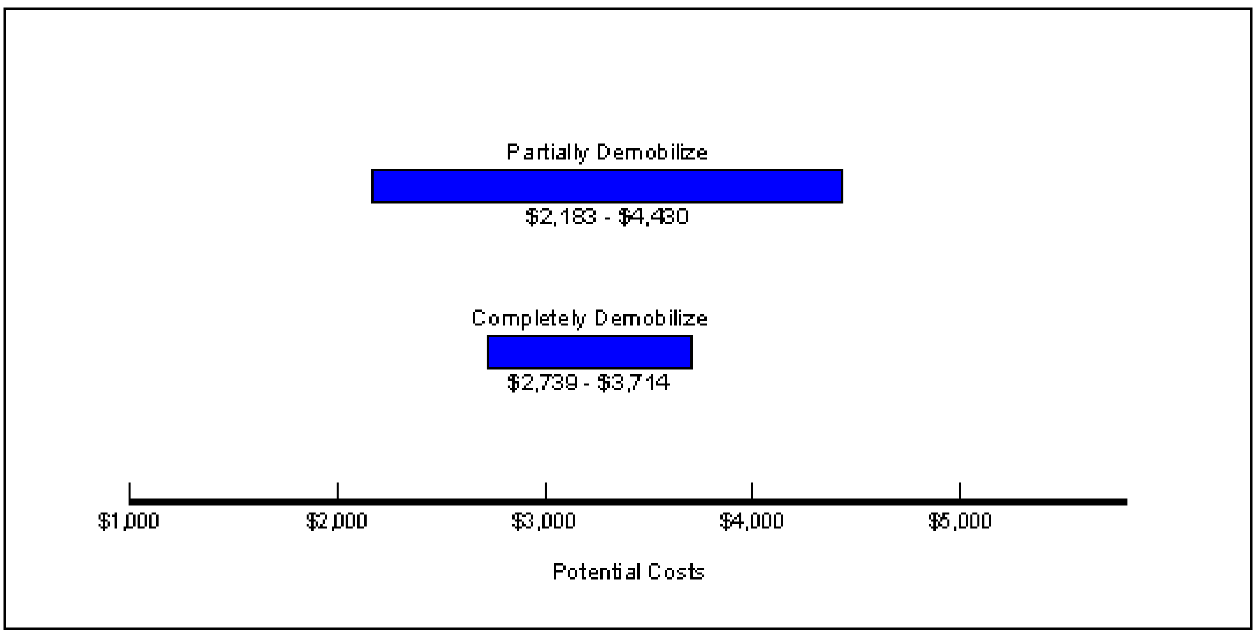


Figure 16: Ranges of Potential Costs for Application 2

The crew reassignment decision made on the project was to partially demobilize the electrical crew. The crew that remained on-site was approximately one-half the size of the original crew.

The resolution provided by the architect was to enlarge the size of the existing chase. The revised design was issued five days after the identification of the problem. The required core drilling of the concrete slabs was performed on the seventh workday, following x-rays of the slabs to locate the post-tensioned cables and rebar. Thus, the total duration was seven workdays or nine calendar days from the identification of the problem to the point when the original scope work could resume. Based on the actual duration of seven workdays, the range of expected costs for the Partial Demobilize option was $3,038 to $4,136 and the range of expected costs for the Complete Demobilize option was $3,376 to $3,904. As the expected costs were approximately equal, it appeared that the decision for partial demobilization was the appropriate decision as it allowed at least some work to be performed during the resolution and implementation preparation time and maintained continuity of at least part of the crew.

During the review of the model and model recommendations for both Application 1 and 2, the management on Project A indicated that the model was an accurate representation of the factors in the crew reassignment decision and the method in which the factors affect the crew reassignment decision. The project management stated that the step-by-step process of considering the various potential resolutions, options, and associated costs, proved valuable in evaluating and justifying the crew reassignment decision. For both Application 1 and Application 2, the information and data gathered for the model application were used as back-up to the change proposal presented to the owner, which was approved for both costs and a time extension. The project management cited the format of the information presented in the model as being valuable in receiving faster-than-average approval of the change orders.

4.2.3. Model Application 3

The placement of the formwork for the slab-on-grade at Project B was underway when it was discovered that the as-designed elevation of the underground piping was eight inches higher than the bottom elevation of the slab. The potential responses from the designer were (A) lower the elevation of the previously-installed underground piping or (B) raise the elevation of the slab-on-grade, which would result in reduced headroom in a portion of the garage. The likelihood of receiving Resolution A was identified as "*probably,*" which was translated to a certainty factor of 0.8. The likelihood of receiving Resolution B was "*probably not*," which resulted in a certainty factor of 0.2. Note that since the as-designed height of the structure was at the maximum allowed by the local building code, it was not possible to place the slab-on-grade at a higher elevation and construct the building to the planned dimensions.

Two time increments were identified for each of the potential resolutions: (1) 2 days to 5 days and (2) 6 days to 10 days. Table 42 contains the certainty factors for the three main elements that are considered as the determinants of the expected duration of the response time for a particular resolution. In addition, the combined certainty factor, obtained using the joint certainty minimum method, is shown.

Table 42: Application 3 – Certainty Factors for Response Time

Resolution A Factor	Response Time Increment	
	2 days - 5 days	6 days - 10 days
Complexity	0.8	0.4
Workload	0.8	0.3
Criticality or Priority	0.9	0.2
Combined Certainty Factor	0.8	0.2
Resolution B Factor	**Response Time Increment**	
	2 days - 5 days	6 days - 10 days
Complexity	0.2	0.9
Workload	0.2	0.8
Criticality or Priority	0.3	0.8
Combined Certainty Factor	0.2	0.8

Although Resolution A would require the addition of a pump, the pump could be installed at any time and would not restrain the removal of the existing pipe and installation of the pipe at a lower elevation. The pipe for the revised installation was readily available. Resolution B would require revised drawings and the re-fabrication of portions of the reinforcing for the columns and shearwalls. The Implementation Preparation Time for Resolution A was identified as zero days with a certainty factor of 1. The Implementation Preparation Time for Resolution B was identified as three days with a certainty factor of 1. The certainty factors for the Implementation Preparation Time are shown in Table 43.

Based on the stage of the project, the crew reassignment options were: (1) Standby and (2) Demobilization. There was no alternative work available on the site.

Table 43: Application 3 – Certainty Factors for Implementation Preparation Time

	Implementation Preparation Time Increment
Resolution	0 days
Resolution A	1.0
	Implementation Preparation Time Increment
Resolution	3 days
Resolution B	1.0

The structural crew costs were $550 per hour for supervision, labor, and equipment, which was a total of $4,400 per eight-hour day. The equipment included a small crane used to off load trucks. The idle rate for the crane resulted in a standby rate of $520 per hour.

The costs for demobilization were comprised of eight hours for demobilization plus eight hours for re-mobilization. Inefficiencies were estimated at 20% to 30% for a time period of five workdays following re-mobilization. Table 44 shows the calculated costs for each time increment for the possible crew reassignment options.

Table 44: Application 3 – Crew Reassignment Costs

Crew Reassignment Option	Time Increment		
	Response Time		Implementation Time
	2 days - 5 days	6 days - 10 days	3 days (Resolution B only)
Standby	$8,320 - $20,800	$24,960 - $41,600	$12,480
Demobilization	$13,200 - $15,400	$13,200 - $15,400	$0
Standby - Demobilization	$8,320 - $20,800	$24,960 - $41,600	$13,200 - $15,400

As shown in Table 44, the Crew Reassignment Options titled Standby and Demobilize represent either placing the crew on standby or demobilizing for the entire duration of the Response Time plus the Implementation Preparation Time. The Crew Reassignment Option titled Standby - Demobilize represents placing the crew on standby during the

Response Time then demobilizing the crew during the Implementation Preparation Time. Although the combination of Demobilization - Standby is possible, Project Management did not consider this as a reasonable option. Thus, this option was not included in the model application. Table 45 summarizes the crew costs for each of the crew reassignment options that were shown in Table 44.

Table 45: Application 3 – Matrix of Crew Reassignment Costs

	States			
	Resolution A		Resolution B	
Crew Reassignment Options	Response Time 2 - 5 days, Implementation Preparation 0 days	Response Time 6 - 10 days, Implementation Preparation 0 days	Response Time 2 - 5 days, Implementation Preparation 3 days	Response Time 6 - 10 days, Implementation Preparation 3 days
Standby	\$8,320 - \$20,800	\$24,960 - \$41,600	\$20,800 - \$33,280	\$37,440 - \$54,080
Demobilize	\$13,200 - \$15,400	\$13,200 - \$15,400	\$13,200 - \$15,400	\$13,200 - \$15,400
Standby - Demobilize	\$8,320 - \$20,800	\$24,960 - \$41,600	\$21,520 - \$36,200	\$38,160 - \$57,000

Since the crew reassignment option of Standby - Demobilize has costs that are equal to or greater than the costs for the option of Standby, the dominated option of Standby - Demobilize was not considered any further. Figure 17 shows the application of the model to the data for the non-dominated options.

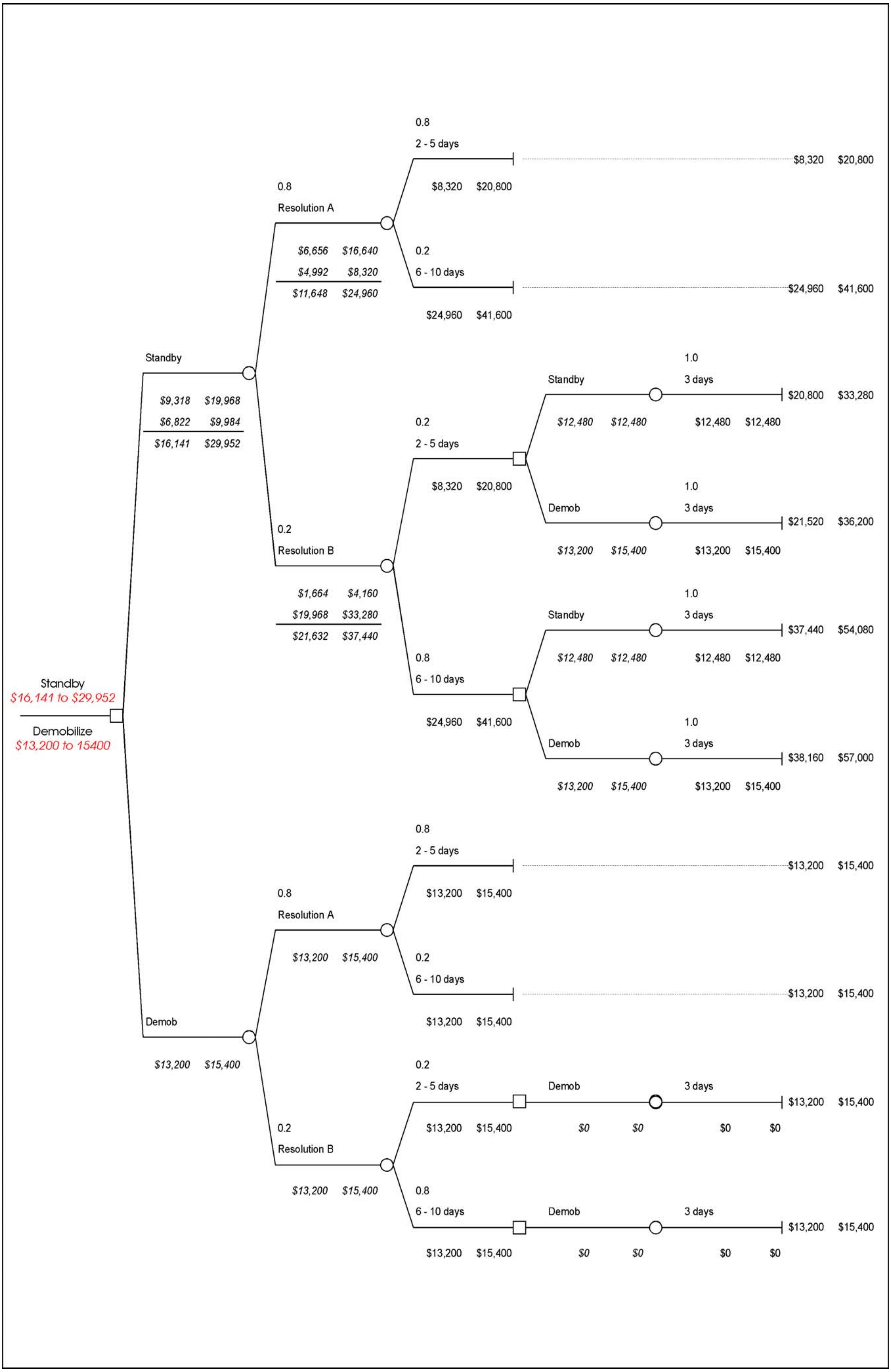


Figure 17: Crew Reassignment Model Applied to Application 3 Data

The application of the model resulted in a range of expected costs from $16,141 to $29,952 for Standby and $13,200 to $15,400 for Demobilize. Therefore, the model shows that the entire range of costs for Demobilize is lower than the expected minimum for Standby. Figure 18 is a graphic depiction of the calculated ranges of potential costs.

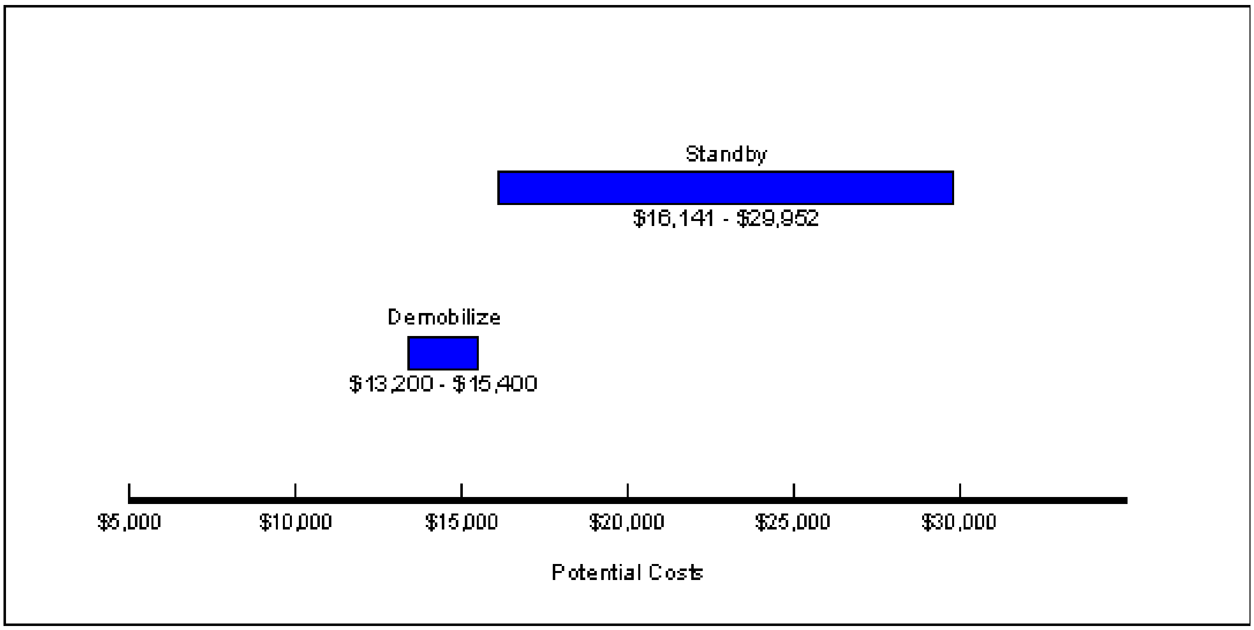


Figure 18: Ranges of Potential Costs for Application 3

The crew reassignment decision made by Project Management was to demobilize the crew. The response from the designer, which was received after six workdays, was to remove and re-install the pipe at an elevation below the slab. Due to the new depth of the pipe a pump was required. However, it was not necessary to install the pump prior to resuming the structural work. Based on the actual duration of six workdays, the costs for Standby would have been $24,960 as compared to the Demobilization costs of $13,200 to $15,400. Note that the Demobilization costs included a range of $4,400 to $6,600 for anticipated inefficiencies following re-mobilization. Project management estimated that the actual inefficiencies were at or below the lower bound of the range. Therefore, the actual costs incurred were estimated at $13,200. Since the Demobilization costs were just over one-half of the costs expected for Standby for the same six-workday duration, the decision to demobilize the crew appeared to be the lowest cost option.

The Project B management assessment of the crew reassignment model is contained at the end of Section 4.2.4.

4.2.4. Model Application 4

On the day of the start of the interior framing on the fifth floor of Project B, the designer issued a stop work order for the framing, indicating that one buyer was purchasing both units on the sixth floor and considering revising the layout of the sixth floor from two units to a single-unit floor plan. However, the decision for the revised layout was not final. Further, the revised floor plan was not ready to be issued for construction. The potential resolutions were (A) frame the sixth floor as a single unit, which required revised plans, or (B) frame the sixth floor as two units, as shown in the existing plans. The Project B representatives indicated that Resolution A "*almost certainly*" would be issued, which was translated to a certainty factor of 0.9. The likelihood of receiving Resolution B was "*probably not*," which resulted in a certainty factor of 0.2.

Two time increments were identified for each of the Response Times. For Resolution A the time increments were: (1) 1 day to 5 days and (2) 6 days to 10 days. For Resolution B the time increments were: (1) 1 day to 3 days and (2) 4 days to 5 days. Table 46 contains the certainty factors for the three main elements that are considered as the determinants of the expected duration of the response time for a particular resolution. Table 46 also shows the combined certainty factors obtained using the joint certainty minimum method.

Although Resolution A would require revisions to the layout of the interior framing, the same framing material would be utilized as originally planned. Other material required due to the revisions would not restrain the construction of the revised framing. As described, Resolution B was to build the sixth floor as shown in the plans. Therefore, since no additional materials, tools, or equipment were necessary to implement either Resolution A or B, the Implementation Preparation Time for Resolutions A and B was identified as zero days with a certainty factor of 1. The certainty factors for the Implementation Preparation Time are shown in Table 47.

Table 46: Application 4 – Certainty Factors for Response Time

Resolution A Factor	Response Time Increment	
	1 day - 5 days	6 days - 10 days
Complexity	0.1	0.9
Workload	0.1	0.9
Criticality or Priority	0.3	0.9
Combined CF	0.1	0.9
Resolution B Factor	**Response Time Increment**	
	1 day - 3 days	4 days - 5 days
Complexity	0.9	0.2
Workload	0.9	0.2
Criticality or Priority	0.9	0.2
Combined CF	0.9	0.2

Table 47: Application 4 – Certainty Factors for Implementation Preparation Time

Resolution	Implementation Preparation Time Increment
	0 days
Resolution A	1.0
Resolution	**Implementation Preparation Time Increment**
	0 days
Resolution B	1.0

Based on the stage of the project, the crew reassignment options were: (1) Standby, (2) Re-Sequence, and (3) Demobilization.

The framing crew costs were $470 per hour for supervision and labor, which was a total of $3,760 per eight-hour day. Note that the follow-on crews had approximately two weeks of work before reaching the sixth floor. Since the maximum expected duration for resolution of this issue was two weeks, there was no expected impact to any other trades.

The costs for Standby were $3,760 per day. The costs for Re-Sequence were two hours for demobilization and two hours for re-mobilization at the new task. In addition, inefficiencies of 25% were expected for five workdays. The costs for Demobilization were comprised of four hours for demobilization plus four hours for re-mobilization. Inefficiencies were estimated at 30% to 40% for a time period of five workdays following re-mobilization. Table 48 shows the calculated costs for each time increment for the possible crew reassignment options.

Since there is no duration for Implementation Preparation Time, there are no combinations of crew reassignment options to be considered. The summary of the crew costs for each of the crew reassignment options is shown in Table 49.

Since the crew reassignment option of Demobilize has costs that are equal to or greater than the costs for the option of Re-Sequence, the dominated option of Demobilize was not considered any further. Figure 19 shows the application of the model to the data for the non-dominated crew reassignment options of Standby and Re-Sequence.

Table 48: Application 4 – Crew Reassignment Costs

Crew Reassignment Option	Resolution A – Time Increment		
	Response Time		Implementation Time
	1 day - 5 days	6 days - 10 days	0 days
Standby	$3,760 - $18,800	$22,560 - $37,600	$0
Re-Sequence	$6,580	$6,580	$0
Demobilization	$13,160 - $15,040	$13,160 - $15,040	$0
Crew Reassignment Option	**Resolution B – Time Increment**		
	Response Time		Implementation Time
	1 day - 3 days	4 days - 5 days	0 days
Standby	$3,760 - $11,280	$15,040 - $18,800	$0
Re-Sequence	$6,580	$6,580	$0
Demobilization	$13,160 - $15,040	$13,160 - $15,040	$0

Table 49: Application 4 – Matrix of Crew Reassignment Costs

Crew Reassignment Options	States			
	Resolution A		Resolution B	
	Response Time 1 - 5 days, Implementation Preparation 0 days	Response Time 6 - 10 days, Implementation Preparation 0 days	Response Time 1 - 3 days, Implementation Preparation 0 days	Response Time 4 - 5 days, Implementation Preparation 0 days
Standby	$3,760 - $18,800	$22,560 - $37,600	$3,760 - $11,280	$15,040 - $18,800
Re-Sequence	$6,580	$6,580	$6,580	$6,580
Demobilize	$13,160 - $15,040	$13,160 - $15,040	$13,160 - $15,040	$13,160 - $15,040

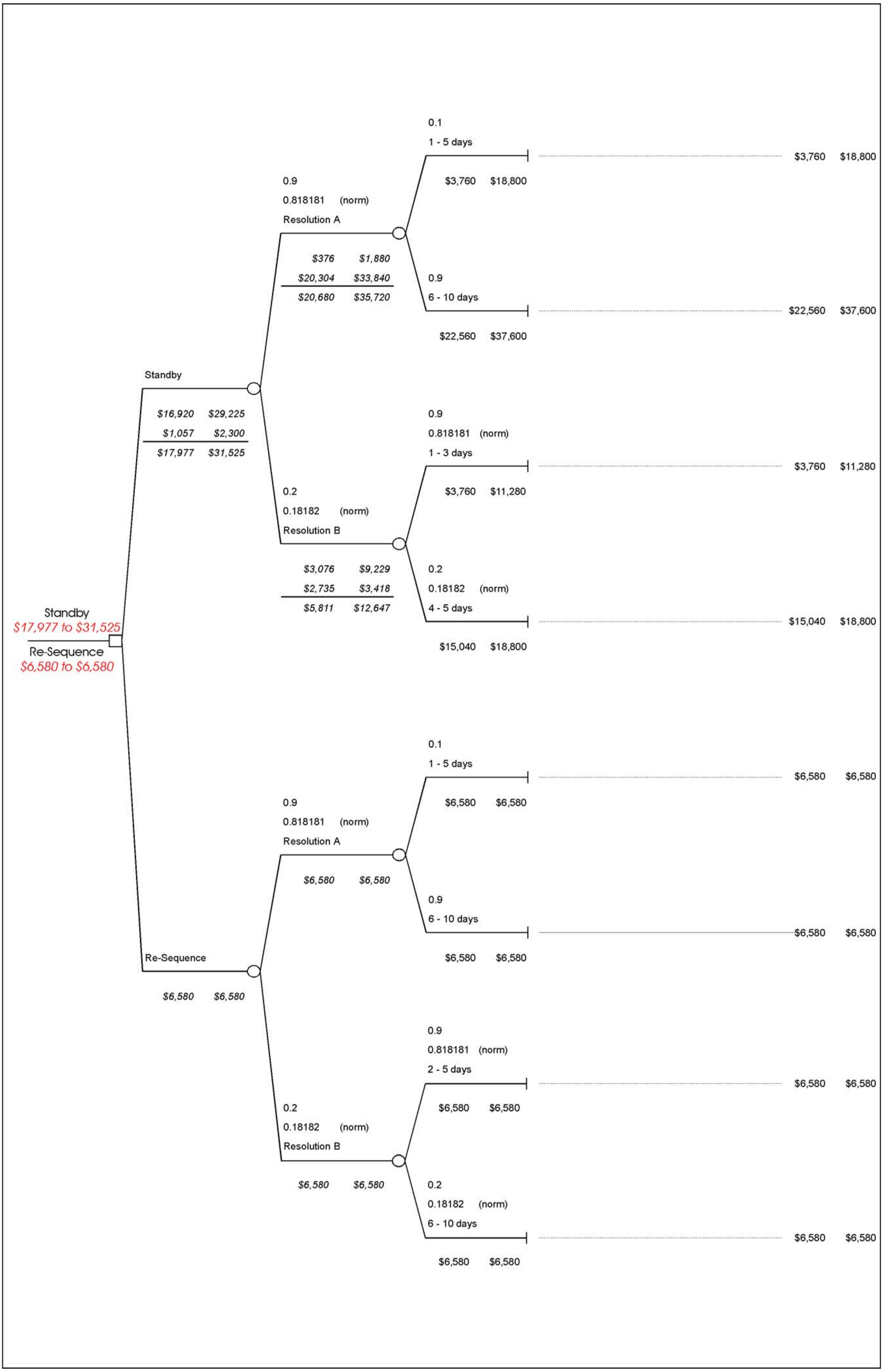


Figure 19: Crew Reassignment Model Applied to Application 4 Data

The application of the model resulted in a range of expected costs from $17,977 to $31,525 for Standby and $6,580 for Re-Sequence. As shown in Figure 20, the model shows that the expected costs for Re-Sequence are lower than the expected range of costs for Standby. Therefore, the model recommendation is to select the crew reassignment option of Re-Sequence.

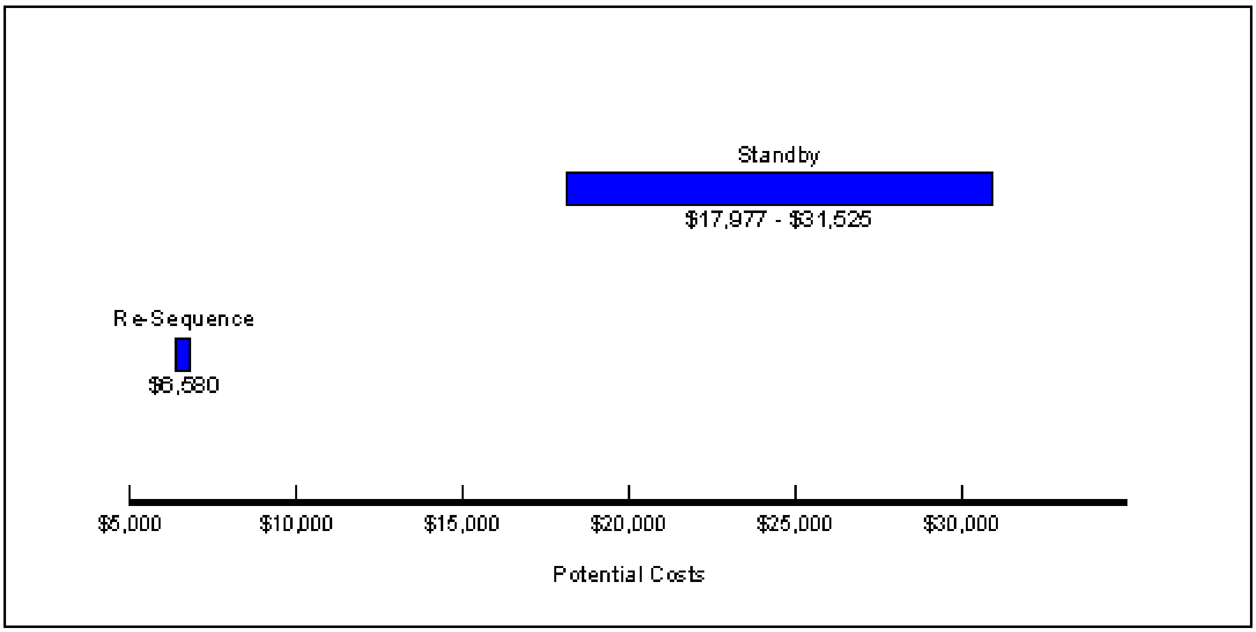


Figure 20: Ranges of Potential Costs for Application 4

Project B management chose to re-sequence the work for the framing crew. As noted, due to the lag between the framing progress and the follow-on trades, it was not necessary to re-sequence any of the follow-on trades.

Three days after the stop work order was issued, the designer issued preliminary drawings showing the revised framing. The construction drawings were received seven days after the stop work order was issued. Allowing for the resumption of the sixth floor framing upon receipt of the preliminary drawings, the costs for Standby for the three days were estimated at $11,280 as compared to the costs for Re-Sequence of $6,580. Therefore, it appeared that the contractor made the most cost-effective crew reassignment decision.

The Project B representatives stated that the model provided a useful format for organizing the pertinent data for the crew reassignment decision, allowing an easy comparison of the alternatives using different durations and/or certainty in the occurrences of the durations or responses under consideration. In addition, it was noted that the model provided information that was useful to the designer or owner in determining the full costs of each change alternative. Project management noted that the costs captured by the model represented the most difficult costs to justify in a change order request. Further, it was indicated that the model provided a tool to evaluate and document those costs, allowing the generation of appropriate back-up for the pricing of change orders. Without the model, project management noted, it was possible to overlook a possible option and incorrectly estimate the costs by performing a less-than-complete evaluation of the loss of productivity. The model was cited as providing the necessary guidelines to avoid these errors. In addition, the crew reassignment costs frequently were difficult to track and justify using the available project documentation. The application of the model would document the timing of the decision, allowing a the capture of all the costs resulting from the decision.

4.2.5. Model Application 5

After the completion of the east wall of the garage foundation on Project C, it was discovered that the structural drawings had shown a regular wall section where a shearwall was required. The potential resolutions that were identified were (A) remove the existing wall section and replace with the proper shearwall configuration and (B) thicken the existing wall section by drilling and doweling reinforcing to tie the wall to an additional wall. The Project C representatives indicated that Resolution A "*maybe would not*" be issued, which was translated to a certainty factor of 0.3. The likelihood of receiving Resolution B was "*probably*," which resulted in a certainty factor of 0.8.

Three time increments were identified for each of the Response Times of each potential resolution: (1) 1 day to 3 days, (2) 4 days to 6 days, and (3) 7 days to 10 days. Table 50 contains the certainty factors for the three main elements that are considered as the determinants of the expected duration of the response time for a particular resolution as well as the combined certainty factors obtained using the joint certainty minimum method. Both potential resolutions had the same certainty factors for each time increment.

Table 50: Application 5 – Certainty Factors for Response Time

Resolution A and B Factor	Response Time Increment		
	1 day - 3 days	4 days - 6 days	7 days - 10 days
Complexity	0.1	0.9	0.1
Workload	0.1	0.8	0.2
Criticality or Priority	0.2	0.9	0.1
Combined Certainty Factor	0.1	0.8	0.1

Both potential resolutions required reinforcing bar that the Project representatives indicated could be fabricated and delivered in one day. Therefore, the Implementation Preparation Time for Resolutions A and B was identified as one day with a certainty factor of 1. The certainty factors for the Implementation Preparation Time are shown in Table 51.

Table 51: Application 5 – Certainty Factors for Implementation Preparation Time

	Implementation Preparation Time Increment
Resolution	1 days
Resolution A	1.0
	Implementation Preparation Time Increment
Resolution	1 days
Resolution B	1.0

Based on the stage of the project, the crew reassignment options were: (1) Standby, (2) Re-Sequence, and (3) Demobilization.

The structural crew costs were $1,800 per hour for supervision, labor, and equipment, which was a total of $14,400 per eight-hour day. No other trades were mobilized.

The costs for Standby were $1,700 per day. The costs for Re-Sequence were four hours for demobilization and four hours for re-mobilization at the new task. In addition, inefficiencies of 20% to 30% were expected for five workdays. The costs for Demobilization were comprised of eight hours for demobilization plus four hours for re-mobilization. Inefficiencies were estimated at 20% for a time period of five to ten workdays following re-mobilization. Table 52 shows the calculated costs for each time increment for the possible crew reassignment options.

The possible combinations of crew reassignment options are Standby - Re-Sequence, Standby - Demobilize, Re-Sequence - Standby, Re-Sequence - Demobilize, Demobilize - Standby, and Demobilize - Re-Sequence. However, since the expected duration of Implementation Preparation Time was only one day, the Project C representatives indicated that the possible combinations were not reasonable. That is, the crew reassignment would not be revised at the end of the Response Time. The summary of the crew costs for each of the crew reassignment options is shown in Table 53.

Table 52: Application 5 – Crew Reassignment Costs

Crew Reassignment Option	Resolution A and B – Time Increment			
	Response Time			Implementation Time
	1 day - 3 days	4 days - 6 days	7 days - 10 days	1 day
Standby	$13,600 - $40,800	$54,400 - $81,600	$95,200 - $136,000	$13,600
Re-Sequence	$28,800 - $36,000	$28,800 - $36,000	$28,800 - $36,000	$0
Demobilization	$36,000 - $50,400	$36,000 - $50,400	$36,000 - $50,400	$0

Table 53: Application 5 – Matrix of Crew Reassignment Costs

Crew Reassignment Options	States		
	Resolution A or B		
	Response Time 1 - 3 days, Implementation Preparation 1 day	Response Time 4 - 6 days, Implementation Preparation 1 day	Response Time 7 - 10 days, Implementation Preparation 1 day
Standby	$27,200 - $54,400	$68,000 - $95,200	$108,800 - $149,600
Re-Sequence	$28,800 - $36,000	$28,800 - $36,000	$28,800 - $36,000
Demobilize	$36,000 - $50,400	$36,000 - $50,400	$36,000 - $50,400

Since the crew reassignment option of Demobilize has costs that are equal to or greater than the costs for the option of Re-Sequence, the dominated option of Demobilize was not considered any further.

Figure 21 shows the application of the model to the data for the non-dominated crew reassignment options of Standby and Re-Sequence.

The application of the model resulted in a range of expected costs from $68,000 to $96,560 for Standby and $28,800 to $36,000 for Re-Sequence. Thus, the model shows that the expected range of costs for Re-Sequence is lower than the expected range of costs for Standby. Figure 22 is a depiction of the calculated ranges of costs.

Project C management chose to re-sequence planned structural work. The resolution was issued by the designer four days after the issue was identified. The resolution was to remove two portions of the wall and replace them with column sections. Thus, the resolution was a combination of Resolutions A and B. The contractor ordered the necessary reinforcing steel and began the work one day after receiving the revised design. Based on the five-day actual duration of the Response Time plus Implementation Preparation Time, the estimated costs for Standby were $68,000, while the estimated costs for Re-Sequence were $28,800 to $36,000.

The review and evaluation of the model by the Project C representatives is included at the end of Section 4.2.6.

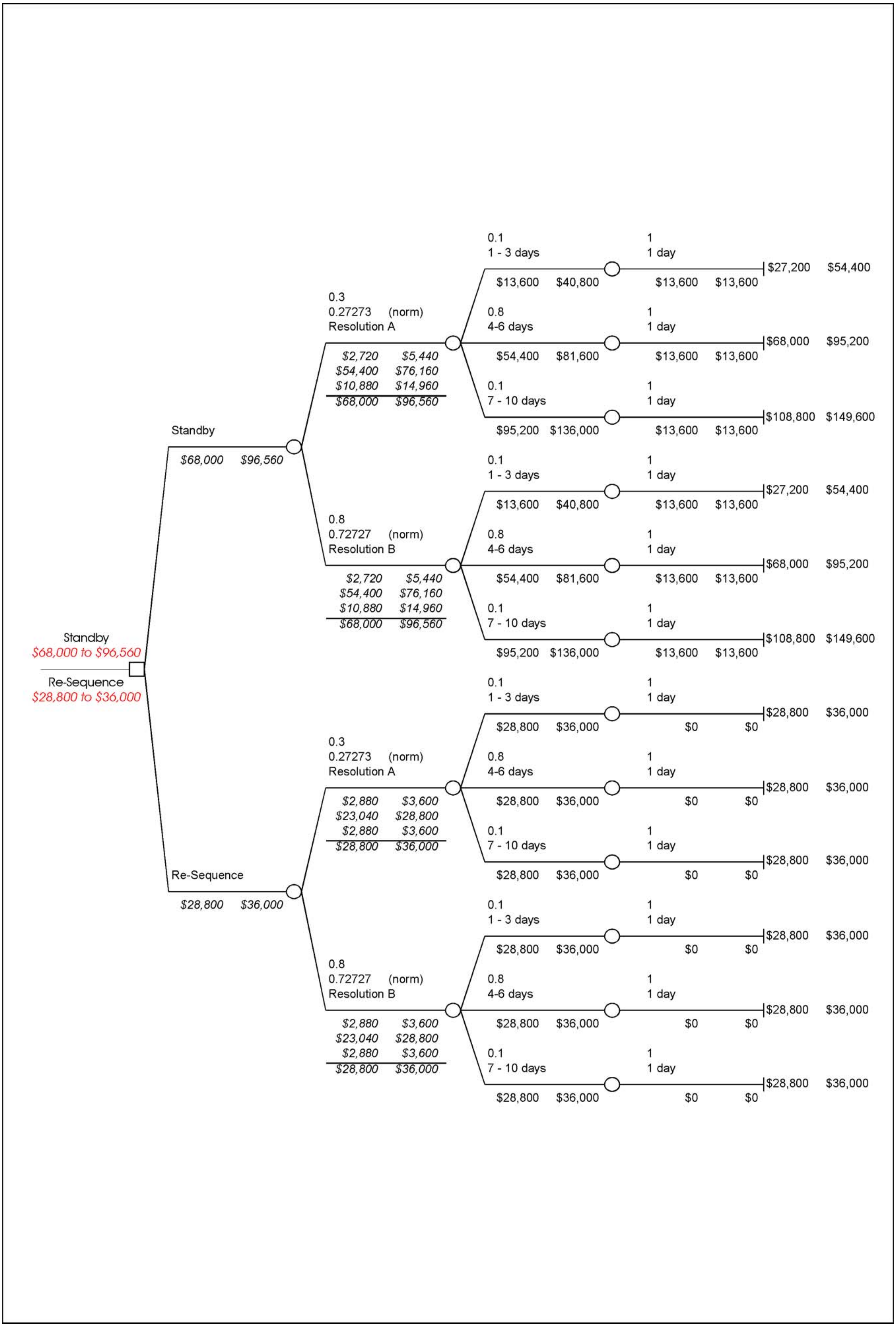


Figure 21: Crew Reassignment Model Applied to Application 5 Data

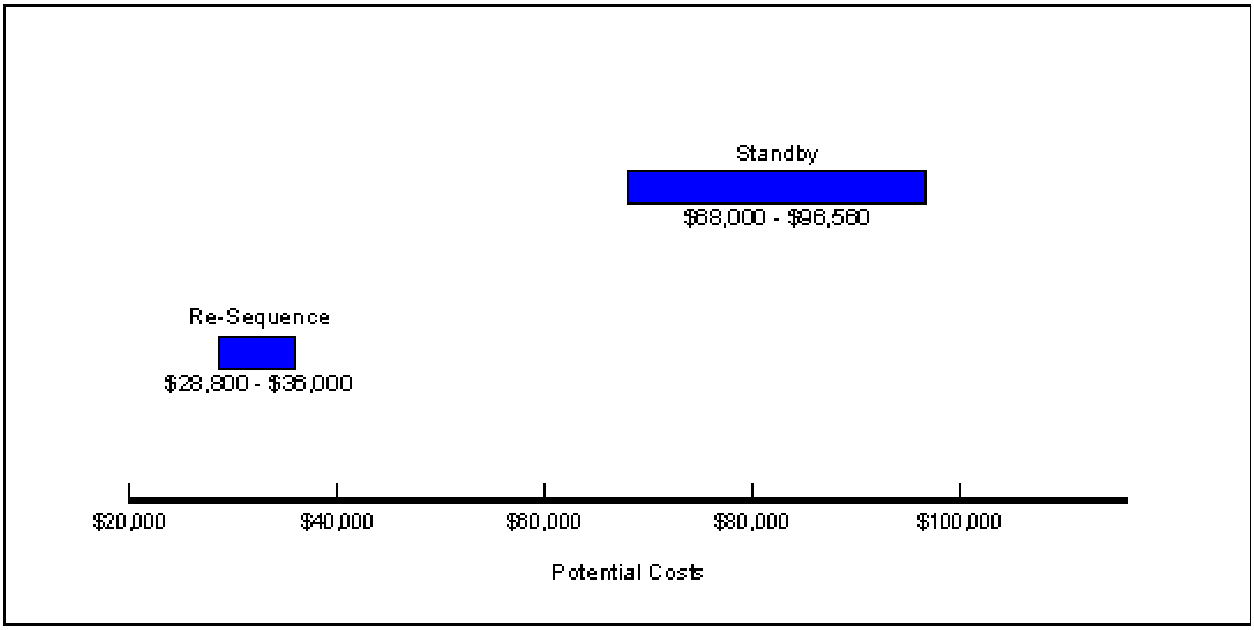


Figure 22: Ranges of Potential Costs for Application 5

4.2.6. Model Application 6

During the installation of the appliances on Project C, it was determined that the position of the washer and dryer in the laundry room did not allow sufficient clearance to access the electrical panel in compliance with the Americans with Disabilities Act. The potential resolutions that were identified were: (A) relocate the electrical panels and (B) replace the washers and dryers with a "stacked" model. Relocating the appliances was not possible due to space limitations.

The Project C representatives indicated that Resolution A "*almost certainly would not*" be issued, which was translated to a certainty factor of 0.1. The likelihood of receiving Resolution B was "*almost definitely*," which resulted in a certainty factor of 0.95.

Three time increments were identified for the Resolution A Response Times: (1) 1 day to 5 days, (2) 6 days to 10 days, and (3) 11 days to 15 days. Two time increments were identified for Resolution B Response Times: (1) 1 day to 3 days and (2) 4 days to 5 days. Table 54 contains the certainty factors for the three main elements that comprise the determinants of the expected duration of the response time for a particular resolution as well as the combined certainty factors obtained using the joint certainty minimum method.

Table 54: Application 6 – Certainty Factors for Response Time

Resolution A Factor	Response Time Increment		
	1 - 5 days	6 - 10 days	11 - 15 days
Complexity	0.1	0.8	0.2
Workload	0.2	0.8	0.2
Criticality or Priority	0.3	0.9	0.1
Combined Certainty Factor	0.1	0.8	0.1

Resolution B Factor	Response Time Increment	
	1 - 3 days	4 - 5 days
Complexity	0.9	0.2
Workload	0.8	0.2
Criticality or Priority	0.9	0.2
Combined Certainty Factor	0.8	0.2

The start of implementation of Resolution A did not require any material that was not readily available. Although Resolution B would require the purchase of new appliances, the receipt of the appliances did not affect any of the trades. Therefore, the Implementation Preparation Time for Resolutions A and B was identified as zero days with a certainty factor of 1. The durations and certainty factors for the Implementation Preparation Time are shown in Table 55.

Table 55: Application 6 – Certainty Factors for Implementation Preparation Time

	Implementation Preparation Time Increment
Resolution	0 days
Resolution A	1.0

	Implementation Preparation Time Increment
Resolution	0 days
Resolution B	1.0

All work was complete on the project except for final testing and punchlist. The various crews were ready to demobilize within three days when the deficiency was identified. The crew reassignment options were: (1) Standby after completion of the punchlist work and (2) Demobilize after completion of the punchlist.

The total costs for the crews that potentially were affected by the change were $475 per hour for supervision and labor, which was a total of $3,800 per eight-hour day. Therefore, the costs for Standby were $3,800 per day. Costs for Demobilize were $3,800 for four hours of demobilization plus four hours of re-mobilization plus costs for inefficiencies of 50% to 60% for five workdays. The relatively high rate of inefficiencies was related to the expectation that tradesmen other than those currently on the project would be sent to the project upon re-mobilization. Table 56 shows the calculated costs for each time increment for the possible crew reassignment options.

Table 56: Application 6 – Crew Reassignment Costs

Crew Reassignment Option	Resolution A – Time Increment			
	Response Time			Implementation Time
	1 day - 5 days	6 days - 10 days	11 days - 15 days	0 day
Standby	$0 - $7,600	$11,400 - $26,600	$30,400 - $45,600	$0
Demobilize	$0 - $15,200	$13,300 - $15,200	$13,300 - $15,200	$0

Crew Reassignment Option	Resolution B – Time Increment		
	Response Time		Implementation Time
	1 day - 3 days	4 days - 5 days	0 day
Standby	$0	$3,800 - $7,600	$0
Demobilize	$0	$13,300 - $15,200	$0

Since the Implementation Preparation Time was zero days there were no crew reassignment combinations to be considered.

Figure 23 shows the application of the model to the data for the crew reassignment options of Standby and Demobilize.

The application of the model resulted in a range of expected costs from $1,846 to $3,909 for Standby and $3,547 to $4,198 for Demobilize. Thus, the model shows that the expected range of costs for Standby is lower than the expected range of costs for Demobilize. Figure 24 is a depiction of the potential ranges of costs.

The response from the designer was not received prior to the completion of the punchlist work. The management on Project C chose to demobilize the crews at that time. The response was received five workdays after the identification of the issue or two workdays after the crews were demobilized. The designer issued a change order to implement Resolution A, which required the relocation of the electrical panel in each unit. Based on the actual duration of the Response Time, the estimated costs for Standby were $7,800, while the estimated costs for Demobilize were $13,300 to $15,200. Therefore, the decision to demobilize the crews did not appear to be the most cost-effective decision.

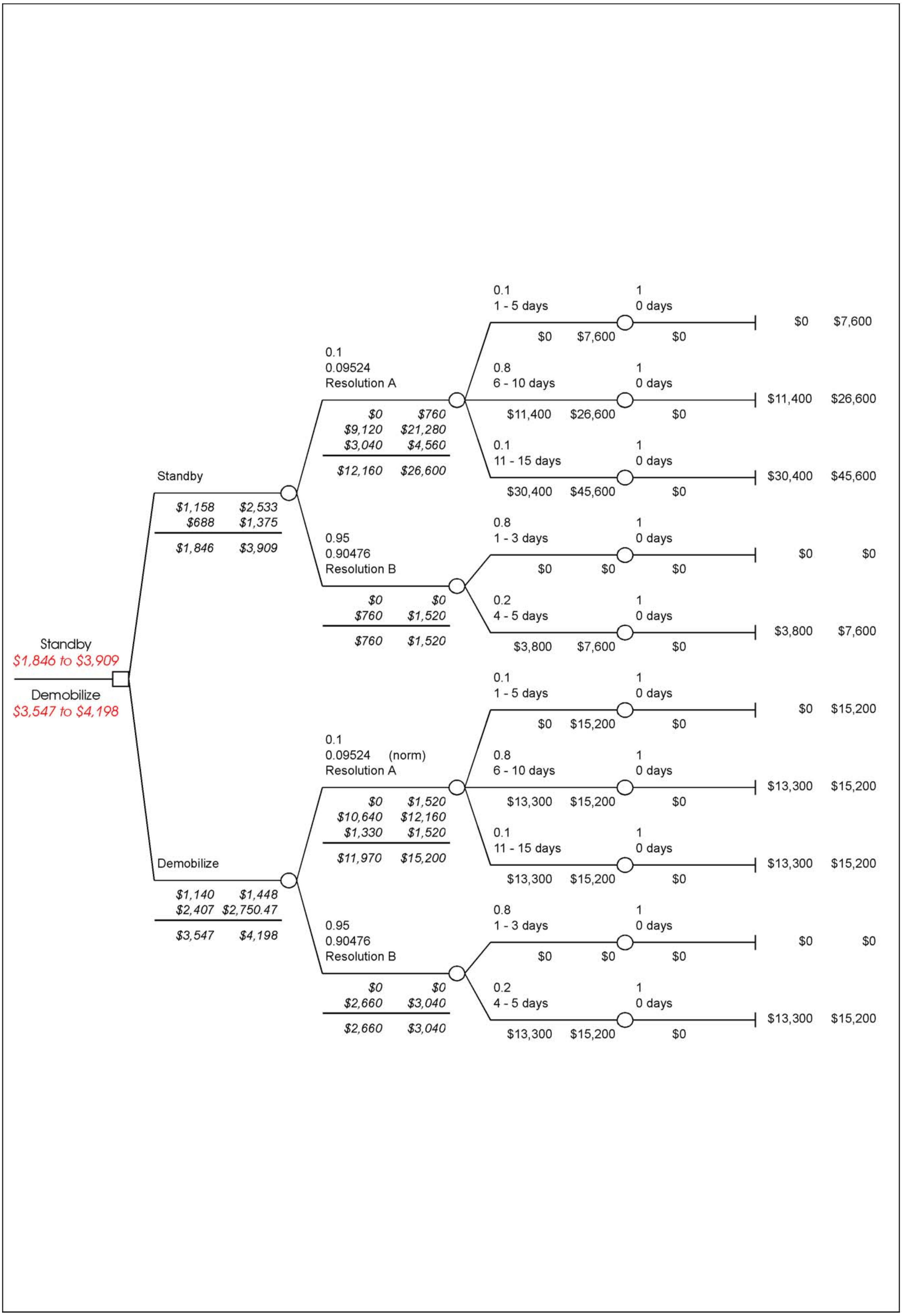


Figure 23: Crew Reassignment Model Applied to Application 6 Data

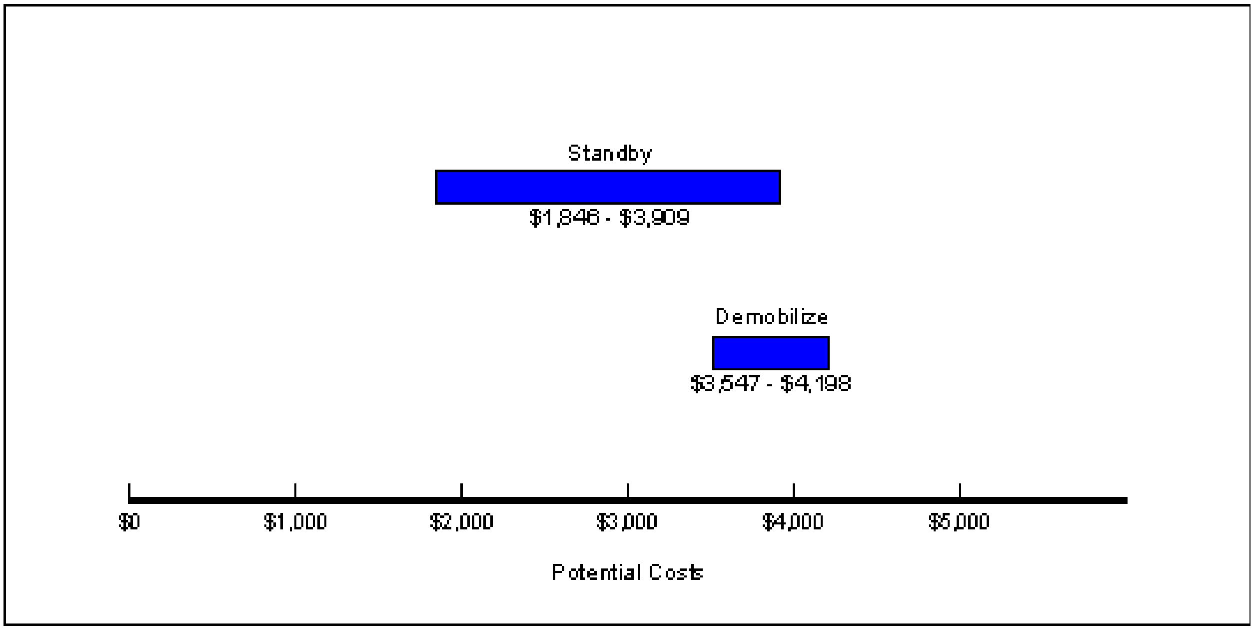


Figure 24: Ranges of Potential Costs for Application 6

The representatives of Project C indicated that the model was useful as a checklist of the items to be considered and for organizing the information for the crew reassignment decision. The Project C representatives also cited the value of having the information in a format that was ready for presentation to the designer or owner to assist in finalizing the change orders, which could result in faster payment for the change work. The information provided by the model was used to substantiate the change order pricing for both changes.

4.3. Summary

The crew reassignment decision support model was applied to six change circumstances on three different projects. The project representatives on all three projects stated that the model outcomes were consistent with their expectations. The project representatives also indicated that the model provided a previously-unavailable method for the evaluation of the crew reassignment options, potential responses, durations, and costs while considering the uncertainty in each of the components.

In summary, all the project representatives that participated in the application of the model noted that the model process forced a thorough consideration of each of the elements that were critical in determining the estimated costs associated with each crew reassignment option, resulting in a more-informed decision than was typically made without the application of the model.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1. Introduction

This dissertation described the methodology used to develop and validate a crew reassignment decision model for changes on a construction project. The need for the model stems from the many factors, as well as the uncertainty associated with many of the factors, that must be incorporated into the crew reassignment decision. The crew reassignment decision support model identified the key factors and established a model architecture that emulated the decision process of the experts that participated in the research. The resulting model combined certainty factors on a decision tree structure. The validity and usefulness model was demonstrated through the prospective application of the model to six change circumstances on three different projects.

5.2. Summary of Findings

As presented in Chapter 2, the initial research indicated that the decision makers preferred to express their beliefs in the likelihood of the various occurrences associated with a crew reassignment decision in verbal terms that did not correspond to standard probability theory. In addition, the events under consideration lacked the repetitive occurrences that allow the development of probability distributions. Finally, the frequency of crew reassignment decisions and the need for quick responses required an analytic method that was easy to use. These considerations led to the conclusion that the crew reassignment decision support model should employ certainty factors as the quantitative method. The structure of the model required the explicit representation of the chronology of events as well as the recognition of the uncertainty of any estimates used in the analysis. This led to the conclusion that a decision tree was the appropriate model structure.

Since certainty factors have not been used in a decision tree structure, part of the research included the development and testing of the techniques to combine the certainty factors with the other elements of the crew reassignment decision. Chapter 3 described the surveys, group meetings, and expert interviews conducted in order to determine each of the elements of the decision and the method in which the elements are combined to evaluate each of the crew reassignment options that are available for a particular decision.

This research culminated in a crew reassignment decision support model that included consideration of the options available for the crew reassignment, the potential resolutions to the issue and the likelihood of receiving each of the potential resolutions, the durations for the receipt of the resolution and the likelihood of each of the durations, the durations for preparation to implement any particular resolution, and the range of costs associated with each crew reassignment option for each duration. In addition, the model included the techniques for combining the certainty factors associated with each of the elements. The outcome of the model is an estimate of the upper and lower bounds for each crew reassignment option.

The model was tested and validated through the contemporaneous application to six change circumstances. Chapter 4 discussed the assessments of the model by the users, who indicated the model provided a complete and concise compilation of the elements of the crew reassignment decision. In addition, the model outcomes were determined to be consistent with the users' expectations. Users also cited the value of the model as a checklist for the information to be considered in the crew reassignment decision, resulting in better-formulated estimated costs. Also, the users cited the documentation created by the model application which could be used to support pricing of change orders.

The crew reassignment decision support model provides a framework that is able to accommodate any number of crew reassignment options, potential resolutions, response durations, implementation preparation durations, or range of costs. The ease of use allows a timely evaluation of a change issue or the update of a previously applied model.

5.3. Contributions

Crew reassignment decisions occur frequently on a construction project. The crew reassignment decision support model provides codification of the considerations in making these decisions and can assist in the identification of cost-effective crew reassignment options while addressing decision-maker preferences and the effects of uncertainty.

The model development identified the key elements of the crew reassignment decision. As noted, these include, the Potential Resolutions, the Response Time, the Implementation Preparation Time, the available Crew Reassignment Options, and the related Costs. Further, the research revealed that the Response Time is dependent on three factors: the complexity of the resolution, the workload of the designer, and the criticality or priority of the issue.

The research also indicated that applying the joint-minimum combination method to the certainty factors for the three elements that comprised the Response Time resulted in a certainty factor that closely matched the single certainty factor provided by the experts. This finding appeared to indicate that the risk attitudes of the experts, as related to the factors affecting the expected Response Time, correlated to the previously devised joint-minimum combining rules for certainty factors.

Included in the model is a method for the application of certainty factors to a decision tree structure. This previously-undocumented application results in an easy-to-use and easy-to-update model. As shown in the crew reassignment decision support model, the certainty factors for the three factors that comprise the Response Time were combined using the joint certainty minimum method. The resulting joint certainty factor and the remaining certainty factors throughout the model were aggregated using the product method for combining certainty factors. The product method of combination parallels the manner in which standard probabilities are combined on a decision tree structure.

5.4. Future Work

The crew reassignment decision support model was developed using 14 participants in the survey and group meeting phase. Four of the participants provided further insight into the crew reassignment decision as part of the group of six construction experts from the areas of institutional and commercial construction. Additional study of the decision process of a larger number of construction industry experts may provide further data for model refinement.

In addition, the model was tested on mid-size, non-union, commercial construction projects. Model testing should be broadened to determine if the model is valid across a range of construction types, sizes of projects, geographical areas, and union projects.

Although the priority or criticality of an issue is included in the determination of the potential response time, the current model does not specifically address schedule considerations. Extension of the model may include schedule requirements as additional decision criteria in determining the crew reassignment.

The model was devised specifically to address the potential productivity loss prior to the performance of the change work. Since the crew reassignment decision may affect the overall resource plan for the balance of the project, the decision may result in downstream productivity effects. Examples of these effects include higher or lower productivity rates on all remaining work as a result of the remobilization of different crews than were present prior to the crew reassignment decision and higher or lower productivity rates due to re-sequencing of work. Both of the cited examples also may result in downstream schedule effects. An extension of the model could include the potential resource and schedule effects on the balance of the project work.

As noted, the research indicated that application of the joint-minimum combination method to the certainty factors for the three elements that comprised the Response Time resulted in a certainty factor that closely matched the single certainty factor provided by the experts.

This finding appeared to indicate that the risk attitudes of the experts regarding the Response Time correlated to the previously devised joint-minimum combining rule for certainty factors. Further study of the risk attitudes of the decision makers may provide additional insight into the appropriate combining methods of the certainty factors for different applications of the model. In addition, understanding of the decision makers' behavior regarding risk may allow refinement of the model in the area of evaluation and assessment of the outcomes.

APPENDIX A: PRODUCTIVITY LOSS MEASUREMENT MODELS

CHAPTER A1: INTRODUCTION

A1.1. General

Changes on a construction project are an everyday occurrence. In fact, essentially every construction contract contains a 'changes clause' that defines the process for identifying and documenting changes. Typically, the contractor and owner can come to terms for the 'bricks and mortar' portion of the costs of a change. However, the costs of delays and productivity losses resulting from changes are common areas of disagreement between the parties. Frequently, these alleged costs form the basis of a claim.

The construction industry and the courts have recognized critical path method schedule analysis as the preferred method of identifying and quantifying critical delays, while the measured mile analysis generally is regarded as the preferred method for the quantification of productivity losses [Singh, 2002; Crowley and Livengood, 2002]. Although a critical path method analysis can be performed on a prospective basis, a measured mile analysis can be performed only retrospectively. Thus, the preferred method for measuring productivity losses can not be employed for the pricing of change orders until after the change work is complete. In fact, there are no widely-accepted methods for the prospective determination of productivity losses due to changes. As a result, when pricing a change order, a contractor typically reserves his/her rights to claim additional costs at a later time for any productivity losses resulting from the performance of the change work. Generally, the 'later' identification of the productivity losses takes the form of a total cost claim, where the planned manhours are compared to the actual manhours, with the difference being attributed to the owner-directed changes. Neither owners nor the courts accept a total cost claim, except under rare circumstances.

The following is a review of the literature regarding factors that can affect construction productivity as well as the methods and models that have been developed for the identification and quantification of productivity losses as a result of changes during a construction project. This review will illustrate the multitude of factors involved and the complex relationship between changes and construction labor productivity.

CHAPTER A2: IMPACTS TO CONSTRUCTION LABOR PRODUCTIVITY

A2.1. Introduction

This chapter provides an overview of the measurement and impacts to construction labor productivity. The first section provides a definition and method of measurement of labor productivity. The second section is a review of the identified factors that can have an adverse effect on labor productivity. The last section is a summary of the studies that have been performed in an attempt to quantify the effects of certain single factors and multiple factors on labor productivity. This review will show that many of the published studies are based on survey or anecdotal information, are based on very limited empirical data, or are based on data from non-construction activities. No forward-looking or prospective model has been developed that has been generally-accepted or validated for use in the variety of circumstances typically encountered on construction projects.

A2.2. Productivity

Productivity is a measure of the amount of work performed compared to the resources expended to perform that work. In construction, the resources typically are measured in manhours, resulting in:

$$\text{Productivity} = \frac{\text{Quantity}}{\text{Manhour}} \qquad \text{(A1)}$$

For example, a measure of productivity could be the number of linear feet of pipe installed per manhour or the cubic yards of concrete placed per crew day. In construction, the ratio frequently is expressed in the inverse, that is, resources per quantity or unit of work. This measure of productivity is referred to as the unit rate. When using the unit rate form of productivity measurement, increases in productivity are represented by lower numbers. This paper will use the quantity per manhour measurement of productivity. Thus, in this paper, an increase in productivity will be represented by a higher number, unless specifically noted otherwise.

A loss of productivity results when more resources are used with no additional work accomplished or when less work is performed with no change in resources. In the literature, the terms efficiency and productivity and the terms inefficiency and loss of productivity are used interchangeably.

Although productivity for an activity usually is estimated as a single value when preparing a bid estimate, the actual planned productivity will vary throughout the course of a project. For most work activities, the initial productivity rate shows an increasing trend. This time period is referred to as the "ramp-up" period. The productivity during this period is affected by the crafts becoming familiar with both the jobsite (mobilization) and the task (learning curves).

The ramp-up period usually is followed by a period of productivity at a sustained level. This represents the time when the work is being performed under expected conditions in a somewhat repetitious fashion. This sustained level of productivity normally represents the highest level of productivity for that activity throughout the course of the project.

The final phase of productivity, or "ramp-down" phase, is characterized by a decreasing trend. This phase is comprised of completion of the work activity and demobilization from the work area. Figure A1 depicts a comparison of the estimated versus the actual planned productivity.

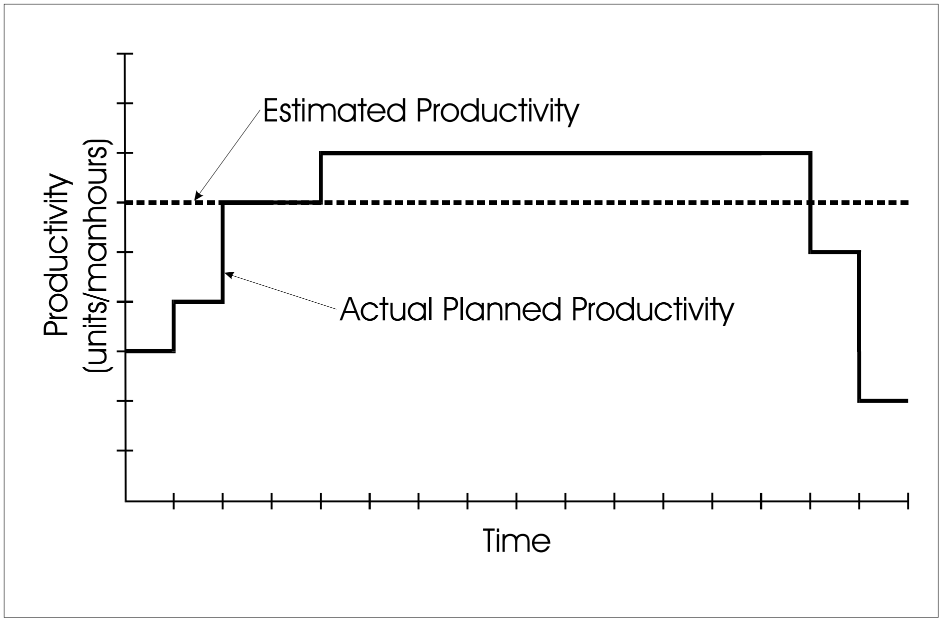


Figure A1: Planned Versus Actual Productivity

At least five prerequisites have been identified for the achievement of a high level of productivity on a construction project: (1) good supervision; (2) effective planning and scheduling; (3) timely availability of materials, equipment, and tools; (4) adequately skilled workers; and (5) the ability to measure site productivity in quantitative terms [The Business Roundtable, 1982]. Many of these same factors have been identified as key areas for productivity improvement in an on-going series of surveys of the top 400 construction companies in the United States [Arditi and Mochtar, 2000]. The results of the surveys, which were conducted in 1979, 1983, and 1993, show that cost control, value engineering, labor training, quality control, and scheduling were consistently identified as having the greatest potential for productivity improvement.

Although the lack of any of these factors has been considered as a cause of decreased productivity, the important question is “decreased as compared to what?” That is, when preparing a bid estimate, a contractor should be cognizant of all the parameters under which the estimate is being prepared. For example, if the contractor is aware of a shortage of qualified workers in a certain needed trade, this information should be factored into the estimate. In the event that better-skilled workers later become available to perform the work, the contractor may realize increased productivity as compared to that used in preparing the estimate. This could result in increased profits for the contractor. Conversely, if lesser-skilled workers are all that are available, reduced productivity and reduced profits may be realized. Again, the important point is the consideration of all pertinent information in preparing the estimate.

A2.3. Causes of Construction Labor Inefficiency

Inefficiencies can be brought about by many events, including acceleration, changes in the work scope, or disruptions and delays to the work. These events are considered as the circumstances that can give rise to inefficiencies. As a result of these circumstances, a project may experience certain factors that affect productivity. The most-often-cited factors include temperature and humidity, physical location, project design and size (constructability and complexity), landscape, access, materials and equipment, labor organization, workers’ skills and familiarization with the work (learning curve), craft supervision, management, working hours (overtime and shift work), manning level and crew composition (trade stacking and congestion), absenteeism, and work sequence [Arditi and Mochtar, 2000; Borcherding and Alarcon, 1991; Bureau of Labor Statistics, 1947; The Business Roundtable, 1980, reprinted 1989; Herbsman and Ellis, 1991; Quraishi, 2003; Thomas and Smith, 1990; Tucker, Haas, Borcherding, Allmon, and Goodrum, 1999]. These factors can have either a positive or negative impact on the expected productivity on a construction project.

Borcherding, Palmeter, and Jansma [1986] identified 65 separate elements or factors that can lead to productivity losses. The factors were grouped into five major categories of unproductive time: (1) waiting or idle, (2) ineffective work, (3) rework, (4) slow work, and (5) traveling. The interactions among the factors were represented through the use of an influence diagram. The 65 separate elements illustrate the quantity, breadth, and complexity of the elements or factors identified as potential causes of inefficiency.

A2.3.1. Types of Changes

Although many of the factors identified can exist on a construction project in the absence of any change, this paper will focus on the effects on labor productivity resulting from a change in the expected conditions. Typically, these changes take the form of a change order or change directive that represents work that is different than that shown in the original contract documents. Changes can be of a minor nature that do not have any effect on the field labor, such as a change in a paint color selection prior to the start of the work; or changes can be of significant scope, such as a change to the foundation system from slab on grade to auger-cast piles or a change to the work hours from a normal day shift to only night shift or weekend work.

In addition, a change can result from either a Type I or Type II differing site condition. A Type I differing site condition is a condition that differs materially from the representation in the contract documents. For example, the geotechnical report indicated an average water table depth of 20 feet below the ground surface; however, water is encountered at a depth of four feet during footer excavation, resulting in the need for dewatering provisions not anticipated. A Type II differing site condition is a condition of an unusual nature not typically encountered for that type of work in that geographical area. For example, groundwater contamination found during dewatering operations, in an area where no contamination was documented previously, resulting in the requirement for monitoring wells, extensive testing, and dewatering restrictions.

The courts have recognized that the effects of performing change work include both the effects directly related to the performance of the changed work and the effects arising from the interaction between changed work and unchanged work [*Triple "A" South v Armed Services*, ASBCA No. 46866]. In the case of the groundwater contamination example noted above, the changed work would be the additional work identified by the need for monitoring wells and water testing. These costs should be easy to document. The effects arising from the interaction between the changed work and the unchanged work could include the resequencing of the foundation excavation work or possibly the delays to the underground utilities to accommodate the new dewatering restrictions. The courts have referred to the effects directly related to the performance of the changed work as "local" or "hardcore," while the effects on unchanged work have been referred to as "impact" or "disruption." In addition, the term "cumulative disruption" has been used to describe those situations arising from the aggregated losses of productivity resulting from multiple changes to the work scope. Thus, local or hardcore effects can be traced directly to a particular change, while cumulative disruption is a consequence of conditions that materially differ from those that were expected at the time of bid, resulting from multiple changes. It is the effects of these cumulative disruptions that are the most difficult to quantify prospectively.

In order for cumulative disruption to be recognized, the courts have used the threshold where "*the number of changes in the work, and the scope of the changes, . . . went well beyond normal experience and reasonable expectations with respect to [projects] of like kind*" [*Atlantic Dry Dock Corp. v United States*, No. 87-974 CIV-J-10]. Conversely, a reasonable or foreseeable number of changes typically will not be recognized as a cause of cumulative disruption. For example, in *Triple "A" South v Armed Services*, ASBCA No. 46866, the court found that the 600 to 700 changes that occurred were not unusual for an eight-month shipyard project.

Although the literature contains no record of any comprehensive studies of the number of changes that can be reasonably expected during a construction project, a 1986 study by the Building Research Board National Council considered the dollar value of changes during construction projects. The study compared contract growth on over $4.7 billion worth of projects administered by the Naval Facility Command, U.S. Army Corps of Engineers, and Veterans Administration. In addition, the study reviewed Census Bureau data for over 59,000 privately-owned projects. The results of the study showed that average cost growth due to changes ranged from approximately 5% to 10%.

It should be noted that a study of the average number of changes on a construction project could be a very difficult undertaking, since it is a common practice to incorporate a number of separate changes into a single change order. Thus, a study that simply counts the number of change orders may provide very misleading results.

Also, as previously discussed, the scope of individual changes can vary greatly. A change can be very minor in nature, resulting in little or no effect on planned resources, or can be so significant as to be considered a cardinal change to the contract. A cardinal change is defined as when the owner causes an alteration in the work that is so drastic that the contractor is required to perform duties materially different from those contemplated under the terms of the contract. Therefore, any study of changes should consider the scope of the work identified by the changes rather than only the number of the changes that occurred.

A2.3.2. Effects of Changes on Productivity

Finke [1998] identified and defined six factors that can cause losses in productivity due to differences in working conditions brought about by a change:

(1) Resource diversion or skill dilution, requiring that the changed (or disrupting) and unchanged (or disrupted) work use the same resources and be performed at the same time.

(2) Work area congestion, requiring that the changed and unchanged work be performed in the same area at the same time.

(3) Stacking of trades, requiring that the changed and unchanged work be performed in the same area, be performed at the same time, and represent different types of work.

(4) Dilution of supervision, requiring that the changed and unchanged work be performed at the same time and have the same supervisors.

(5) Interruptions of otherwise continuous work, requiring that the changed work forces in-progress unchanged work to be temporarily stopped.

(6) Delay, requiring that the change forced unchanged work to be performed at a different time than would otherwise have been the case, and the unchanged and/or delayed work, now acting as the changed work, causes one of the five working conditions listed above.

The relationship between the circumstances that give rise to inefficiencies and the factors that cause inefficiencies is illustrated as follows: A significant design change occurs to a critical path activity late in the project. The contractor is directed to complete all work without delaying the planned project completion date. In order to comply, the contractor hires additional craftsmen for a new crew to perform the change work as well as increasing the size and work hours of each existing crew to perform the unchanged work, which is affected by the performance of the change work. In this scenario, the design change is the "circumstance" that creates the conditions for the potential loss of productivity, while overtime, learning curve, manning level, crew size, and dilution of supervision are some of the specific factors that may affect the productivity rate on both the changed and unchanged work.

Schwartzkopf [1995] identified four phases of cost and schedule impacts resulting from a change. Phase 1 is the identification of a potential change and determination of the resolution. For example, the change may be the result of a discrepancy between the drawings and the field conditions, which is resolved through the issuance of a change order that requires additional material. Phase 2 encompasses the material procurement to implement the change. Phase 3 is the performance of the change work. Phase 4 is the work performed after the change work is complete.

Note that the crew either can be idle or assigned to another task during the resolution of the discrepancy and material procurement. In the event that the crew is idle during Phases 1 and 2, the impact to productivity is easy to calculate. The loss is the cost of the number of hours of idle time. However, if the crew is assigned to another task, there may be a certain amount of lost time due to mobilization of tools and equipment to another work area; a loss of productivity while learning the new task; reduced productivity due to stacking of trades and congestion if assigned to work concurrent with other workers in a confined area; and dilution of supervision if assigned to a remote work area.

During the performance of the change work in Phase 3, it is possible that additional productivity losses may be incurred. For example, there may be congestion in the area as a result of additional trades, material, or equipment that would not have been present had the change not occurred. Thus, losses of productivity may be experienced by other trades and crews in addition to the initial crew that was affected by the change. This illustrates the court-defined “impact” or “disruption” discussed in the previous section.

Finally, the resumption of the original contract work in Phase 4 may incur productivity losses for the same reasons as cited for Phase 3. This productivity loss could occur if the circumstances under which the unchanged work is being performed are different than expected prior to the change. As with the other phases, the potential impacts are not restricted to the crew initially affected by the change.

In order to predict the loss of productivity that may be experienced in the simple example above, one must consider the effect of the interaction of all of the identified factors. The following section is a review of the studies found in the literature that address both single factors and multiple factors that can affect construction labor productivity.

A2.4. Studies of Factors Affecting Productivity

A list of the studies that have been performed on the loss of productivity attributable to individual factors, such as crew composition, learning curves, overtime, and weather, is included in Table A1. Table A2 contains a list of studies performed on the loss of productivity due to the effects of circumstances, which can represent multiple, simultaneously-occurring factors.

Table A1: Summary of Studies: Effects of "Factors" on Productivity

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Factor: Absenteeism					
Sargent	2003	"Absenteeism and turnover impact on labor productivity for electrical contractors" Project specific factors affect productivity losses associated with absenteeism and turnover.	Survey and empirical (observation); Statistical	31 projects (surveys) and 5 project (observations); Indeterminate	Electrical; Miscellaneous; Nationwide.
Factor: Crew Composition and Overmanning					
US Army Corps of Engineers	1979	*Construction Modification Impact Evaluation Guide* Crew Size Above Optimum vs. Productivity. For example, 50% above optimum predicts a 10% loss of productivity.	Indeterminate	Indeterminate	Indeterminate
Sanders, Thomas, and Smith	1989	"An analysis of factors affecting labor productivity in masonry construction" Suggests two patterns for crew size in masonry work: production-oriented and piece-meal work.	Empirical (observation); Statistical	11 projects; Indeterminate	Miscellaneous masonry construction; 1986-1988; Pennsylvania

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Factor: Design (Constructability and/or Complexity)					
Low	2001	"Quantifying the relationships between buildability, structural quality and productivity in construction" Correlation coefficient of 0.635 for relationship between productivity and buildability.	Empirical (database); Linear regression	37 projects; Indeterminate	Indeterminate; Indeterminate; Singapore
O'Connor, Larimore, and Tucker	1986	"Collecting constructability improvement ideas" Major productivity improvement problem cited was availability of information.	Survey; Statistical	1 project; Indeterminate	Refinery expansion 1980s; Texas
Sanders and Thomas	1991	"Factors affecting masonry-labor productivity" Productivity adversely affected by unusual design requirements.	Empirical (observation); Analysis of variance	11 projects; Indeterminate	Miscellaneous masonry construction; 1986-1988; Pennsylvania
Factor: Learning Curve					
Everett and Farghal; Farghal and Everett	1997; 1997	"Data representation for predicting performance with learning curves"; "Learning curves: accuracy in predicting future performance" Method or formula for predicting total remaining costs, etc. for activities with learning effects. (See Farghal and Everett)	Indeterminate — historical data from previous reports	54 construction activities; Indeterminate	Miscellaneous — with the majority of data from residential construction

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Gates and Scarpa	1972	"Learning and experience curves" Proposed uses and learning rates for various activities.	Indeterminate; previously-published data	Indeterminate	Indeterminate
Thomas, Mathews, and Ward	1986	"Learning curve models of construction productivity" Comparison of straight-line and non-linear types of curves.	Not applicable	Not applicable	Not applicable
United Nations	1965	"Effect of repetition on building operations and processes on site" Two phases: Operation-Learning and Routine-Acquiring.	Empirical (observation); Statistical	1 project (45 units); Indeterminate	Residential; 1960s; Finland
Ward and Thomas	1984	"A validation of learning curve models available to the construction industry" Study of the setting of concrete planks in multi-story building.	Empirical (observation); Statistical	1 project; 1 contractor	Apartment building; 1980s; Pennsylvania

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Factor: Material Management					
Bilal and Thomas; Thomas, Sanders, and Bilal	1990; 1992	"A comparative analysis of labor productivity of masons in seven countries"; "Comparison of labor productivity" Losses of 84% due to storage and organization, 57% due to material handling and distribution, and 87% due to material availability.	Empirical (observation); Statistical	13 projects (465 days or records); Indeterminate	Commercial masonry construction; 1980s; Seven countries
Sanders, Thomas, and Smith	1989	"An analysis of factors affecting labor productivity in masonry construction" Calculated 45% loss of productivity due to material distribution and availability problems.	Empirical (observation); Statistical	11 projects; Indeterminate	Miscellaneous masonry construction; 1986-1988; Pennsylvania
Thomas, Riley, and Sanvido	1999	"Loss of labor productivity due to delivery methods and weather" Losses due to material delivery systems between 9% and 16%.	Empirical (observation); Statistical and multiple regression	3 projects; Indeterminate	Miscellaneous structural steel construction; 1980s and 1990s; Pennsylvania
Thomas and Sanvido	2000	"Role of the fabricator in labor productivity" Case studies of the effect of late deliveries, out-of-sequence deliveries, and fabrication errors. Loss of productivity calculated between 16.6% and 56.8%.	Empirical (observation); Statistical	3 projects; Indeterminate	Miscellaneous; 1990s; Pennsylvania

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Thomas, Sanvido, and Sanders	1989	"Impact of material management on productivity — A case study" Compares unimpacted to impacted project; 18% loss of productivity due to poor material storage and handling practices.	Empirical (observation); Statistical	2 projects; Indeterminate	Commercial structural steel erection; 1980s; Pennsylvania
Factor: Overtime					
Bureau of Labor Statistics	1947	*Bulletin No. 917, Hours of Work and Output* Studies conducted in manufacturing environment in the 1940s.	Empirical (observation); Statistical	Indeterminate	Manufacturing; 1940s; Indeterminate
Construction Industry Institute	1988	*The Effects of Scheduled Overtime and Shift Schedule on Construction Craft Productivity* Losses in productivity from working overtime are not automatic; possible to work 60-hour weeks (in short intervals) without serious losses.	Empirical (indeterminate); Statistical	7 projects; Indeterminate	Industrial; Indeterminate
Mechanical Contractors Association of America	1994	*Change Orders / Overtime / Productivity* Section OT-1 has tables showing overtime "multipliers."	Anecdotal	Not Applicable	Indeterminate - mechanical; information gathered in late 1960s or early 1970s
NECA	1989	*Overtime and Productivity in Electrical Construction* Tables and charts of "multipliers."	Empirical (database); Statistical	Indeterminate	Miscellaneous electrical projects; 1964; Southeast Michigan

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
The Business Roundtable	1989	*Scheduled Overtime Effect on Construction Projects* Charts for 50- and 60-hour work weeks; Significant drop in productivity during the first week of overtime, followed by a gradual improvement through the third week, then continuous decline until leveling out at the ninth week.	Empirical (database); Statistical	1 project; Indeterminate	Industrial; 1970s - 1980s; Wisconsin
Thomas	1992	"Effects of scheduled overtime on labor productivity" Literature review. Concludes the available literature contains many references to other studies with little original data; "*strange and largely unbelievable results*."	(Literature review)	Miscellaneous	Miscellaneous
Thomas and Raynar	1997	"Scheduled overtime and labor productivity: quantitative analysis" Shows losses of 10-15% for 50- and 60-hour work weeks. Since this data concurs with The Business Roundtable, concludes that the BRT curves are reasonable estimates of losses due to overtime. Second part of study looked at the reasons for inefficiency losses during overtime. Concludes that losses resulted from inability to provide materials, tools, equipment, and information at an accelerated rate. Thus, considers overtime losses in productivity a result of other causes.	Empirical (database); Statistical	4 projects (121 weeks of data); Indeterminate	Industrial — electrical and piping; 1989 - 1992; Indeterminate
Factor: Remobilization (see Disruptions and/or Delays in "Circumstances" Table)					

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Factor: Sequence					
Bennett and Thomas	1990	"A case study of the validity of daily crew-based productivity measurements" 27% reduction of productivity due to out-of-sequence work.	Empirical (observation); Statistical	1 project (148 days); 1 contractor	Concrete formwork; 1980s; Pennsylvania
Bilal and Thomas	1990	"A comparative analysis of labor productivity of masons in seven countries" Out-of-sequence work on 13 days. 20% reduction in productivity due to out-of-sequence work.	Empirical (observation); Statistical	13 projects (465 days or records); Indeterminate	Commercial masonry construction; 1980s; Seven countries
Sanders, Thomas, and Smith	1989	"An analysis of factors affecting labor productivity in masonry construction" Calculated 75% loss of productivity on days when work sequence problems were experienced.	Empirical (observation); Statistical	11 projects; Indeterminate	Miscellaneous masonry construction; 1986-1988; Pennsylvania
Factor: Shiftwork					
Mechanical Contractors Association of America	1994	*Change Orders / Overtime / Productivity* Section OT-2 addresses shiftwork. Cites percentage loss of efficiency associated with various "factors."	Anecdotal; Indeterminate	Indeterminate	Indeterminate - mechanical; information gathered in late 1960s or early 1970s

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Factor: Supervision and Management					
Logcher and Collins	1978	"Management impacts on labor" High correlation between productivity and presence of or interaction with supervision.	Empirical (observation); Regression	5 projects (2 to 5 days per project); 1 contractor	Vinyl floor tile installation; 1976 and 1977; Boston and New York City
Sanders, Thomas, and Smith	1989	"An analysis of factors affecting labor productivity in masonry construction" 41% loss of productivity on days when foreman not present.	Empirical (observation); Statistical	11 projects; Indeterminate	Miscellaneous masonry construction; 1986-1988; Pennsylvania
Smith	1987	"Increasing onsite production" Problems result from lack of training, insufficient numbers, and incompetence.	Indeterminate	Indeterminate	Miscellaneous
Thomas, Maloney, Horner, Smith, Handa, and Sanders	1990	"Modeling construction labor productivity" Developed two models: (1) Factor Model — accounts for project, site, and management factors; (2) Expectancy Model — why a crew exerts an effort and how this effort relates to productivity.	Not applicable	Not applicable	Not applicable

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Thomas, Sanvido, and Sanders	1989	"Impact of material management on productivity — a case study" Comparison of two projects: 239% additional manhours for steel erection attributable to inexperience of contractor. Comparison to ten comparable projects: 296% more manhours due to material distribution, unavailability of scheduled work areas, lack of scaffolding, poor site layout.	Empirical (observation); Statistical	2 projects; Indeterminate	Commercial structural steel erection; 1980s; Pennsylvania
Thomas and Zavrski	1999	"Construction baseline productivity: theory and practice" Proposes two indices to measure performance: disruption index and project management index.	Empirical (database); Statistical	23 projects; Indeterminate	Concrete formwork and structural steel; Indeterminate; Indiana and Pennsylvania

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Factor: Subcontractors					
Hsieh	1998	"Impact of subcontracting on site productivity: lessons learned in Taiwan" Study of subcontracting in Taiwan (160 questionnaire responses and interviews with 31 general contractors)	Survey; Statistical	160 responses to 1080 mailed questionnaires	General contractors; 1995; Taiwan
Factor: Trade Stacking or Overmanning					
US Army Corps of Engineers	1979	*Modification Impact Evaluation Guide* Curve for Effect of Crowding on Labor Productivity: % Crowding vs. % Labor Loss to Inefficiency.	Indeterminate	Indeterminate	Indeterminate
Gunduz	2004	"A quantitative approach for evaluation of negative impact of overmanning on electrical and mechanical projects" Formula to calculate probability of overmanning.	Survey; Binary logistic regression and statistical	97'overmanned' projects and 39 'regular' projects	Electrical and mechanical with 200,000 manhours or less; indeterminate; Miscellaneous
Logcher and Collins	1978	"Management impacts on labor" Productivity unrelated to sf. ft. per person — in all cases area per person > 300 sq. ft.	Empirical (observation); Regression	5 projects (2 to 5 days per project); 1 contractor	Vinyl floor tile installation; 1976 and 1977; Boston and New York City

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Sanders, Thomas, and Smith	1989	"An analysis of factors affecting labor productivity in masonry construction" 65% loss of efficiency for congestion.	Empirical (observation); Statistical	11 projects; Indeterminate	Miscellaneous masonry construction; 1986-1988; Pennsylvania
Smith	1987	"Increasing onsite production" Reports density vs. productivity; max productivity at 320 sq. ft. per person; theoretical lower limit at 100 sq. ft.	Indeterminate	Indeterminate	Miscellaneous
Factor: Union versus Non-Union					
Bilal and Thomas	1990	"A comparative analysis of labor productivity of masons in seven countries" No statistical significance between union and nonunion workers.	Empirical; Statistical	13 projects (465 days or records); Indeterminate	Commercial masonry construction; 1980s; Seven countries

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Multiple Factors					
Sonmez and Rowings	1998	"Construction labor productivity modeling with neural networks" Factors considered: quantities completed, job type, crew size, percent overtime, percent laborer, temperature, humidity, precipitation, concrete pump. Concluded that the effect of factors on productivity may vary from task to task, and that models with fewer significant factors predict better than models with many factors without regard to significance.	Empirical (database); Regression and neural network modeling	8 projects; 1 contractor	Miscellaneous structural concrete construction; 1992 - 1994; Iowa
Factor: Weather — Temperature and Humidity; Rainfall					
Bracken and Thomas	1990	"Development of a baseline curve for structural steel erection" Temperature effects on structural steel erection. Removed data for over 85% humidity and known disruptions.	Empirical (observation); Statistical	5 projects; Indeterminate	Miscellaneous structural steel; 1980s; Pennsylvania
El-Rayes and Moselhi	2001	"Impact of rainfall on the productivity of highway construction" Decision support system for quantifying impact of rainfall on productivity and duration of highway projects.	Not applicable	Not applicable	Not applicable
Grimm and Wagner	1974	"Weather effects on mason productivity" Erection of 283 standard masonry wall panels. Results shown on isopleth.	Empirical (Controlled field experiment - observation); Statistical	51 workers over 9-month period	Miscellaneous masonry construction; 1972; Texas

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Hancher and Abd-Elkhalek	1998	"The effect of hot weather on construction labor productivity and costs" Model developed by assigning weights using previously-published factors. Model then used to generate a set of productivity curves.	Indeterminate - previously-published models and factors	Indeterminate	Indeterminate
Hester and Kuprenas	1987	*A Report to Dow Chemical and the Construction Industry Institute on the Productivity of Insulation Installation Studied the installation of pipe insulation*.	Empirical (indeterminate); Statistical	1 project (354 days); 1 contractor	Process plant pipe insulation; 1980s; California
Koehn and Brown	1985	"Climatic effects on construction" Combination of data from a variety of sources; potential data manipulation may make results suspect.	Indeterminate - previously-published literature	Indeterminate	Indeterminate
NECA	1974	*The Effect of Temperature on Productivity* Two electricians in climate-controlled chamber installed connections for electrical wall fixtures.	Empirical (Laboratory observation); Statistical	1 crew of two men (6 days)	Laboratory conditions
Thomas, Riley, and Sanvido	1999	"Loss of labor productivity due to delivery methods and weather" Losses due to weather (35%) and temperature (30%).	Empirical (observation); Statistical and multiple regression	3 projects; Indeterminate	Miscellaneous structural steel construction; 1980s - 1990s; Pennsylvania

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Thomas and Yiakoumis	1987	"Factor model of construction productivity" Insensitive to high humidity. Other factors confounded in model.	Empirical (observation); Multiple regression	3 projects (78 days); Indeterminate	Miscellaneous structural steel and masonry construction; 1986; Pennsylvania

Table A2: Summary of Studies: Effects of “Circumstances” on Productivity

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Circumstance: Acceleration					
Thomas and Oloufa	1996	“Strategies for minimizing the economic consequences of schedule acceleration and compression” Method to measure the loss of productivity due to differences between planned and actual labor consumption rates. Partitioned data into levels related to maximum planned manpower.	Empirical; Non-linear regression	5 projects; Indeterminate	Miscellaneous electrical construction; Indeterminate
Thomas	2000	“Schedule acceleration, work flow, and labor productivity” Formula to measure loss based on changes in labor resources. Partitioned data into levels related to maximum planned manpower.	Empirical (database); Nonlinear regression	3 projects; Indeterminate	Miscellaneous electrical construction; 1990s; Indeterminate

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Circumstance: Change Orders					
Assem	2001	"Estimating productivity loss due to change orders" Neural network models for predicting productivity loss based on timing and type of change work.	Expert reports; claims and existing data; Neural network modeling	33 cases selected from 117 projects; indeterminate	Miscellaneous; mainly Canada
Construction Industry Institute	2000	"Change orders and their cumulative impact" Two step procedure: (1) formula to measure evidence or probability of impact due to changes and (2) formula to quantify impact. Independent variables: percent change, management time on project, owner-initiated changes, productivity tracking, overmanning, and change order processing time.	Survey; Linear regression	116 projects; 68 contractors	Miscellaneous mechanical and electrical construction; Indeterminate
Hanna, Russell, and Vandenberg	1999	"The impact of change orders on mechanical construction labour efficiency" Two equations for the loss of efficiency due to change orders on mechanical work on impacted (32 projects) and unimpacted (11 projects) projects. Independent variables were timing of the changes and amount of change hours as a percentage of the total actual hours.	Survey; Stepwise linear regression	43 projects; 14 contractors	Miscellaneous mechanical construction; Indeterminate

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Hanna, Russell, Gotzion, and Nordheim	1999	"Impact of change orders on labor efficiency for mechanical construction" Second phase of model development described in Hanna, Russell, and Vandenberg (1999). Combined data with previous data. Independent variables were timing of the changes, amount of change hours as a percentage of the total actual hours, and number of changes.	Survey; Stepwise linear regression	61 projects; 26 contractors	Miscellaneous mechanical construction; Indeterminate; 19 states
Hester and Kuprenas	1987	*A Report to Dow Chemical and the Construction Industry Institute on the Productivity of Insulation Installation* Loss of efficiency shown as a function of the number of change orders per week.	Empirical (database); Statistical	1 project; Indeterminate	Oil refinery — concrete, structural steel, and above-ground piping; 1980s; California
Leonard	1988	"The effects of change orders" Developed statistical model to estimate loss of productivity due to change order hours as a percentage of actual contract hours. All data was from projects that generated claims.	Expert reports and claims; Linear regression	57 projects (90 cases); Indeterminate	Miscellaneous; 1970s and 1980s; mainly Canada

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Moselhi, Leonard, Fazio	1991	"Impacts of change orders on construction productivity" Based on same data as Leonard (1988). Concluded that "*On average, there is a 30% loss of efficiency when changes are being performed . . . The key variable affecting efficiency is believed to be the time of the change*."	Expert reports and claims; Linear regression	57 projects (90 cases); Indeterminate	Miscellaneous; 1970s and 1980s; mainly Canada
Mechanical Contractors Association of America	1994	*Change Orders / Overtime / Productivity* Section CO-2 lists "factors" and associated percentage loss of productivity.	Anecdotal; Statistical	Indeterminate	Indeterminate
Thomas and Napolitan	1995	"Quantitative effects of construction changes on labor productivity" Concluded that "*On average, there is a 30% loss of efficiency when changes are being performed. . . The key variable affecting efficiency os believed to be the time of the change*." However, the study presented no information regarding the timing of the changes for the data analyzed.	Empirical (database); ANOVA and multiple linear regression	3 projects (522 workdays); Indeterminate	Industrial electrical and piping; 1989-1992; Indeterminate

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Circumstance: Disruptions and/or Delays					
Finke	1998	"A better way to estimate and mitigate disruption" (No model actually developed.) Proposed method to build a model to estimate disruption, including consideration of the schedule to mitigate the impact.	Not applicable	Not applicable	Not applicable
Frantazolas	1984	"Learning curves and work interruptions in construction" Effects of 6-week delay due to a labor strike on structural concrete operations: some activities experienced reduced productivity, others increased.	Empirical (database); Plot of time v productivity	1 project; Indeterminate	Hotel - concrete construction; 1980s; Maine
Gates and Scarpa	1972	"Learning and experience curves" Model to calculate productivity losses as a function of length and timing of delay. (Hypothetical; never corroborated.)	Not applicable	Not applicable	Not applicable
O'Connor	1969	"Overcoming the problems of scheduling on large central station boilers" Includes Foster Wheeler chart of effects of delays on remobilization.	Empirical (database); Plot of length of delay to length of remobilization	5 projects; Indeterminate	Power plants; 1960s; Ohio Valley

Author	Date	Description	Data Source; Type of Analysis	No. of Projects; No. of Contractors	Type of Projects; Dates; Locations
Thomas and Oloufa	1995	"Labor productivity, disruptions, and the ripple effect" Showed decline in performance factor (actual verdus estimated productivity) as management disruption index increased. Also, showed decline in performance as number of disruptions increased.	Empirical (database); Statistical	19 projects; Indeterminate	Miscellaneous construction (mostly masonry) ; 1990s; Seven countries
Thomas, Sanders, and Bilal	1992	"Comparison of labor productivity" Sanders and Thomas model (1990, 1991) applied to masonry projects in seven countries.	Empirical (observation); Statistical	13 projects (465 days or records); Indeterminate	Commercial masonry construction; 1980s; Seven countries

The 52 entries in Table A1: Summary of Studies: Effects of “Factors” on Productivity, were derived from 39 published reports. Since several of the reports addressed more than one factor, these reports appear in more than one section of Table A1. A review of the data used in the various studies shows that 24 of the reports were based on empirical data; 4 were based on surveys or anecdotal information; and 7 were based on information of an indeterminate nature. The remaining four reports were not based on quantitative data.

Further review of the 24 reports that were based on empirical data shows that four of the reports were based on an indeterminate number of projects. The remaining 20 reports were based on between 1 and 37 projects, with a mean of 7.7 projects, a median of 4.5 projects, and a mode of 1 project. However, the number of projects may be a misleading measure of the quantity of the data used in a study. In most cases only limited portions of the projects were considered. For example, although the study of the effect of out-of-sequence work by Bilal and Thomas [1990] was based on data from 13 projects, only 13 days of data were used to calculate the stated 20% reduction of productivity attributed to out-of-sequence work. Since the quantity of data used for this analysis was so limited, the conclusions appear to be of equally limited value.

An additional concern with the empirical data used in the various studies listed in both Tables A1 and A2 stems from the potential differences in the data due to the data collection methods. In the studies that indicated the method of data collection, both direct observation and existing database records were employed. When using direct observation, the observer must have in-depth knowledge of the activity under study as well as an understanding of general construction practices, since few construction trades are restricted to a single activity over the course of a day. In the case of multiple observers, it is imperative that the observers use a uniform basis for the measurement of the activity. Thus, a precise definition of the work being observed and standard forms of measurement must be established. With the exception of several of the studies on which Thomas was an author, few of the studies indicated that consideration was given to this issue.

When existing project data are used, the subjectivity of the recorders of the data may result in inconsistencies among data from multiple projects. It may be possible to address any subjectivity in the recorded data through interviews to establish the parameters used by the personnel responsible for the records. The studies that used existing data did not indicate that any consideration was given to this issue.

As discussed in Thomas and Raynar [1997], the project selection process should ascertain that projects contained in the study are not affected by unusual external events, such as labor unrest or unique construction techniques. Again, with the exception of several of the studies involving Thomas, the standards used in project selection, if any, were not indicated.

In general, the studies listed in Table A1, regarding the effects of individual factors on construction labor productivity, have been based on limited data collected using a variety of methods. As a result, many of the conclusions appear to be of limited value in the quantification of productivity losses due to actual conditions experienced on a construction project.

Of the studies listed in Table A2: Summary of Studies: Effects of “Circumstances” on Productivity, that were based on empirical data, only the studies by Leonard [1988] and Thomas and Oloufa [1995] were based on data from a reasonably large number of projects. However, the data used by Leonard was obtained from a company that prepares construction claims. Thus, all of the data in the Leonard study were from projects on which claims were generated. Further, the productivity rates and losses used in the study were the rates and losses that had been calculated as part of the various claims. That is, Leonard did not calculate the loss of productivity using any single method or criteria. Rather, the productivity rates and productivity losses used in the analysis had been calculated by others as part of the claims preparation process. The study does not provide any information regarding the methods that were used to calculate the productivity rates or productivity losses. In regard to the data used in the Thomas and Oloufa study, only masonry activities were considered. Thus, the findings of this study may not be applicable to other construction activities.

In summary, the literature does not contain any studies of the effects of multiple factors on construction labor productivity that have been based on an analysis of a significant, unbiased sample of data from a cross section of activities and projects.

CHAPTER A3: METHODS OF MEASURING OF INEFFICIENCY

A3.1. Introduction

The various methods that are most-commonly used to measure the losses of productivity on construction projects are reviewed in the first section of this chapter. Each method is described, along with the advantages, disadvantages, and data requirements. Examples of the application of selected methods are provided. Additional attempts at the development of productivity-loss models are discussed in the second section of this chapter. As noted, none of the proposed models have gained acceptance in the courts or the construction industry. Finally, a summary comparison of the various, most-commonly used methods discussed is provided.

A3.2. Most-Commonly Used Methods of Measuring Inefficiency

The following list of the most-commonly used methods is in order of the most acceptable to the least acceptable, as viewed by the legal system [Jones, 2001; Patton and Gatlin, 2000; Shea, 1988]:

(1) Measured mile analysis

(2) Measured mile for comparable work

(3) Measured mile for comparable projects

(4) Statistical models

(5) Expert witness testimony.

(6) Industry standards and factor-based methods

(7) Modified total cost method

(8) Total cost method

It should be noted that the legal system is only involved in the determination of inefficiencies in an “after-the-fact” capacity. That is, a claim is presented for a legal decision after the work has been performed. Therefore, the legal system places no weight on a method that can be used prospectively to determine the impacts to productivity. However, essentially all contracts include a clause that requires that no work is to be performed without an executed change order. Thus, a prospective method would be valuable to owners and contractors in determining all of the costs associated with change work prior to the performance of the work. In addition, a prospective method that considers the impact on the unchanged work also may be useful in determining whether or not a time extension is due as a result of the effects on the activities identified with the unchanged work.

The following is a discussion of each of the eight methods listed above, along with an application example for selected methods.

A3.2.1. Measured Mile Analysis

The measured mile analysis, or impacted versus unimpacted work analysis, is the court-preferred method for the measurement of inefficiencies, as it is based on actual, as-built data from the project and activities in question. Using this method, an unimpacted productivity rate is established by measuring the work accomplished during an unimpacted period of time or in an unimpacted area of work [Calvey and Zollinger, 2003]. The productivity rate attained during the unimpacted portion is considered the “measured mile” and becomes the basis from which any inefficiencies are measured. This rate is compared to the productivity achieved during the impacted segment of the work in order to establish the loss of productivity, if any.

The work being compared must be the same type of work and of a similar nature and complexity. Further, all the impacts to the work during the impacted portion of the work must be attributable to a single cause or party, since it will not be possible to discern the amount of inefficiency attributable to each of the causes or parties using the measured mile analysis. The measured mile can be used to quantify inefficiencies attributable to any cause.

In order to employ this method, adequate project documentation must be available to establish both unimpacted and impacted productivity rates. Typically, if this information is available, it is found in the daily work reports, pay applications, payroll records, and schedule updates, which should provide the analyst with the number of manhours expended on a particular task and the quantity of work accomplished. The data must be available for the unimpacted work as well as the impacted work.

It is important to note that a measured mile analysis does not depend on the contractor's planned productivity rate. Instead, the basis of measurement is the demonstrated productivity rate. Thus, any underlying errors in the bid estimate are eliminated from consideration in a measured mile calculation.

Example of Measured Mile Analysis:

A drainage contractor installed drainage piping and structures for a road widening project from April 17 through June 8. During this period, a total of 4,390 linear feet of pipe and 11 structures were installed. As a result of an unmarked fiber optic cable, that was located within the planned trenching between stations 212+20 and 218+80, the contractor's productivity allegedly was adversely affected. The area in which the unforeseen obstruction was encountered contained a total of 650 linear feet of pipe and two structures. Since the drainage pipe and structures could not be relocated, it was necessary for the drainage contractor to excavate alongside the cable, using a smaller-than-planned excavator followed by hand digging when in very close proximity to the cable.

The project records, as summarized in Table A3, showed that the allegedly impacted work from station 212+20 to station 218+80 was performed between April 30 and May 11.

Table A3: Data for Measured Mile Example

Date	Linear Feet	Manhours	Comments
April 17	0	48	Mobilize; Receive pipe delivery
April 18	40	48	Set up laydown yard; Install pipe
April 19	120	48	Install 36" pipe; Install one structure
April 20	180	48	Install 36" pipe
April 23	160	40	Install 36" pipe
April 24	120	40	Install 36" pipe; Install one structure
April 25	60	40	Install 36" pipe; Rain half-day
April 26	160	40	Install 36" pipe
April 27	140	40	Install 36" pipe; Install one structure
April 30	40	40	Install 36" pipe; Hit fiber optic cable in trench at 8:30 a.m.
May 1	40	40	Install 36" pipe & 1 structure; trench alongside fiber optic cable
May 2	80	40	Install 30" pipe; trench alongside fiber optic cable
May 3	80	32	Install 30" pipe; trench alongside fiber optic cable
May 4	70	40	Install 30" pipe; trench alongside fiber optic cable
May 7	60	40	Install 30" pipe; trench alongside fiber optic cable
May 8	80	40	Install 30" pipe; trench alongside fiber optic cable
May 9	40	40	Install 30" pipe & 1 structure; trench alongside fiber optic cable
May 10	80	40	Install 30" pipe; trench alongside fiber optic cable
May 11	80	40	Install 30" pipe; trench alongside fiber optic cable
May 14	120	40	Install 30" pipe & 1 structure
May 15	160	40	Install 30" pipe
May 16	180	40	Install 30" pipe

Date	Linear Feet	Manhours	Comments
May 17	90	40	Install 30" pipe; Rain half day
May 18	140	32	Install 30" pipe & 1 structure
May 21	180	40	Install 30" pipe
May 22	160	40	Install 30" pipe
May 23	120	40	Install 30" pipe & 1 structure
May 24	180	40	Install 30" pipe
May 25	160	40	Install 30" pipe
May 28	---	---	Holiday
May 29	140	40	Install 30" pipe & 1 structure
May 30	160	48	Install 30' pipe
May 31	100	48	Install 30" pipe & 1 structure
June 1	160	40	Install 30" pipe
June 4	160	40	Install 30" pipe
June 5	180	40	Install 30" pipe
June 6	160	40	Install 30" pipe
June 7	120	40	Install 30" pipe; Install one structure
June 8	90	40	Install 30" pipe; Demobilize equipment
Total	4390	1552	

A review of the project records shows that the pipe sizes and ratio of linear feet of pipe to number of structures were similar during both the impacted time period of April 30 through May 11, and the unimpacted balance of the work.

The calculated productivity rate for the unimpacted time period is 3460 linear feet / 984 manhours = 3.52 linear feet per manhour (or a unit rate of 0.28 manhours/linear foot). Note that this calculation does not use the data for April 17 and 18, as these days represent mobilization and preparation time; or June 8, as this day represents demobilization work. In addition, the calculation does not use the data for April 25 or May 17, as the productivity on these days was affected by one-half day of rain, while the impacted time period recorded no rain events.

The productivity rate during the impacted time period is 650 linear feet / 352 manhours = 1.85 linear feet per manhour (or a unit rate of 0.54 manhours/linear foot). The comparison of these rates results in the calculated loss of productivity or inefficiency rate as follows:

$$\frac{3.52 \text{ lf/mh} - 1.85 \text{ lf/mh}}{3.52 \text{ lf/mh}} = 0.47 \text{ inefficiency rate} \qquad \text{(A2)}$$

Applying the inefficiency factor to the manhours expended during the impacted time period shows that 0.47 x 352 manhours = 165.44 manhours were expended as a result of the lower productivity rate experienced while excavating alongside the unforeseen fiber optic cable. The damage calculation associated with these manhours should include all crew costs for the 165.44 manhours, including equipment and supervision. In addition, if this activity was on the critical path of the project schedule at any time during the impact event, a time extension and extended general conditions may be due.

The greatest difficulties in applying the measured mile method are the quality and quantity of data needed and the amount of effort that must be expended to extract the data from the project records. The information succinctly shown in Table A3 frequently is not available. Further, even when the information is contained in the project records it can be difficult and time consuming to obtain the data in the format necessary to perform the calculations. As a result, it can be expensive to undertake the determination of inefficiencies through the measured mile method.

In addition, since the measured mile method can be used only with actual data, this method can not be used prospectively. Also, the measured mile method will provide a measurement of the inefficiencies experienced during a particular period of time. As noted earlier, in the event that there were multiple causes of inefficiency occurring simultaneously, the measured mile method will provide no measure of the inefficiency attributable to each of the causes.

Finke (1998b) suggests the calculation of the variability of the data from the unimpacted time period as an additional step in the measured mile analysis. Using the standard deviation of the data, one can calculate the probability of observing the impacted productivity rate given a mean equal to the unimpacted productivity rate and assuming a normal distribution. This additional information can help either to support or refute the contention that the alleged impact caused a loss of productivity.

A3.2.2. Comparison of Similar Work with the Impacted Work

In the event that the manhours and related quantities are not available to perform a measured mile analysis for the impacted work, an analysis of similar work on the project can be undertaken. The selection of "similar" work should consider the nature and complexity of the work. For example, one could use the loss of efficiency experienced for electrical conduit installation as a substitute for small-diameter mechanical piping.

Using the example of basing the analysis on the productivity rates for electrical conduit, the calculations are the same as described in the measured mile analysis. The inefficiency rate obtained is applied to the manhours expended on small-diameter mechanical piping during the impacted time period. The same cautions contained in the description of the measured mile process are applicable.

Naturally, there may be reasons why the inefficiency rate for the electrical conduit installation could differ from that experienced for the small-diameter piping. However, in the face of a lack of project data for the small-diameter piping, the use of similar work calculations may be the best method available. If possible, the inefficiency factors for multiple types of "similar" work should be calculated and compared for differences and congruences. This exercise could help to identify reasons why certain types of work should be considered as similar, while others should not.

Both the difficulties and limitations noted for the measured mile method are applicable to the comparison of similar work with the impacted work.

A3.2.3. Comparison of Similar Projects with the Impacted Project

Occasionally, there is no unimpacted portion of a project that can be used to established a "measured mile." In that instance, the comparison of similar projects is the best alternative. It is critical that the projects selected for comparison are as similar as possible to the subject project. This method is less accurate than the measured mile analysis since it suffers from using data from a project other than the project in question.

The calculations are the same as described in the measured mile analysis, except that the unimpacted data is obtained from the records of the comparable project(s). The same cautions contained in the description of the measured mile process are applicable.

As noted, the comparable project(s) should be as similar as possible to the impacted project. Consideration should be given to all possible differences between the work, such as the skill of the trade crews, size of the crews, access to work areas, work hours, and supervision. If necessary, adjustments should be made for identified differences. It should be noted that every adjustment adds subjectivity to the analysis, resulting in calculations that can be questioned and possibly defeated by an adversary or disallowed by the decider of fact.

Again, both the difficulties and limitations noted for the measured mile method are applicable to the comparison of similar projects with the impacted project.

A3.2.4. Statistical Models

Statistical models, such as regression analysis, can be used to assess the impacts on productivity. Statistical models may be useful for determining losses in productivity when the application of the measured mile method is not possible or will not provide the desired information. For example, there may be a number of factors believed to have contributed to productivity losses during a particular time period. Using the measured mile approach it will not be possible to discern the contribution of each of the factors to the loss of productivity. However, statistical methods used in concert with a measured mile analysis may assist in this determination.

Regression analysis can be used to determine to what extent changes in a dependent variable can be explained or predicted by changes in independent variables. For example, it could be hypothesized that productivity is related to the number of Requests for Information issued each week. In this case, productivity is the dependent variable and the number of Requests for Information is one of the independent variables. Regression analysis will provide an indication of the correlation between productivity and the independent variables, including the number of Requests for Information. A high degree of correlation indicates that there may be a trend between the dependent and independent variables. A low degree of correlation would suggest that there is no trend. Thus, regression analysis can be used to show that there is or is not a relationship between the variables.

Typically, in a claim that uses regression analysis as the basis for an inefficiency analysis only simple linear regression is used. For the example cited above, the model would consist of productivity as the dependent variable and the number of Requests for Information as the sole independent variable. The following is an example of the way in which regression analysis typically is used in a claim.

Example of Simple Linear Regression Analysis:

The project data for the number of Requests for Information (RFI) issued each week, along with the quantity of mechanical duct installed, are shown in Table A4.

Table A4: Sample Data for Regression Analysis Example

Week No.	Number of RFIs	Mechanical Duct Installation
1	4	280 lf
8	3	380 lf
9	3	360 lf
2	5	300 lf
3	5	210 lf
4	8	180 lf
5	4	310 lf
6	3	330 lf
7	5	270 lf
10	1	300 lf
Total	41	292 lf/week

Applying linear regression analysis to the data in Table A4 results in a regression model of:

$$y = 393.11 - 24.66\, x_1 \qquad \text{(A3)}$$

Where y is the dependent variable representing productivity and x_1 is the dependent variable representing the number of RFIs. A review of the regression output shows that the intercept is 393.11. This is interpreted to mean that when there are no RFIs the expected productivity is 393 lf/week. The slope of the model, -24.66, is negative, which is the direction of the expected slope. That is, as the number of RFIs increases, the productivity decreases. The coefficient of determination, r^2, is 0.55. This means that the model explains 55 percent of the variability in the productivity, y. That means the number of Requests for Information explain only 55% of the variability in the weekly quantity of mechanical duct installation. This indicates that there are other factors affecting the duct installation rate that are not included in the model. The general rule of thumb is that a model with an r^2 value of less than 0.70 to 0.75 may not be acceptable. However, in many claims the r^2 value of 0.55 that was obtained with from given data would be represented as meaning that 55% of the inefficiencies or overrun resulted from the Requests for Information.

As noted, regression analysis used in conjunction with a measured mile analysis can provide useful information. However, it is important that all possible causes of inefficiencies are considered during the model development and that the data is analyzed to determine whether a linear or non-linear model would be more appropriate.

A3.2.5. Expert Witness Testimony

Expert witness testimony typically will be used when data are not available to perform one of the previously-described methods of analysis. Most often, an expert witness will be asked to proffer an opinion on the percent or range of inefficiency that would result from the conditions encountered “based on the expert’s experience.” This percent of inefficiency is then applied to the manhours expended to determine the loss of productivity. The success of expert witness testimony lies wholly in the court’s acceptance of the credentials and testimony provided by the expert. Frequently, expert witness testimony is used in conjunction with industry-published factors, which are discussed in the next section.

A3.2.6. Industry Standards and Factor-Based Methods

Several trade organizations publish manuals regarding the loss of productivity due to individual factors such as weather, overtime, crew size, congestion, supervision, and other factors discussed in Chapter 2. This section summarizes the methods and quantitative factors presented in several of the most-frequently cited trade publications.

Only one trade organization, Mechanical Contractors Association of America, currently publishes a list of factors and associated percentage loss of productivity that can be used for the calculation of productivity losses due to multiple factors. The publications by other organizations are limited to the productivity losses incurred from individual factors. It should be noted that National Electrical Contractors Association no longer includes the checklist of factors related to productivity losses in the NECA Manual of Labor Units. The last publication date of the NECA checklist was 1976.

A3.2.6.a. Mechanical Contractors Association of America

The Mechanical Contractors Association of America (MCAA) publishes a booklet titled *Change Orders, Overtime, Productivity* [1994]. The section titled "Factors Affecting Labor Productivity" contains a tabular list of 16 factors, characterized as being beyond the direct control of the contractor, that may affect productivity. Each factor has a percentage loss which could occur for minor, average, and severe conditions. Table A5 is a summary of the factors and the associated percentages of loss.

Table A5: MCAA Factors Affecting Productivity

Factor	Percentage of Loss if Condition: Minor	Average	Severe
Stacking of Trades	10%	20%	30%
Morale and Attitude	5%	15%	30%
Reassignment of Manpower	5%	10%	15%
Crew Size Inefficiency	10%	20%	30%
Concurrent Operations	5%	15%	25%
Dilution of Supervision	10%	15%	25%
Learning Curve	5%	15%	30%
Errors and Omissions	1%	3%	6%
Beneficial Occupancy	15%	25%	40%
Joint Occupancy	5%	12%	20%
Site Access	5%	12%	30%
Logistics	10%	25%	50%
Fatigue	8%	10%	12%
Ripple	10%	15%	20%
Overtime	10%	15%	20%
Season and Weather Change	10%	20%	30%

The instructions for the use of the factors state that the values are a percentage to add onto labor costs for change orders and/or original contract hours. However, there are no guidelines as to how to handle multiple or overlapping factors. That is, the MCAA publication does not indicate whether multiple factors should be summed, weighted, or combined in some other way.

A review of the factors in Table A5 shows that the summing of multiple factors can lead to very large productivity losses. For example, using the sum of just four factors: Stacking of Trades, Crew Size Inefficiency, Dilution of Supervision, and Ripple, gives a calculated loss of productivity of 40% for minor conditions, 70% for average conditions, and 105% for severe conditions.

According to the declaration of a representative of the MCAA, the information contained in the factors is not based on empirical data, but was gathered anecdotally from the membership of MCAA's Management Methods Committee in the late 1960s or early 1970s. The factors have been unchanged since first published in 1971.

It should be noted that the MCAA states that: the factors are expressly intended to be used only as a point of reference; the specific values must be applied after careful consideration and review of the facts surrounding the loss of productivity; and the factors are intended to be used in conjunction with the experience of the particular contractor. A review of several court cases where MCAA factors were used as the basis of the calculation of productivity losses showed that the courts frequently reduced the amount of the factors used in the claim calculations when determining the award for productivity losses [*American Sprinkler Corporation of America v Veterans Administration*, VABCA No.

3086; *Stroh v General Services Administration*, GSBCA No. 11029; *Clark Construction Group, Inc. v VAMC West Palm Beach*, VABCA No. 5674].

The main advantage of using industry standards or factor-based methods is the ease of application. The method requires only a few calculations, using the published factors and readily-available project information, such as the total number of manhours expended on the project. Another advantage of the use of published factors is that this method can be used prospectively, allowing the advance pricing of change orders that can include all costs for the work.

A3.2.6.b. Overtime

The most-frequently cited reports on the effects of overtime on productivity are Bureau of Labor Statistics Bulletin No. 917 [1947]; Department of the Army "Construction Modification Impact Evaluation Guide" [1979]; The Business Roundtable Report C-2 [1989]; and National Electrical Contractors Association (NECA) "Overtime and Productivity in Electrical Construction" [1989]. Each of these publications contains tables and charts that identify the loss of productivity associated with working hours in excess of the standard 40-hour workweek.

Although it is one of the most-frequently cited sources for quantifying the effects of overtime in construction claims, Bureau of Labor Statistics Bulletin No. 917 was based on studies conducted in the 1940s of productivity in manufacturing processes. For obvious reasons, the results of these studies may not be appropriate for use in quantifying the losses of productivity on a construction project.

The Department of the Army "Construction Modification Impact Evaluation Guide" [1979] includes a graphic depiction of the losses of productivity over a four-week time period for work schedules ranging from five nine-hour days per week to seven ten-hour days per week. The near-linear curves show losses of productivity at the end of the fourth week that range from a low of approximately 3% for the five nine-hour days per week schedule to a high of approximately 37% for the seven ten-hour days per week schedule. The Guide notes that the curves are presented merely as information on trends and are not meant to apply to any particular project.

Report C-2 published by The Business Roundtable [1989] addresses the effects of scheduled overtime on construction projects. The reported source of the data used to develop the charts and tables contained in Report C-2 was a series of jobs performed over a ten-year period on a single project in Wisconsin. Thus, the analysis and cost effects presented in Report C-2 were based on a construction project where overtime schedules were used for an extended period of time.

The report contains a chart showing the effects on productivity for both 50-hour and 60-hour workweeks. The chart depicts a sharp decline in productivity during the first week of overtime, followed by a gradual improvement through the third week. Productivity again declines from week four through week nine, after which there is a leveling from week nine through week twelve. The report does not address the effect of overtime for any time period beyond twelve weeks or any workweek durations other than 50-hour and 60-hour workweeks.

The NECA "Overtime and Productivity in Electrical Construction" [1989] booklet includes tables and charts showing the loss of productivity for week one through sixteen for schedules ranging from five ten-hour workdays per week to seven twelve-hour workdays per week. The respective productivity losses at the end of week sixteen range from approximately 31% to 62%.

The NECA factors appear to be based on the data from the Bureau of Labor Statistics studies from the 1940s. However, original data from a NECA study conducted in 1964 in southeast Michigan correlate closely to the Bureau of Labor Statistics data. Thus, NECA concludes that this gives *"substantial confidence in the applicability of the BLS values to electrical contracting*" [NECA, 1989, p9].

Additional individual factors were addressed in the various reports identified in Table A1 found in Chapter 2.

A3.2.7. Modified Total Cost Method and Total Cost Method

The final and most imprecise methods to establish a measurement of inefficiencies are the modified total cost method and the total cost method. The total cost method is simply a comparison of the total costs in the contractor's bid estimate to the total costs actually expended. In this regard, the total cost method is really a quantification of damages rather than a measurement of inefficiency. In the case where the total cost method is being used to quantify inefficiencies, the total manhours in the bid estimate are compared to the total manhours expended.

The total cost method can be used only when the following four requirements are met: (1) the contractor's actual losses are impractical to prove, (2) the contractor's bid estimate was reasonable, (3) the contractor's actual costs were reasonable, and (4) the contractor was not responsible for any of the cost increases [*Servidone Construction Corp. v. United States,* 931 F2d 860 (Fed.Cir. 1991); *Southwest Marine, Inc. v Armed Services, ASBCA No. 36854*].

In the event that the four requirements of the total cost method can not be met, it may be possible to quantify the inefficiencies using the modified total cost method. This method allows the contractor's estimated costs to be corrected for errors in the bid and/or for those portions of the cost overruns attributed to the contractor to be broken out of the calculations. These additional considerations are undertaken in an effort to improve the accuracy of the measurement of the impact, thereby increasing the likelihood that the measurement will be accepted.

Since both the total cost method and the modified total cost method can be easily challenged, they are truly measurements of last resort. However, the ease of application of these methods, as well as the fact that these methods tend to maximize a contractor's potential recovery, make them popular with contractors.

A3.3. Proposed Productivity-Loss Models

Several models have been proposed for the measurement of the loss of productivity resulting from multiple factors or multiple changes. These models include:

(1) Forward Pricing Model

(2) Leonard Model

(3) Thomas-Yiakoumis and Thomas-Smith Model

(4) Hanna, Russell, Gotzion, and Nordheim Model

(5) Thomas and Oloufa Model

(6) Disruption Distribution

Although none of these models have been accepted by the courts or the construction industry as the method of choice for the measurement of inefficiencies, these models do represent the published attempts at creating alternatives to the previously-described, court-accepted methods. The following is a description of each of the six models.

A3.3.1. Forward Pricing

Kasen and Oblas [1996] developed and used the Forward Pricing Model during a portion of the construction of a water treatment plant in Seattle, Washington. The model was described as an attempt "to identify and integrate all known variables into one procedure for settlement" [Kasen and Oblas, 1996, p14]. The Forward Pricing formula for determining the value of the impact of a change is:

$$\text{Impact} = D \times (T + C + F) \times M_v \times M_n \qquad \text{(A4)}$$

In Equation A4,

D = the sum of the direct costs that have impacts.

T = timeliness, representing the time between the notice to proceed and the scheduled start date of the activity related to the change work. For the Seattle project, this factor received full impact value for changes with five weeks or less of time and no impact value for those changes with 12 weeks or more of time, with decreasing gradations for weeks 5 to 12.

C = complexity of the disciplines or trades involved in the change work. Participation for each trade is determined by the direct cost breakdown for the change work.

F = the future factor or the future impact dealing directly with the timing of the change and the current schedule float. For the Seattle Project, changes with float of five weeks or less received full value, and changes with float of 12 weeks or more received no impact value, with decreasing gradations for 5 to 12 weeks.

M_v = the cumulative value multiplier, representing the total dollar value of changes that actually have impact. For the Seattle Project, this factor was applied only when the cumulative dollar value of changes having impact reached the minimum value of 2% of the base contract value. The factor reached its maximum value when impact changes amounted to at least 11% of the contract value.

M_n = the cumulative number multiplier, representing the number of changes that actually have impact on the contact. For the Seattle project this factor was applied when the changes having impact numbered a minimum of 200 changes, and reached a maximum value when there were at least 1,100 impact changes. The parameters for this factor represented heavy industrial work of two years or more duration.

The authors explain that the factors, multipliers, and thresholds are intended to be negotiated by the owner and contractor on a project-by-project basis.

The advantage of the Forward-Pricing Model is that it supports prospective pricing of change orders, allowing for change orders to be executed as full and total compensation for the change work. The main disadvantage of the model is the difficulty in arriving at mutually agreeable factors, multipliers, and thresholds for both the owner and the contractor. Typically, owners are concerned with awarding compensation for productivity losses that may not be experienced, and contractors are reticent to accept calculated productivity losses that subsequently may be found to be less than the losses actually experienced.

A3.3.2. Leonard Model

The Leonard Model was developed for the purpose of predicting the productivity losses due to changes orders [Leonard, 1988]. The model is based on data from 90 cases drawn from 57 projects that were mainly located in Canada and constructed between 1978 and 1988. In the development of the model, three relationships between change orders and productivity were considered: (1) the frequency of change orders, which was measured as the number of change orders divided by the number of months of the contract; (2) the average size of change orders, which was measured as the change order hours divided by the number of change orders; and (3) the percentage of change order hours, which was measured as the number of change order hours divided by the actual contract hours, expressed as a percent.

The results of the simple linear regression analysis of the data showed a low degree of correlation between the number of change orders and productivity losses (coefficient of correlation of 0.13) and the average size of change orders and productivity losses (coefficient of correlation of 0.18). However, the correlation coefficient was measured as between 0.82 and 0.90 for the percentage of change order hours and productivity losses for cases where change orders were the only identified major cause of productivity-related impact. The results of the analysis were summarized in figures that depicted a straight-line function between the percentage of change orders and the percentage loss of productivity.

The instructions on using the model require that two measures must be determined: (1) total actual manhours for the change order work and (2) total manhours spent by the contractor on both the changes and original contract work. Using the total actual manhours expended on the contract, the total actual contract manhours are calculated by subtracting the change order manhours and any non-productive manhours that were attributable to the contractor or non-compensable circumstances, such as deficiency rework or inclement weather. Next, the percentage of change orders is calculated by dividing the change order manhours by the total actual contract manhours and multiplying the result by 100. Using this number, one can read directly from the appropriate figure the percentage loss of productivity. The percentage loss of productivity is applied to the actual contract manhours to determine the total loss of productivity due to change orders.

Using the data given in Table A3 for the Measured Mile example, the following loss of productivity was calculated with the Leonard Model, the total actual contract manhours are calculated by subtracting change order manhours and manhours lost due to inclement weather from the total actual manhours. This yields: 1552 - 165 - 40 = 1347 manhours; total change order manhours were 165 manhours. This gives a ratio of 165 / 1347 = 12.25%. From the Leonard Model for Civil and Architectural work, where changes are the only cause of lost productivity, the predicted percent loss of productivity is approximately 14%. Multiplying 14% times the actual contract manhours of 1347 manhours results in a calculated loss of 189 manhours on the original contract work as a result of performing the change work.

This example tells us that, exclusive of the 165 manhours attributed directly to the change work, an additional 189 manhours of lost productivity would be expected as a result of performing the change work. These additional manhours represent the effects of change work on unchanged work. Thus, a total of 354 manhours (165 + 189) would be expected to be expended as a result of the identified change work.

As acknowledged throughout Leonard's study, the measured mile method (called the differential method) is the preferred method for the calculation of productivity losses. In the example given, comparing the predicted productivity loss obtained from the Leonard model to the calculated loss using the measured mile shows that the Leonard model gives a predicted loss of productivity that is (354 mhs - 165 mhs) / 165 mhs = 114% higher or more than twice as much as the calculated loss using the measured mile. This inflated estimate may be due to the fact that Leonard's study was based on the effects of multiple changes; whereas the measured mile example reflects only a single change. In addition, the great difference in the two calculations may result from the fact that all of the data used by Leonard were from the records of a construction claims company. That is, the data were extracted from contractors' claims, claim analyses, expert reports, and files only from projects for which claims were prepared. Thus, the data may not be representative of the construction industry in general.

A3.3.3. Thomas-Yiakoumis and Thomas-Smith Model

Thomas and Smith [1990] proposed a model for determining the expected productivity unit rate for anticipated conditions associated with a change. This model was based on an earlier, similar model that predicted crew productivity based on ideal productivity rates modified by various categories of factors that affect labor productivity [Thomas and Yiakoumis, 1987]. Using data from 11 masonry projects located in central Pennsylvania, the authors identified the types of disruption experienced and developed frequency and impact factors for each of the disruption types. The occurrence frequency is based on the number of disruptions divided by the number of disrupted days on the projects. The impact factors represent the relative impact as measured against undisturbed productivity. The types of disruptions, relative frequency, and impact factors are summarized in Table A6.

Table A6: Disruption Frequency and Relative Impact Factors

Disruption	Occurrence Frequency	Impact Factor
None	1.000	1.000
Weather	0.064	3.125
Congestion	0.069	2.857
Sequencing	0.024	4.000
Materials	0.033	1.852
Rework	0.004	2.439
Supervision	0.018	1.695
Staffing	0.002	1.724
Other	0.049	4.762

The equation for determining the expected productivity unit rate is:

$$E(Pr) = Pnorm \times (1 + \sum_{i=1}^{n} f_i R_i) \qquad \text{(A5)}$$

Where

E(Pr)	=	the expected productivity unit rate for the anticipated change conditions.
f_i	=	the relative frequency of the factor i.
R_i	=	the relative average impact for factor i.
n	=	the number of factors experienced for the change.

The calculated expected productivity unit rate is to be used for the remaining contract work as well as the change work. Note that the unit rate measurement of productivity is labor hours divided by output units. Thus, decreases in productivity are represented by higher unit rates.

Example: The start of construction of a masonry foundation is delayed due to unforeseen site conditions. As a result of the delay, the foundation work will be constructed during the rainy season, which is less conducive to high productivity for masonry foundation work. In addition, as a result of the delay, the masonry work will be performed concurrent with the completion of the underground utilities, necessitating multiple crews working in the same areas.

The expected productivity is calculated using the factors for weather and congestion:

$$E(Pr) = Pnorm \times (1\ ((0.064)(3.125) + (0.069)(2.857))$$

$$= Pnorm \times (1.397)$$

Thus, the expected productivity unit rate is 39.7% higher than the normal productivity unit rate. As noted, when using the unit rate measurement for productivity, decreases in productivity are represented by higher unit rates.

The advantage of this model is the ease of use, once the factors are established. However, significant research and data analysis would be necessary to develop the factors for each trade or contractor. The literature contained no record of this model being used as the basis for the calculation of productivity losses for the settlement of a claim on any project.

A3.3.4. Hanna, Russell, Gotzion, and Nordheim Model

Hanna, Russell, Gotzion, and Nordheim [1999] used stepwise regression analysis to develop a model to predict the effects of change orders on labor productivity. The data used were from surveys completed by 26 mechanical contractors on 61 construction projects. The methodology and factors used were first presented by Hanna, Russell, and Vandenberg [1999].

During the model development, several factors were considered that proved to be statistically significant, such as the timing of changes, the number of changes, and the amount of change orders. Additional factors considered were: the type of project, construction delivery system, owner type, specified work performed, number of years of experience of the project manager, number of similar projects completed by the project manager, and number of similar size projects completed by the project manager. None of these additional factors were included in the final model as they were not found to be statistically significant in predicting the loss of productivity.

The final model for projects impacted by change orders was given as:

$$\text{Delta \% Total Labor Hours} = -0.169 - 0.001534 * \text{CHGEST} - 0.00073 * \text{NUMCHG} + 0.07034 * \text{WTIMING} + 0.000032 * \text{NUMCHG} * \text{CHGEST} \qquad \text{(A6)}$$

Where

CHGEST = amount of change, which is measured as the estimated change order hours as a percentage of base estimated hours.

NUMCHG = number of change orders on the project.

WTIMING = timing of the changes; the project is divided into six segments: before construction (0 factor); 0 - 20% (0.20 factor); 20-40% (0.30 factor); 40 - 60% (0.35 factor); 60 -80% (0.10 factor); and 80 - 100% (0.05 factor).

The calculated value of Delta % Total Labor Hours is applied to the actual total labor hours expended on the project to arrive at the total number of labor hours lost due to inefficiency. It should be noted that the final model had an R^2 value of 0.544, which indicates that almost half of the change in the labor hours is a result of factors not considered by the model. Typically, an R^2 value of at least 0.70 to 0.75 is desired.

The advantage of using this type of model is the relative ease of application, since the required data normally can be extracted from the project records without a great deal of effort. However, since the model requires the total number of hours actually expended on the project, this model only can be used retrospectively. Although it may be possible to use the model in a prospective manner, the authors provide no guidance on the procedure to be followed for this case. An additional disadvantage of the model is that the low R^2 value of the final model may make the use of the model susceptible to challenge. The literature contained no record of this model being used as the basis for the calculation of productivity losses for the settlement of a claim on any project.

A3.3.5. Thomas and Oloufa Model

Thomas and Oloufa [1996] developed a model for the quantification of labor inefficiencies resulting from schedule acceleration and compression of electrical work on construction projects. The data used in the development of the model represented approximately 400 weeks of construction from five projects.

The general steps in the application of the model are:

(1) Calculate the planned or unimpacted weekly labor consumption percentages.

(2) Calculate the actual weekly labor consumption percentages.

(3) Calculate the difference between the planned and actual weekly labor consumption percentages. This difference is referred to as the 'weekly labor rate deviation.'

(4) Identify the phases of the work based on the actual manpower level. The model uses four phases:

Phase 1 - begins when there are at least two electricians continuously assigned to the project until the workforce reaches $0.4M_p$, where M_p = the planned maximum number of electricians.

Phase 2 - the number of electricians consistently exceeds $0.4M_p$ until the M_p is exceeded.

Phase 3 - the number of electricians exceeds M_p until the number decreases to M_p.

Phase 4 - the number of electricians is M_p until the number decreases to less than $0.4M_p$.

(5) Use the curves provided for the appropriate phase and the calculated weekly labor rate deviation to determine the weekly performance ratio (PR) value.

(6) Calculate the gross weekly inefficient workhours based on the PR value and the actual workhours:

$$\text{Gross Inefficient Workhours} = \text{Actual Workhours} - \frac{\text{Actual Workhours}}{\text{Performance Ratio}} \qquad \text{(A7)}$$

(7) Calculate the net weekly inefficient manhours by multiplying the Gross Inefficient Manhours by and adjustment factors based on the type of project: 1.05 for industrial; 0.92 for commercial; 0.82 for institutional; and 1.00 for other.

(8) Calculate the overall percentage loss of efficiency:

$$\text{Project Loss of Efficiency (\%)} = \frac{\text{Total Inefficient Hours}}{\text{Actual Hours - Inefficient Hours}} \times 100 \qquad \text{(A8)}$$

(9) Validate by correlating weekly inefficiencies to specific events.

The advantage of this model is the relative ease of application. With the exception of the planned manpower curves, the required data normally is found in the project records. The planned manpower curve occasionally can be obtained from a resource-loaded schedule, if available, or directly from the electrical contractor. However, since the model requires the actual weekly manhours expended on the project, the model is limited to retrospective applications.

An additional disadvantage is that the methodology "*involves a comparison of actual labor consumption rates to the planned rate on normal or unimpacted projects*" [Thomas and Oloufa, 1996]. This assumes that the planned productivity rates are reasonable and attainable for the subject project, and that the planned consumption rates are the most efficient. It makes a much more compelling argument to use demonstrated productivity rates rather than unproven, planned productivity rates as a basis of comparison. Also, the application of the method may result in an overstatement of the productivity losses.

Depending on the "phase" during which manhours are recorded, the model indicated significant efficiency losses even in situations when significantly fewer manhours were expended than were planned.

A3.3.6. Disruption Distribution

Finke [1998] proposed to quantify disruptions caused by changes through the use of a disruption distribution method. The method, was described as analogous to the moment distribution method in structural analysis [Finke, 1998, p494]:

> ". . . each activity in a contractor's scope of work will represent a separate joint in a structural frame, with each such joint being connected to every other joint by a member of some stiffness greater than or equal to 0. If it is determined that one activity can have no disruptive effect on another activity (because, for example, the potentially disrupted activity has already been completed) the sensitivity of the causal relationship linking the two activities will be 0 and no disruption will be distributed through it. . . ."

The model defined both qualitative and quantitative sensitivity factors. The qualitative sensitivity factors, which would have a value of either zero or one, included consideration of location, time of performance, resource type, and supervisor. The quantitative sensitivity factors, which could be greater than or equal to zero, would reflect the degree to which changes in one activity would disrupt other activities based on consideration of the type of work, crew size, and crew composition.

The disruption was to be quantified by multiplying the qualitative and quantitative sensitivity factors by the number of manhours added to the working conditions represented by the factors. As with the moment distribution method, the process of determining the disruption is iterative, resulting in the number of manhours of disruption for each of the causes for which a calculation is performed.

As noted by Finke, the disruption distribution method presented is not “a complete ready-to-use method” in that no values for the qualitative factors are given. Further, Finke noted that the amount of detailed information required and the computations involved may make the disruption distribution method impractical. In fact, Finke suggests that the best use of the disruption distribution method may be to show how difficult such an analysis would be, thus making the argument for the use of existing, easy-to-use factor-based models. The literature contained no record of this type of model being used as the basis for the calculation of productivity losses for the settlement of a claim on any project.

A3.4. Summary Comparison of Methods

Table A7 contains a summary comparison of the most-commonly used methods of measuring losses of labor productivity in construction. Due to the vast differences in and the lack of industry acceptance of the Proposed Productivity-Loss Models discussed in Section 3.3., those methods are not included in Table A7. As shown in Table A7, the only commonly used methods that can be applied prospectively are Industry Standards or Factor-Based Methods and Expert Testimony. However, these methods are highly subjective and may not be accepted by certain courts. Further, as previously noted, many of the existing Industry Published Factors are not based on empirical data and/or may not be applicable for construction.

Table A7: Summary Comparison of Commonly Used Productivity Loss Measurement Methods

Method	Description	Source of Data	Characteristics: Legal Acceptance	Characteristics: Level of Objectivity	Characteristics: Ease of Application	Characteristics: Accommodates Multiple Factors	Characteristics: Based on Verifiable Data	Characteristics: Prospective Application
Measured Mile	Comparison of impacted to unimpacted productivity rates for similar work on the same project.	Project daily reports, pay applications, cost records	●●●●●	●●●●●	●	●	●●●●●	●
Measured Mile for Comparable Work	Comparison of impacted to unimpacted productivity rates for different work on the same project.	Project records for comparable work	●●●●	●●●	●	●	●●●●	●
Measured Mile for Comparable Projects	Comparison of impacted productivity rate on one project to unimpacted productivity rate on a different project(s).	Records for comparable project(s)	●●●●	●●●	●	●	●●●●	●
Statistical Models	Statistical methods, such as regression analysis, to determine the productivity loss attributable to various factors.	Records for affected work and model factors	●●●●	●●●	●●	●●●●●	●●●	●
Industry Factors	Published factors by trade and construction organizations are applied to a pool of manhours.	Various industry publications	●●●	●	●●●●●	●●●●●	●	●●●●●
Expert Opinion	Testimony provided by an expert witness.	Expert experience	●●	●	●●●●●	●●●●●	●	●●●●●
Modified Total Cost	Difference between the actual total costs and the amount bid - adjusted for bid errors and losses due to contractor actions.	Project cost records	●●	●	●●●●	●	●	●
Total Cost	Difference between the actual total costs and the amount in the bid.	Project cost records	●	●●	●●●●●	●	●	●

Characteristics ●●●●● = high; yes ● = low; no

APPENDIX B: PARTICIPATION OF HUMAN SUBJECTS MEMO

University of Central Florida

Office of Research

November 16, 2004

Angela Sist
5375 Lake Lizzie Drive
St. Cloud, FL 34771

Dear Ms. Sist:

With reference to your protocol entitled, "Decision Support Model for Construction Crew Reassignments," I am sorry to inform you that, per federal regulations, the Institutional Review Board (IRB) Committee was unable to approve your protocol since your research was already completed prior to IRB review. We will be happy to consider any future studies that you might have. IRB approval must be obtained prior to beginning your research.

After reviewing your submission, we have determined that the research was low risk to human subjects and probably would have been approved had it been submitted prior to implementation. Should you have any questions, please do not hesitate to call me at 407-823-2901.

Cordially,

Sophia F. Dziegielewski

Sophia Dziegielewski, Ph.D.
Chairman
Institutional Review Board (IRB)

Copy: IRB Files - Unapproved

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