A FUZZY LOGIC APPROACH TO MODEL DELAYS IN CONSTRUCTION PROJECTS

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By

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ABSTRACT

Delays in construction projects are inevitable; as a result claims and disputes arise among different construction parties. Different causes of delay can come into play, therefore, there is a need to identify and classify different causes of project delay. Estimation of the likelihood of delay resulting from different factors that contribute to project delay is essential to project success. Different factors that contribute to project delay affect the likelihood of project delay in different effectiveness degrees. There is a pressing need to estimate the likelihood of delay by implementing analysis methods and examining these methods. Probabilistic fault tree analysis and fuzzy fault tree analysis are two methods suggested by this research to estimate the likelihood of delay.

Fuzzy fault tree analysis is performed by planners and managers since they select the delay causes that are applicable to a given project and categorize these delay causes into enabling, triggering, and procedural causes. Then, managers assess the degree of effectiveness of each cause of delay to overall project delay. Assessment of the contributing causes of delay and their degree of effectiveness on project delay uses subjective judgment linguistic terms. The result of the fuzzy fault tree analysis is a likelihood of delay membership function that is compared to the predefined fuzzy logic model to assess the degree of severity of the likelihood of delay. Likelihood of delay

membership function is further quantified using the weighted average defuzzification method.

Different fuzzy logic models are implemented into the fuzzy fault tree analysis, using Visual Basic software, these models are Baldwin’s rotational model, the Angular model, the Translational model and the Triangular model. Recommendation of the fuzzy logic model that is best applied to a given scenario needs further sensitivity analysis and is beyond the scope of this research. Validation of the fuzzy fault tree analysis computer model is performed. Some suggestions by experts are implemented into the computer model while other suggestions are deferred to future research. The computer software suggested by this study is an attempt to help reduce delays in construction projects that can cause time loss.

To Mom, Dad, and my family and friends

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[1] Al-Humaidi, H. M., and Hadipriono, F.C., "A fuzzy Logic Model to Avoid Electrocution During Mobile Crane Operation," Proceedings of The Fifth International Conference on Engineering Computational Technology, held in Rome, Italy, 30 August-2 September 2005.

FIELDS OF STUDY

Major Field: Civil Engineering

Specialization: Construction Engineering and Management

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LISTS OF SYMBOLS

D	A fuzzy set representing a linguistic value
Đ	A universe of discourse
$\cap$	Conjunction (similar to intersection in set theory)
$\in$	Contained in
D$\subset$ *Đ*	D is a subset of *Đ*
U	Disjunction (similar to union operation in set theory)
$\forall$	For all
$\forall d \in D$	For all d contained in D
d	Fuzzy element of fuzzy set D
$\int$	Integral
$\mu_{D1}(d)$	Membership function of fuzzy set d
μ	Membership value
$\subset$	Subset

LIST OF ABBREVIATIONS

FFT	Fuzzy Fault Tree
FT	Fault Tree
FTA	Fault Tree Analysis
MCS	Minimal Cut Set

CHAPTER 1

INTRODUCTION

1.1 Introduction

Projects that take longer than expected and run over budget are very common in the construction industry. Failure of projects to meet the planned predicted completion time is sometimes inevitable. As a result, expanded time estimates are entered into major tasks to prevent delay problems. Contingency planning is a common practice in the construction industry to prevent such problems. However, even with contingency planning on major project tasks, many projects still exceed the predicted planned time. Riad et al. (1989) claim that delays are the major cost of construction disputes. Furthermore, delays on a construction site are normally inevitable and many claims arise, sometimes resulting in litigation.

Usually there is no way of predicting how likely it is that a given project will meet its milestones and its predicted completion date. Uncertainty is an inherent aspect of project management. In the planning phase, an estimated project schedule is modeled and a critical path determined, where all activities are future events. Uncertainty arises from different aspects such as task duration, resources encountered in execution and the dependency of tasks on the completion of other tasks. But in the execution phase, other non-controllable factors such as weather, resource limitations, and managerial actions can cause alterations in the planned schedule and result in delays, especially if the task is part of the critical path. Delay in critical activities or near critical activities result in project delay. Some amount of delay on non-critical-path tasks can be tolerated, but any slippage on critical-path tasks directly results in delay of the project as a whole.

1.2 Background of Study

Several factors can contribute to delays of a project. Analyzing the causes of delays is an essential task for resolving any conflicts or claims. According to Schumacher (1996) most delay claims are complicated. Although many researchers emphasize the high cost and the associated risk related to litigating delay claims, few emphasize the responsibility for project delays. To avoid delays that might result in claims and disputes, the link between the actual tasks undertaken, the time required to complete them, and the ultimate cost estimate of the resources involved all need to be examined.

Resource allocation and assessment has been widely studied in stationary mass production. The adoption of such ideas into the construction industry can be questionable for several reasons. First, construction projects are performed in an open system where uncontrollable factors from the outside can significantly impact the production rate and most importantly, the quality. Uncontrollable factors such as weather conditions and unforeseen soil conditions that are beyond management control could significantly affect the construction process. Second, each project is a new challenge due to the fact that projects are temporary and unique, whereas manufacturing is a repetitive process. Therefore, implementation of the quality control management practices that are widely used in closed repetitive systems such as manufacturing become questionable in open unique systems.

1.3 Objective of Study

This study will analyze different causes of project delays, based on a review of the literature. The delays will then be seperated into three categories, based on their causes. These categories are procedural delay causes, triggering delay causes and enabling delay causes. The study will then examine the causes, and analyze them using different methods, including probabilistic and fuzzy models.

1.4 Scope and Limitations

This study is focused on triggering, enabling, and procedural delay causes. Unlike enabling and triggering delay causes, which directly impact the project schedule and result in project delay, procedural delay causes can directly or indirectly impact the project schedule. Direct procedural delay causes have an immediate direct impact on the project schedule, whereas indirect procedural delay causes first affect enabling delay or triggering delay causes separately or simultaneously, which then affect the project schedule.

Factors that have a negative impact on project schedule are identified without further classification. For example, weather conditions are triggering delay causes.

However, classification of weather conditions such as rain, heat, and cold are beyond the scope of this study.

Only negative factors that impact project schedule are modelled in the study. For example, only bad weather conditions are studied in this research and if weather conditions are good then management would not study this factor and no analysis would be needed.

1.5 Potential Benefits

This research will benefit the construction industry by introducing a simple user-friendly software tool that can be used to model expected project delay as a result of different contributory factors. Traditional methods of analysing project delay can be erroneous in predicting the amount of expected project delay for several reasons. First, experts tend to give their opinion about project delay using linguistic terms, which are hard to model using traditional scheduling methods such as the critical path method of scheduling. Second, traditional methods are linear in their nature but the time consumed as a result of delay is a non-linear function. Third, projects are unique in their nature, and traditional methods of scheduling planned project durations are based on the subjective judgments of experts, who use their opinion knowledge of the time required to complete a task. However, the analysis of project delay using traditional scheduling methods can be complex, especially if concurrent delays take place.

1.6 Expected Outcomes of Research

This research will introduce a new classification of delay based on causes of delay as well as suggest methods of analysing the likelihood of delay given a set of factors that contribute to overall project delay. Both a probabilistic fault tree analysis and a fuzzy fault tree analysis will be introduced. Furthermore, different fuzzy models using the translational, rotational, angular, and triangular models will be applied to the fuzzy fault tree analysis, and a comparison of these four different models will be made so that a specific fuzzy fault tree model can be recommended as the appropriate model to analyse project delay.

1.7 Research Tasks

This research is conducted to achieve several tasks. The topic of project delay is studied to identify classification on delay and delay analysis based on the literature. Once the literature is examined, a new classification of project delay based on causes of delay is suggested with an appropriate classification method. The next research task is to find different methods of modeling project delay using probabilistic and fuzzy logic models to model causes of project delay that contribute to overall project delay. Once the models are constructed, a suggested model of project delay is recommended and the final step of the research is to validate the suggested delay model. To validate the suggested delay model, a sample of experts involved in actual construction projects will examine and test the project delay model suggested by this study.

The research tasks of this study can be summarized in the following four tasks:

1. Identification of causes of project delay based on the literature.
2. Classification of causes of project delay using an appropriate classification method.
3. Determination of appropriate method(s) to model different causes of delay that contribute to overall project delay.
4. Validation of the model.

Figure 1 provides the detailed stages of the research needed to achieve the tasks listed above.

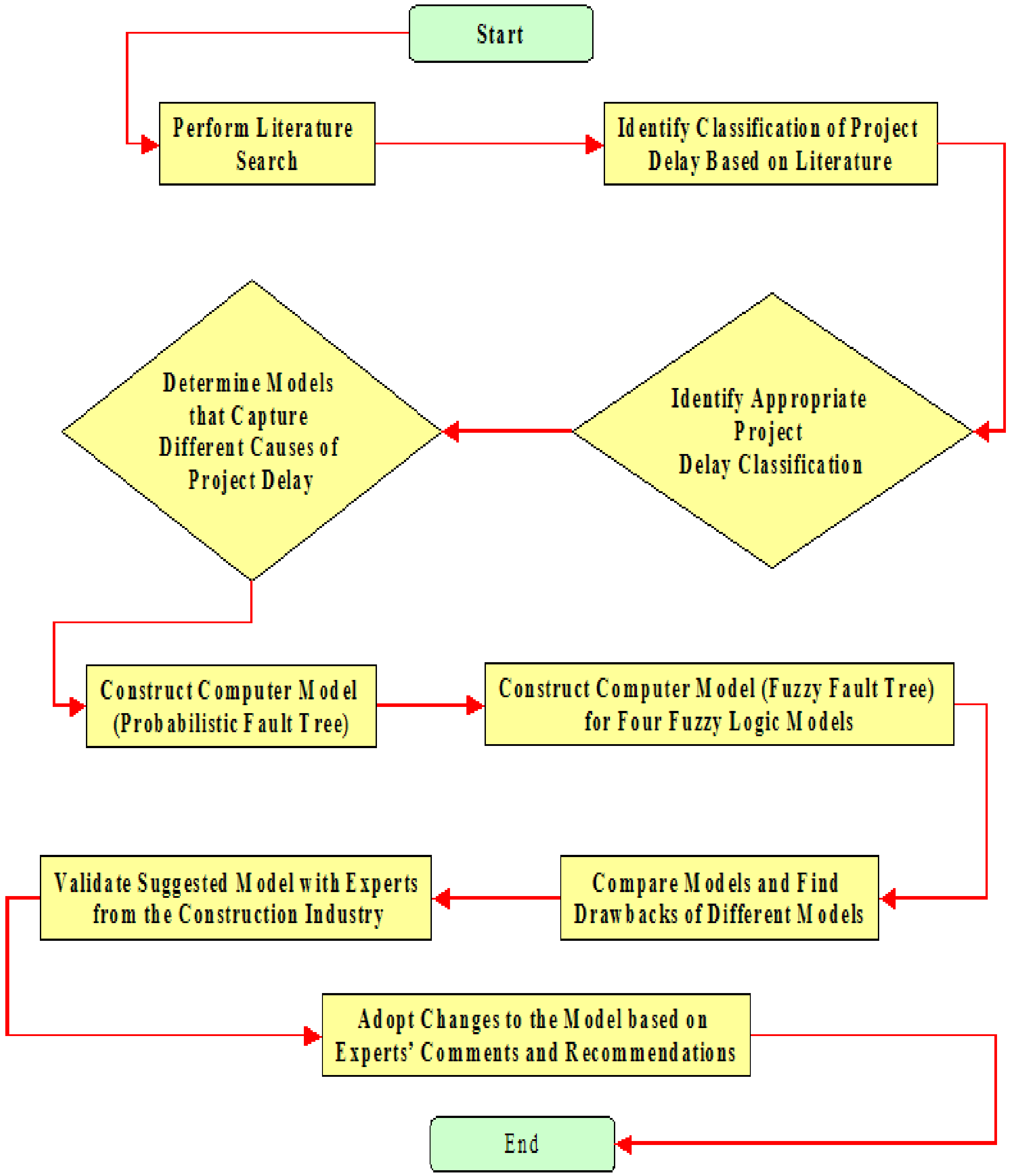


Figure 1. Research Stages.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Commercial software scheduling tools are widely used in construction projects. Such tools depend on graphical theory to determine the critical path of a list of activities and the relationship between these activities. Antill and Woodhead (1989), define scheduling as “the determination of the timing of the operations comprising the project and their assembling to give the overall completion time.” Scheduling can only take place after planning the process of choosing the method and determining the order of work. The critical path method is a planning and management tool that is widely used in the construction industry. According to Antill and Woodhead, the critical path method is a representation of the project plan by a schematic diagram or network that illustrates three aspects of the schedule. These aspects are the sequence, the interrelation of all the component parts of the project, and the logical analysis of the network.

Typical scheduling practice options can be presented in a bar chart format (Gantt chart), or a resource versus time chart. Adjusting the project schedule to limited resources availability is not an option in commercial scheduling tools and software. During the actual execution of the project, unexpected delays and problems are often encountered. In such cases, the consequences of these delays can cause project delays, easily impacting the project completion date and possibly resulting in conflicts, disputes and claims.

Disputes in construction projects are usually caused by changes in the scope of work. Change is a common practice in construction projects; changes can cause variation in project time, cost or both. Antill and Woodhead's (1989) definition of work change is related to alterations, variations, deductions, extras, or omissions of work. When work changes occur in construction projects, delays may also occur. Some delays may result in late completion of the entire project, whereas other delays may not effect the project completion date, since these are not as critical. Popescu and Charoenngam (1994) define delay as either the enforced time gap between the completion of an activity and the start of its succeeding activity(s), or the enforced increase in activity duration.

2.2 Construction Project Delay

Construction management focuses on best practices of managing resources such as materials, equipment, and labor. The challenge that faces managers in the construction industry is how to balance time, cost, and quality. Time delays are very clear measurements of project success as a simple comparison between actual and planned time could provide managers with project status.

Delays in construction projects are inevitable and usually result in cost and schedule overruns, and might result in claims and disputes among different parties involved in the project. Current methods used to predict the delay amount are based on static scheduling techniques such as bar charts or dynamic scheduling techniques such as the critical path method.

2.2.1 Delay Classification

According to an earlier work by the author related to project schedule and project delay classification Al-Humaidi (2002), classification of delay causes can follow different logic. Based on the topical literature about project delay topic, we can classify project delays according to their origin, timing, and compensability. Figure 2 provides an overview of delay classification. Classification of delays according to origin is when the delay is analyzed based on the party responsible for the delay. The party responsible for the delay can be the owner, the designer, or the contractor. The second classification of delay is based on compensability of delay. Compensable delays are classified further into excusable delays or non-excusable delays. Excusable delays may be further classified into excusable compensatory or non-compensatory delays depending on contract terms and conditions. Non-excusable delays are delays that do not entitle the contractor to either time extension or cost compensation. The third classification of delay is based on timing of delay. If two or more delays occur simultaneously, then a concurrent delay takes place. If a single delay takes place at a time, then a non-concurrent delay occurs.

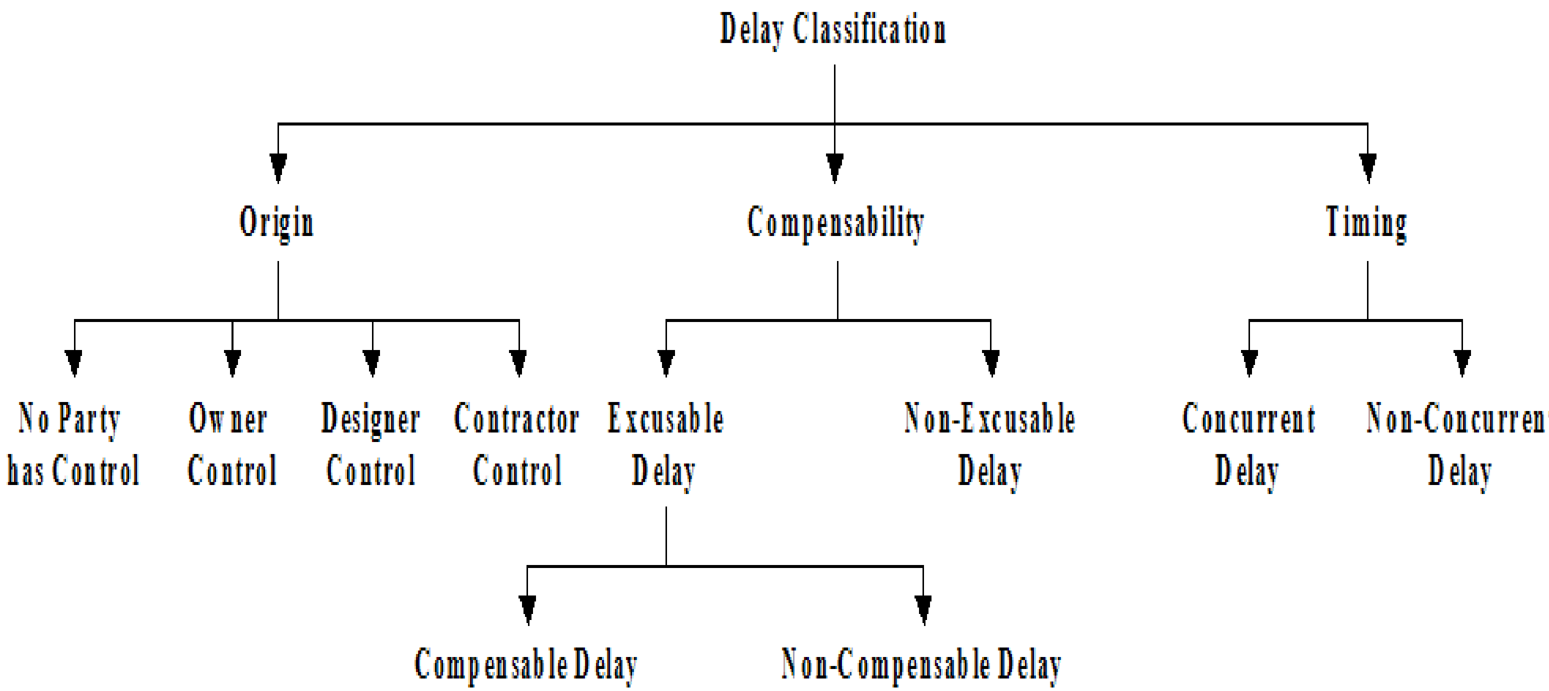


Figure 2. Delay Classification Al-Humaidi (2002).

2.2.1.1 Delays Classified by their Origin Al-Humaidi (2002)

According to Antill and Woodhead (1989) delays are classified according to their origin and the party responsible for the delay. They divide delays into the following categories:

1. Those over which neither party to the contract has any control.
2. Those over which the owner has control.
3. Those over which the designer has control.
4. Those over which the contractor has control.

Figure 3 provides a graphical representation of the different types of delays classified based on their origin. Figure 4 provides a classification of delays according to their origin.

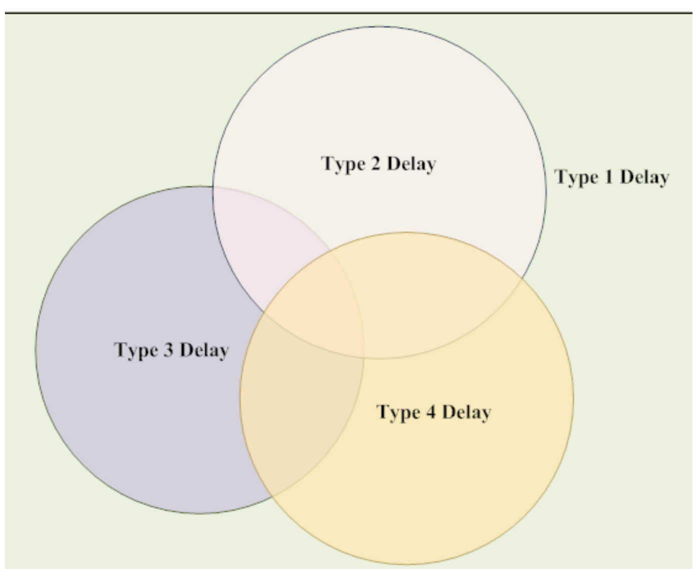


Figure 3. Different Types Of Delays Based On Origin Al-Humaidi (2002).

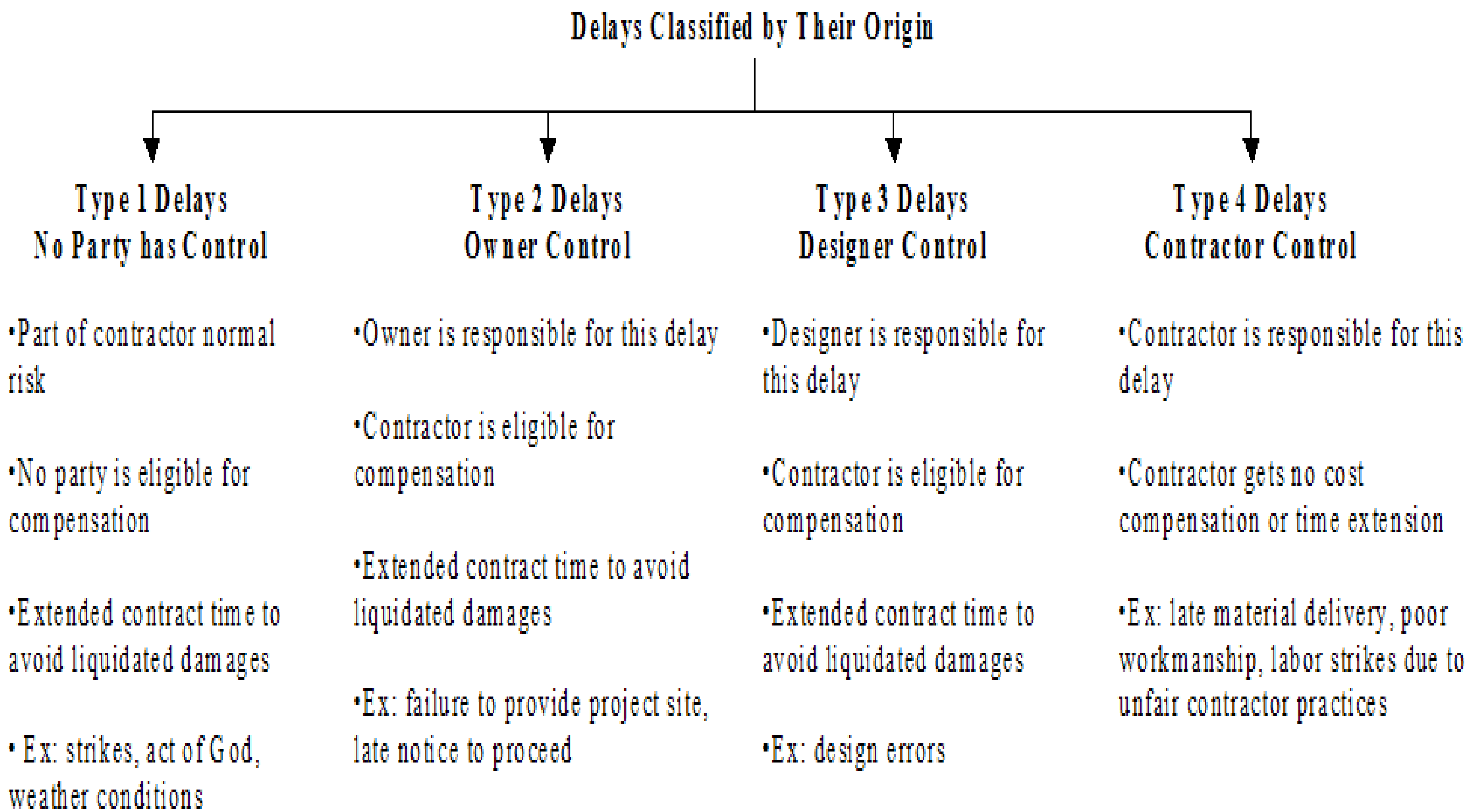


Figure 4. Delay Classification According To Origin Al-Humaidi (2002).

Delays of Type 1 are part of the contractor's normal risk, and hence neither party is eligible for compensation, but the contract time may be extended to avoid liquidated damages imposed on the contract. Examples of this kind of delay are strikes, acts of God, and weather conditions. In delays of Type 2 the contractor should receive a fair and reasonable compensation for both time and cost. Examples of Type 2 delays are delays that occur due to design errors, late notice to proceed, and failure to provide project site. In Type 3 delays the contractor receives no compensation at all. Examples of delays over which the contractor has control are late material delivery, poor workmanship, and labor strikes due to unfair practices. In Type 4 delays the contractor is responsible for the delay and therefore, the contractor is not eligible for cost compensation or time extension. Examples of Type 4 delays are delays due to late material delivery, poor workmanship, and those resulting from strikes caused by contractor's unfair labor practices.

2.2.1.2 Delays Classified by their Compensability Al-Humaidi (2002)

Excusable delays are "delays that entitle the contractor to additional time for completion of the contract work, arising from causes beyond the contractor control" (Popescu, 1994). Excusable delays may be further classified as excusable compensatory or non-compensatory delays, depending on contract terms and conditions. Excusable delays occur due to various factors that can be classified as:

1. Beyond the control of either party.
2. Within owner or architect/engineer control.

The first case results in time extension to avoid any liquidated damages, whereas the latter case results in time extension and compensation to the contractor. Owners are liable to contractors for delay damages only if the delay was caused solely by compensable delays. This type of causation is sometimes referred to as “but for” causation; that is, “but for” the compensable cause of delay, the delay would not have occurred Finke (1999).

Excusable non-compensatory delays entitle the contractor to additional time but not additional compensation. Neither party causes this type of delay. Examples of excusable non-compensatory delays (Type 1 delays) are acts of God, acts of public enemy, and unusual delays in transportation, such as freight embargo, unusual weather conditions, and strikes.

Excusable compensatory delay is one that entitles the contractor to extend direct costs, indirect costs, and project time. Excusable compensatory delays are usually due to acts or omissions of the owner or the designer. Compensatory delays are attributable to change orders. Examples of owner’s excusable compensatory delays (Type 2 delays) are late notice to proceed, failure to provide proper financing, failure to provide owner furnished materials or components, interfering with or obstruction of work on the project, and delay in change orders. Examples of designer’s excusable compensatory delays (Type 3 delays) are defective plans and specifications, failure to provide drawings on schedule, delay in review or approval of shop drawings, stop-work order, conflicts in drawings, and defective design.

Non-excusable delays are delays that do not entitle the contractor to either time extension or cost compensation. This type of delay occurs due to the contractor's failure to meet contractual obligations. Non-excusable delays are usually identified when disputes arise, since it is difficult for the owner to identify this type of delay at early stages of the project since the construction schedule is seldom maintained with sufficient details. Examples of non-excusable delays (Type 4 delays) are slow mobilization, inadequate labor force, strikes caused by unfair labor practices, poor workmanship, late delivery of materials and components, and failure to coordinate multiple subcontractors. Classification of delays based on their compensability is shown in Figure 5.

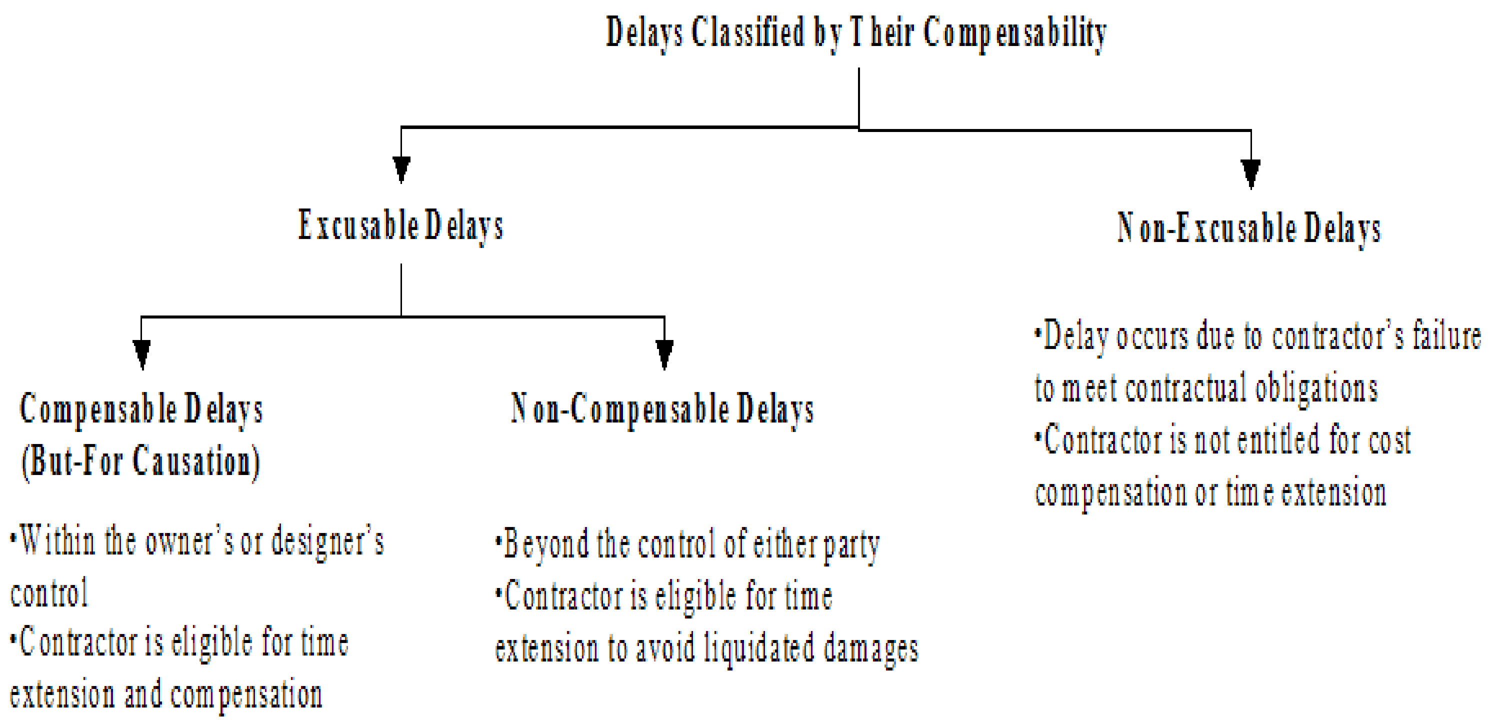


Figure 5. Delay Classification According To Compensability Al-Humaidi (2002).

2.2.1.3 Delays Classified by their Timing Al-Humaidi (2002)

Concurrent delay is defined as “the occurrence of two or more delays arising from independent causes and affecting a project during the same or overlapping time period” (Popescu et al., 1994). Courts examine this type of delay by determining the responsibility for concurrent delay and determining whether parties are seeking compensation or time extension. Rubin et al. (1983) suggested the following guidelines for classifying these kinds of concurrent delays:

- If excusable and non-excusable delays occur concurrently, only a time extension is granted to the contractor.
- If excusable compensable and excusable non-compensable delays occur concurrently, the contractor is entitled to time extension but not to damages.
- If two excusable compensable delays occur concurrently, the contractor is entitled to both time extension and damages.

Classification of delays based on their timing is depicted in Figure 6.

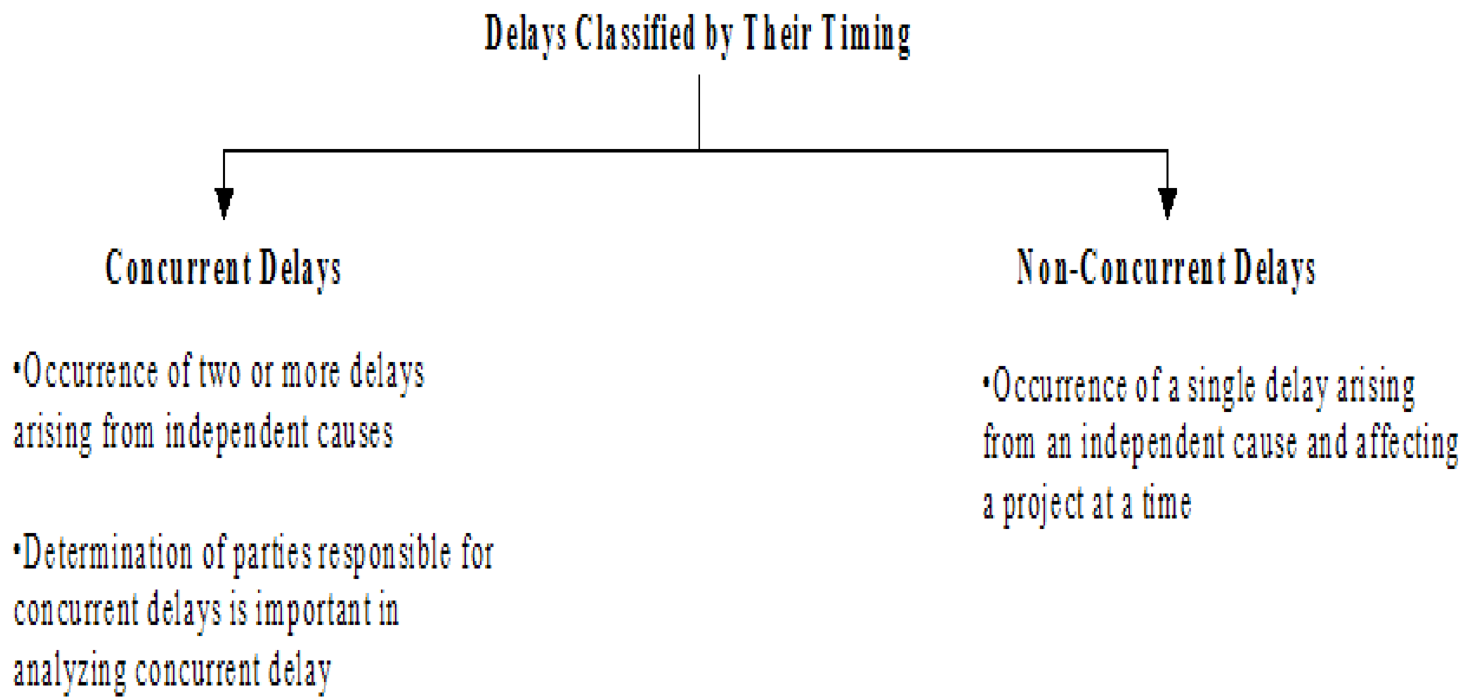


Figure 6. Delay Classification According To Timing Al-Humaidi (2002).

2.2.1.4 Causes of Delay

After researching the different classification of delays, it becomes clear that the topic of delay in projects is complex. Identifying the party responsible for a specific delay can be difficult, especially if concurrent delays take place. Thus, it is easier to successfully analyze overall project delay based on its causation than the factors suggested by different types of delay classification. Once these causes are studied, the resulting unfavorable outcome of delaying the project schedule can be quantified using probabilistic values. Such analysis is more valuable in planning stages and in the "what if" type of analysis in order to determine the different possible scenarios that could result in project delay. Furthermore, the party that caused the delay can be counted liable for a specific amount of delay. In general, causes of delay can be classified into three categories: procedural, triggering, and enabling. The following sections discuss these different classifications in further detail.

2.2.2 Procedural Delay Causes

Causes of delay can be classified into three categories, procedural, triggering, and enabling. Procedural causes are frequently hidden events that produce both enabling and triggering events and arise from the interrelationship among various parties involved in the project. Procedural delay causes are further classified into four categories. These four categories are managerial causes, legal causes, financial causes, and operational causes. Managerial causes that contribute to project delay are caused by management actions or inactions that affect time schedule. Contracting strategy selected to undertake the project can result in delay. For example, the responsibility of each party involved in the project is determined according to the contracting strategy since in lump sum contracting method; most responsibilities are undertaken by the contractor. In contrast, in the cost plus fee type of contracting, the owner is responsible for most work. Selection of the contracting method and the party that is experienced with the construction method affects the progress of work. Selection of the project delivery system can impact the progress of work and affect the scheduled time of project completion. For example, the design bid build type of contracting requires the completion of each stage prior to the start of the next stage whereas in the design bid type of contracting, fast tracking of the project can save time and the selection of the project delivery system can affect the planned time schedule for completing the work. The level of planning prior to starting work is highly related to the likelihood of deviations from the plan. A detailed plan can provide management with information that alerts management prior to the execution phase. In case poor planning is undertaken, scope of work can be unclear to parties involved in the project. Unclear scope definition can result in different interests among different parties involved in the project and incorrect decisions in terms of selection of alternatives and acquisition of resources. Erroneous decisions in the planning phase and improper scope definition can result in changes and variations in the execution phase which might lead to deviations from the plan and result in time delays. Legal causes such as acquisition of permits and disputes and conflicts among different parties involved in the project can result in time delays. Furthermore, financial resources can result in time overruns. In case financial resources are not available when needed, or in case cost estimates are erroneous, project time can be affected, since work needs to be slowed down or stopped until financial resources are available. Operational tasks are related to work undertaken in the project execution phase. The method implemented to complete task(s) can affect the time schedule. In cases where creative construction methods and constructability analysis reviews are undertaken in the early planning stages, the time needed to complete task(s) in the execution phase can be minimized. Furthermore, the value engineering concept can be implemented where creative methods add value to the project. Value engineering in terms of acquisition of resources when needed is a concept in construction that could save time and/or money. In cases where value engineering concept is not implemented, delays in the project can take place since non-creative methods that acquire time are implemented in delayed projects. Resources such as financial resources, experienced workers, and material or equipment need to be studied in advance and planned for so that these resources are acquired when needed to save project time. Figure 7 below provides a classification of procedural delay causes.

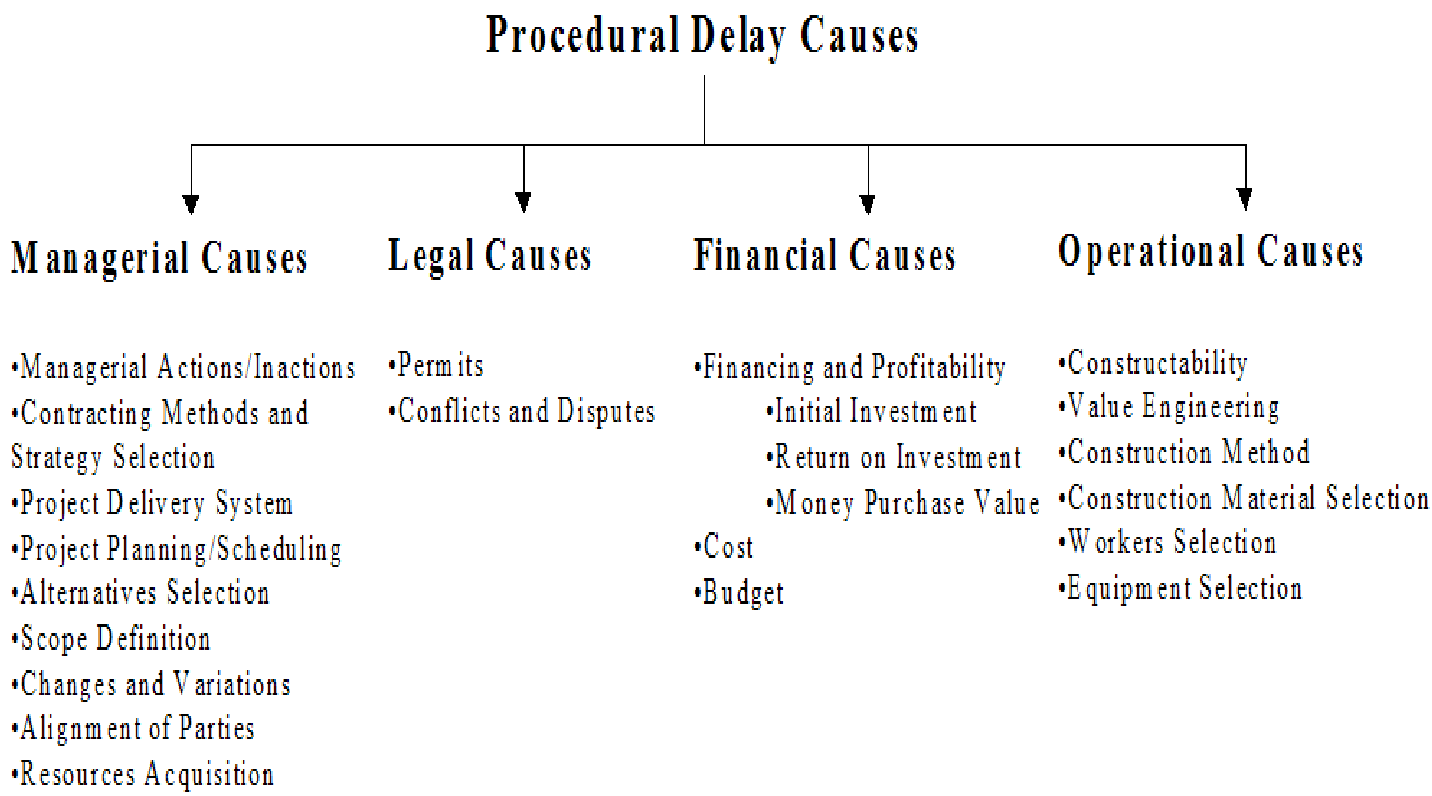


Figure 7. Procedural Delay Causes.

2.2.3 Triggering Delay Causes

Triggering delay causes can be defined as external delay causes such as environmental conditions (adjacent buildings, utility lines and power lines, which are external to the project but can significantly impact the progress of work). Other external causes of project delay are classified into weather conditions, underground conditions, and natural disasters. Weather condition causes such as rain, extreme temperatures, extreme high humidity or snow can stop work. The second classification of triggering or external causes of project delay is related to underground conditions. Underground conditions can cause uncertainty if limited planning is performed in early project stages. Underground conditions, which can result in project delay, include subsoil conditions especially when not enough boreholes are taken or when the subsoil is not studied carefully. For example, a boulder can be a major source of project delay if found during excavation. Underground water level can be another source of uncertainty especially if no or minimum planning was done. Underground utilities such as old pipelines or utility lines can also be a major source of project delay, especially if construction is performed on an historic site with limited existing plans for underground utilities. The third source of external uncertainty is related to natural disasters such as floods, hurricanes, and earthquakes. This external source of uncertainty differs from the other two external causes of delay. The major difference between the natural disaster cause of external uncertainty and weather and underground conditions is that the first two external causes can be managed through adequate planning and management whereas the natural disaster external cause of uncertainty is related to random events, which are unpredictable. Figure 8 below provides the classification of triggering delay causes.

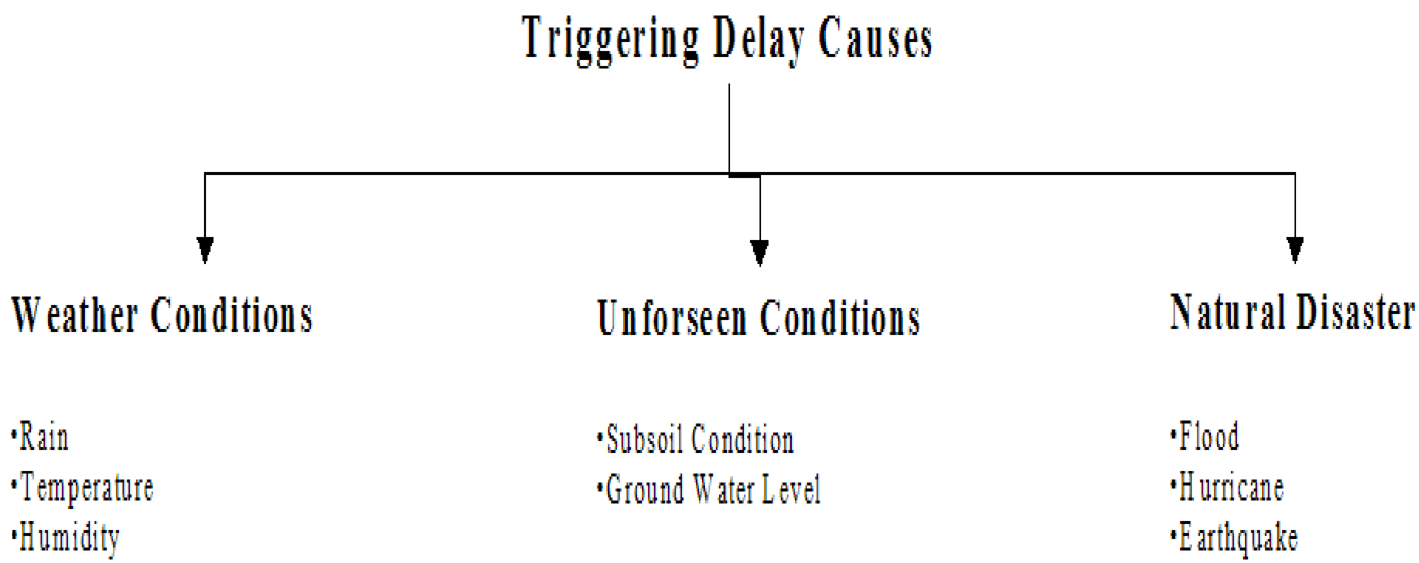


Figure 8. Triggering Delay Causes.

2.2.4 Enabling Delay Causes

Enabling delay causes can be defined as internal delay causes such as material related causes, workers related causes and equipment related causes. Material related causes are related to material availability when needed. In case material is not available when needed, project time might be affected especially if the installation of material is considered as a critical activity. Furthermore, worker related causes such as availability of skilled workers when needed and productivity of workers can affect the project time schedule and may result in time overruns. Equipment related causes are another cause of delay that is internal to the project. Equipment availability when needed and equipment functionality can affect the project time schedule and result in project delays. Figure 9 below provides classification of enabling delay causes.

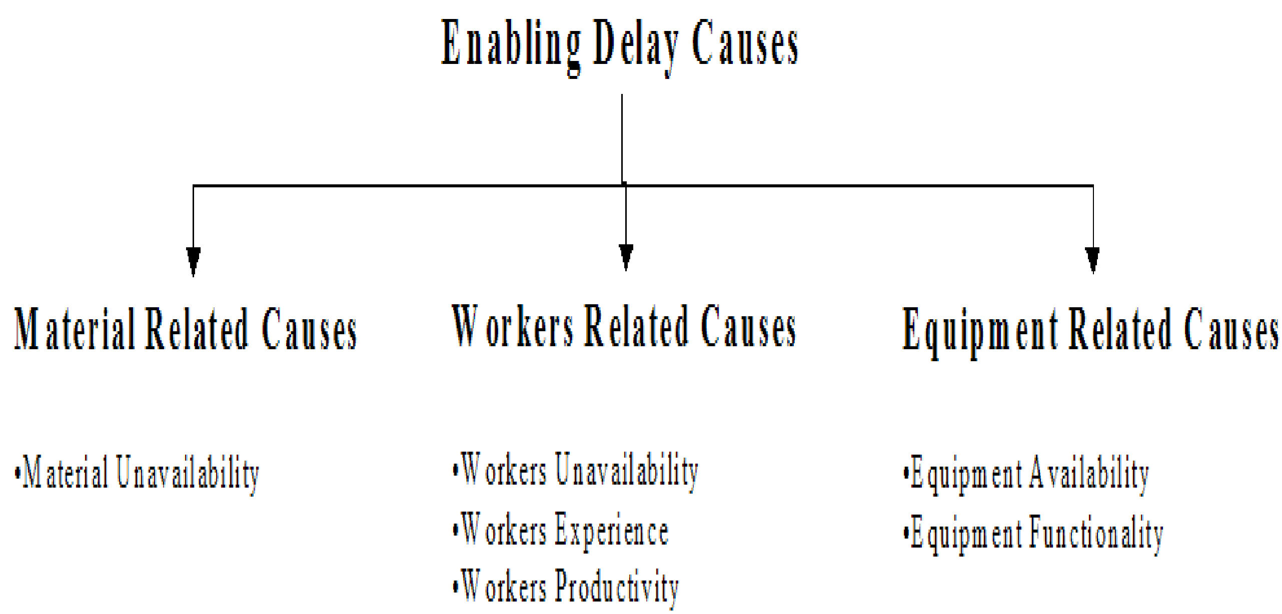


Figure 9. Enabling Delay Causes.

2.3 Earlier Work about Fault Tree Analysis

In "Modified Fault Tree Analysis for Structural Safety," Hadipriono and Toh (1989) introduced a modified fault tree analysis for structural systems. The study was a qualitative approach to assess the minimal cut sets that result in the occurrence of the top undesired event. The authors introduced modifications to the fault tree analysis, first in the analysis of the structural components, where the term failure was determined along a range of modes of failures such as buckling, shear or tensile failures which might take place simultaneously. Second, the laws of mechanics in structural systems and knowledge of structural behavior is essential to analyze causes and modes of structural failure.

In their research, Hadipriono and Toh (1989) related structural components failures to enabling, triggering and conditional events. An enabling event is an internal event that is caused by design or construction deficiencies. A triggering event is an external event that precipitates the failure. A conditional event is related to progressive fault where one component failure leads to the failure of another structural component. Structural dependency affects system logic and the failure of one component (A) is related to another component (B), therefore failure of component A should be modified to failure of component A given the failure of component B.

The fault tree analysis was explained in detail by Hadipriono and Toh where three gates were introduced, the AND gate, the OR gate and the INHIBIT gate. In the AND gate relationship, the top undesired event (structure failure) is caused by the failure of components A and B. In the OR gate, the structural failure of the top undesired event is caused by the failure of component A or the failure of component B. If structure failure is caused by failure of component A given that component B failed, it is conditional failure, a progressive type of failure where failure of one component leads to the failure of the next component.

In order to develop a modified fault tree analysis, the authors emphasized the importance of studying the structure being analyzed. Furthermore, the authors suggested the following basic rules in modified fault tree analysis:

1. Select the stages of the structure that the modified fault tree will represent. The modified fault tree is an analysis tool that should be developed prior to construction stage. The modified fault tree should include all potential events that may occur during construction and should be modified and updated to accommodate changes during and after construction.
2. Define the top undesired event in terms of what the fault is and when it might occur.
3. Determine the limit and the boundary of the analysis. All progressive faults should be further developed to the enabling and triggering events level.

4. Develop each progressive fault into its enabling and triggering events through appropriate gate. Three gates are suggested for progressive type of failure; the OR gate, the AND gate and the INHIBIT gate.
5. Define each event sufficiently to assure clarity of the analysis.

Minimal cut sets are useful to determine modes of failure and to identify the weak links in the components and the weak design and construction process spots. Evaluation of the minimal cut sets is performed by translation of the fault tree into algebra of events represented by Boolean expressions. The Boolean techniques principal to this study are summarized as:

1. Idempotent laws:

   $X+X = X$

   $X.X = X$

2. Law of absorption:

   $X.(X+Y) = X$

   $X+(X.Y) = X$

   $X.(X.Y) = X.Y$

3. Distribution laws:

   $X+(Y.Z) = (X+Y).(X+Z)$

   $X.(Y+Z) = (X.Y)+(X.Z)$

Boolean techniques show that an AND gate increases the size of a cut set while an OR gate increases the number of cut sets. The authors then illustrated the qualitative use of the modified fault tree analysis for structural systems using an example and a case study to show the mode of failure of the top undesired event (structure failure) and listed the minimal cut sets to illustrate the mode of failure.

Hadipriono and Toh (1989) provided a qualitative analysis of structured failure through the implementation of a modified fault tree analysis. The paper introduced enabling, triggering, and conditional causes of failure and illustrated the concept of modified fault tree analysis using an example and a case study to explain the concept of modified fault tree analysis. The ranking of the minimal cut sets or the most important mode of failure could not be suggested using qualitative analysis, since a quantitative analysis is necessary to quantitatively determine the most important mode of failure and to manage these most important modes of failure in the construction phase.

There is a need to implement a modified fault tree analysis for project delay that provides both qualitative and quantitative measures of delay. Fault tree analysis is modified by Hadipriono (1988) for project delay in his paper entitled: "Fault Tree Network Analysis for Construction." Further discussion of this paper is provided below.

In this paper, Hadipriono modified the fault tree analysis to capture characteristics of construction planning and scheduling. A top undesired event (project delay) was analyzed using a logical diagram that provides causality relationship among activities that result in project delay. In general, activities in a project can be either critical activities or non-critical activities. Critical activities lie on the critical path with no slack. Therefore, any delay in the start or the completion of critical activities result in project delay. An AND gate or an OR gate was suggested for critical activities fault tree analysis to capture the mode of failure in modified fault tree analysis. Non-critical activities lie on the non-critical path and have a total-float, where total-float is the time difference between the late start and the early start of an activity or the late finish and early finish of an activity. The total-float is usually composed of free-float and interference-float. Free-float is the time slack of an activity whose completion does not result in delaying any successive activity. The free-float is obtained from the difference between the early finish of an activity and the minimum early start of the successive activities. The interference-float is the difference between the total-float and the free-float. In constructing fault trees with non-critical activities, one must consider the time at which the free-float of an activity is exhausted, since the delay of this activity alone may not result in the delay of the successor activity. An INHIBIT logic gate was suggested to analyse non-critical activities since the delay of a successor activity is conditioned on the free-float being exhausted for the activity. The modified fault tree analysis of project delay is a process that begins with the delay of the last activity and proceeds deductively with the preceding activities.

The modified fault tree analysis can be implemented for deterministic procedures and for probabilistic procedures. In deterministic procedures, a modified fault tree with critical and non-critical activities can be illustrated using a deductive process where AND and OR gates are implemented for critical activities interrelationships and an INHIBIT gate for non-critical interrelationships. In probabilistic procedures, the preliminary modified fault tree analysis is expanded where delay definition is further expanded to either the failure of an activity to start at its early start date and causes the early finish date to be extended or the failure of an activity to be completed at its early finish despite the success in the early start of combination of both. In that case, delay takes place as a result of failure of the activity to start at its early start date, which was caused by delay of preceding activities or constraints that were due to either resources needed or the environment. In the second case, where the early start of an activity is met but delays take place as a result of constraints due to either resources or the environment, the limits of the tree expansion are dependent upon the project analysis and the need.

The cut set evaluation is beneficial to simplify the tree and provide a list of basic events that result in the top undesired event (project delay). Evaluation of the minimal cut sets is performed by translation of the fault tree into an algebra of events represented by Boolean expressions. The Boolean techniques principal properties summarized above are implemented to identify minimal cut sets. The rank of importance of the minimal cut sets can be evaluated either qualitatively, based on the sequence, or quantitatively, based on probabilistic figures or both qualitatively and quantitatively.

Illustration of the modified fault tree analysis for both deterministic and probabilistic procedures is provided through an example. The ranking of the minimal cut sets using qualitative and quantitative analyses is provided to rank order the importance of minimal cut sets.

In construction projects, both deterministic and probabilistic approaches suggested by Hadipriono (1988) are questionable for several reasons. First, each project is unique, so the implementation of historical data into an analysis can be questionable. Second, the subjective judgment of experts is considered a critical source of information for the analysis; therefore there is a need to implement a method that captures subjective expressions of the experts. Thus, the method suggested by Hadipriono (1988) should be modified to provide a fault tree analysis that accounts for method drawbacks.

In "Fuzzy Fault Tree Analysis for Structural Safety", Fujino and Hadipriono (1996) introduced the fuzzy fault tree analysis method for safety assessment of structures. The authors base their implementation of fuzzy logic on the use of subjective judgment to analyze structural safety. The authors introduced an historical review of the fault tree analysis as it was first used in the late 1950s and early 1960s in aerospace industry. The authors stated that the fault tree analysis method has been widely used as a tool in many areas to assess structural safety. The authors then introduced Zadeh's method of implementation of Boolean linguistic values based on the fuzzy set concept. The authors introduced the fuzzy fault tree analysis and the difference between this method and the fault tree analysis method. In the fault tree analysis method, the state of the system is represented by bi-valued expressions such as *failure* or *no failure*. In contrast, the fuzzy fault tree analysis recognizes partial states of the system such as partial failure states.

Fujino and Hadipriono introduced fuzzy logic models that used Boolean linguistic variables and represent these variables mathematically. A major difference between fault tree analyses and fuzzy fault tree analyses noted by Fujino and Hadipriono is that n partial states are considered in fault tree analysis since all input and output values take on only 0 or 1. Therefore, once an event occurs, it triggers the occurrence of the upper level event. On the other hand, in fuzzy fault tree analysis an effectiveness value is encountered to calibrate input values in a gate operation. The authors mentioned the ramp-type models where fuzzy values are represented by monotonic non-decreasing or non-increasing functions. This model was introduced by Baldwin and Guild (1980) where a ramp-type model is introduced using linguistic hedges such as the membership function modified with linguistic hedges. Other models the authors introduced are the translational models, where a fuzzy set has one or more convex shapes such as a triangle and sine curve. In such models no relationships between the fuzzy sets and the Boolean base terms and linguistic hedges are drawn. Fujino and Hadipriono selected the ramp type models because ramp type models represent the characteristics of Boolean linguistic values more clearly than other model.

According to Fujino and Hadipriono, the essential gates for the fuzzy fault tree analysis were discussed. These gates are the fuzzy AND, the fuzzy OR, the fuzzy mean, the fuzzy sum, and fuzzy logic gates. Furthermore, the fuzzy AND and the fuzzy OR operations were implemented in the analysis. The fuzzy AND operation is used for an intersection in set theory. The fuzzy AND operation takes the minimum membership value of the input values. The fuzzy OR operation takes the maximum membership value of the input values. In both the fuzzy AND and the fuzzy OR operations only one input could affect the output. Another operation suggested in the study is the Fuzzy Mean operation, where all inputs affect the output. A Fuzzy Mean is an operation that can manipulate the average of more than one input value. Thus the mean operator output value is between those of AND and OR. The fuzzy sum operator is used to account for the occurrence of all or either one of the contributing events. The fuzzy logic operation represents a conditional relation. This fuzzy logic operation uses the Truth Functional Modification (TFM) and the Inverse Truth Functional Modification (ITFM). Fujino and Hadipriono (1996) introduced several examples related to structural safety assessment.

Although delays in construction projects are very important, a top down, deductive fault tree analysis has never been used to analyze their effects on projects. This study would continue with implementation of the probabilistic fault tree analysis and the fuzzy fault tree analysis. Furthermore, the fuzzy fault tree analysis would implement different Boolean linguistic variables using different fuzzy logic models. Once these different analyses are introduced in the following chapters, a suggested method will be recommended.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Interpretation of project delay is both quantitative and qualitative in its nature. Quantitative analysis of project delay involves employing probabilistic assessment methods and probability theory to quantify the predicted amount of delay. Probability distribution along with data and information are vital to perform these quantitative assessment analyses. Qualitative aspects of project delay are subjective and contain many uncertainties especially in quantifying the amount of project delay. Project delay with all its inherent uncertainty is a prime candidate for fuzzy logic application. A fuzzy logic method employing a fuzzy fault tree to represent likelihood of project delay membership functions for a set of fuzzy values has been developed. The method can address subjective, qualitative, and quantitative uncertainties involving the estimation of project delay likelihood.

Fault trees are tools that are used to analyze an unfavorable outcomes using conditional probability theory and can therefore be used to analyze project delay. Fault tree is a top down method that can be used to analyze an unfavorable outcome. Project delay is an unfavorable outcome that can be analyzed using fault tree analysis where probabilities are assigned to the fault tree branches and the branches that have the highest probability of occurrence are given the highest attention and management action is taken to control these high probability scenarios.

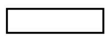
3.2 Fault Tree Analysis for Project Delay

Project schedules can be very complex and the effect of different components on the system as a whole is difficult to evaluate without an analytical tool. Analysis tools are classified to inductive or deductive. It is suggested by Vargas and Hadipriono (1995) that inductive techniques attempt to find out what would happen if fault occurred in the system. However, they suggested that deductive methods followed the opposite approach going from consequences to causes. Since the probability of project delay is of interest in this analysis, the analysis goes from consequences to causes and the recommended analysis method is the deductive fault tree analysis.

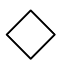
A fault tree analysis is a deductive, top-down method of analyzing project delay. Fault tree is a tool where a graphical model is created by deductive reasoning leading to various combinations of events that leads to the occurrence of top undesired event. The fault tree analysis method is described by Vargas and Hadipriono (1995) as "an analysis method, which seeks to identify all of the failure methods that can cause a system failure."

Fault tree analysis starts by defining the top undesired event, which in this research is project delay. Then the top undesired event is examined by identifying scenarios of events that must occur in order for the top undesired event to occur. Also, the form in which the lower undesired events are logically connected needs to be defined. The connection of the lower level events is expressed using AND or OR gates. Lower level events can be classified into the following types:

1. Basic events: These events are the lowest events that can be obtained.



2. Events that can be decomposed further: These events can be decomposed further to lower level events. Therefore, these events are decomposed until basic events are obtained.



3. Undeveloped Events: These events can be further developed but since they are not important, these events are not further developed. Usually these events are not important because the probabilities of occurrence are very small or the effect of the occurrence on the system is negligible.

The fault tree analysis requires the development of a tree-like diagram that provides possible scenarios that can result in the occurrence of the top undesired event "project delay." The outcome of interest from fault tree analysis is the occurrence probability of the top undesired event. In large fault trees, computation of the occurrence probability of the top undesired event could be difficult because of the size of the fault tree. In such cases a minimal cut set defines the path or the scenario that leads to the occurrence of the top undesired event. Minimal cut set is defined by Ayyub (2003) as "a set of basic events where the joint occurrence of these basic events results in the occurrence of the top event."

Vargas and Hadipriono (1995) noted that the fault tree analysis method is limited in that it only depicts the events or combination of events that in the analyst's opinion can lead to the top event occurrence.

3.2.1 Probabilistic Fault Tree Analysis

A probabilistic approach that can be implemented to analyze delay is the fault tree. Fault trees are tools that are used to analyze an unfavorable outcome using conditional probability theory. Probabilities are assigned to the fault tree branches and branches that have the highest probability of occurrence are given the highest attention and a management action is taken to control these high probability scenarios.

3.2.2 Fuzzy Fault Tree Analysis

It is unrealistic to evaluate the occurrence of a top event by using a crisp value without considering the inherent uncertainty and imprecision of each basic event. The fuzzy set theory can be used to deal with this kind of phenomenon. Fault tree analysis has been widely used in the past 40 years in many areas especially in reliability analysis. Fault tree is a model that graphically and logically represents the various combinations of possible events. Fault tree analysis is a deductive analysis that identifies possible modes of occurrence of an undesired event (delay in schedule). Fault tree analysis is a graphical model that reads both parallel and sequential components that can result in the occurrence of the top undesired event (project delay). The objective of fault tree analysis is to identify systematically all possible modes of occurrence of project delay. The structure of the fault tree is that the undesired event (project delay) appears as top event in the fault tree. The sequence of events that lead to the undesired event are logically linked by branches to the top undesired event (project delay) by standard AND and OR gates. Fault tree analysis provides a fault tree diagram that provides logical and causal relationship among different contributing causes. Furthermore, different contributing causes are ranked based on their importance determined by probability of occurrence. The probability of the top undesired event (project delay) is also determined using Boolean algebra.

Boolean algebra is an algebraic structure that captures properties of set operations and logic operations. Boolean algebra deals with the set operation of intersection, union, compliment, and logic operations of AND, OR, and NOT. Fault tree analysis is used when crisp probability values are introduced. When historical data is available, probabilistic analysis can be employed. However, in delay analysis, historical data is usually incomplete, and in projects where historical data is carefully observed, the unprecedented nature of projects, where each project is different, implies that use of probability theory is questionable. Additionally, the subjective judgment of knowledgeable people is important in assessing the condition of the contributing causes of delay and the degree of effectiveness each delay cause contributes to the overall project delay. Limitations in implementation of probability theory and the use of linguistic expressions leads to a need to develop a fault tree analysis that can accommodate such issues.

In order to develop a fault tree analysis that can accommodate the above problems, a modified fault tree analysis with fuzzy set concepts is introduced. Furthermore, modified fault tree gates such as AND, OR, and FUZZY MEAN gates are implemented to accommodate the above problems.

A fuzzy fault tree algorithm is developed by the alpha-cut method. The alpha-cut of a fuzzy set A is the crisp set ${}^{\alpha}A$ that contains all the elements of the universal set X whose membership grades in A are greater than or equal to the specified value of alpha. An alpha-cut of the membership function A (denoted ${}^{\alpha}A$) is the set of all x such that A(x) is greater than or equal to alpha (a). Mathematically,

$${}^{\alpha}A = \{x \mid A(x) >= \alpha\} \quad [1]$$

3.2.2.1 Fuzzy Set Theory

Lotfi Zadeh first introduced the theory of fuzzy sets in 1965 in his paper "Fuzzy Sets." Zadeh defined a fuzzy set as "a class of objects with a continuum of grades of membership." In a fuzzy set, each object is assigned its own membership value, which determines the degree to which the object belongs to a fuzzy set. Membership values range between zero and one. Fuzzy set theory proposed a paradigm shift from ordinary crisp sets with a membership value of either zero or one. In fuzzy sets linguistic terms are quantified by the implementation of rules of fuzzy set theory.

3.2.2.2 Fuzzification

Fuzzification is the process of converting crisp and deterministic values into fuzzy and uncertain values. If vagueness and imprecision are inherent in the linguistic term being described, then the variable is fuzzy. Different fuzzy set models can describe a fuzzy set. Among these different models are the fuzzy rotational models and the fuzzy translational models. A detailed explanation of these models is represented in Chapter 4.

3.2.2.3 The Angular Model

Angular models with rotational characteristics have been developed by Hadipriono and Sun (1990). In the angular model, linguistic values are represented with angles that range between $+\prod/2$ and $-\prod/2$.

Simple trigonometric equations are applied to determine the membership value. The following equations are implemented to determine the membership value, μ_θ, of any given linguistic term, which ranges from *very positive* ($\theta = +3\prod/8$) *to very negative* ($\theta = -3\prod/8$).

$$\tan(\theta) = \mu_\theta / x \qquad [2]$$

$$\mu_\theta = x \tan(\theta) \qquad [3]$$

The calculation of the membership value can be illustrated using Figure 10 where simple trigonometric calculation is implemented to determine the membership value of any given linguistic term.

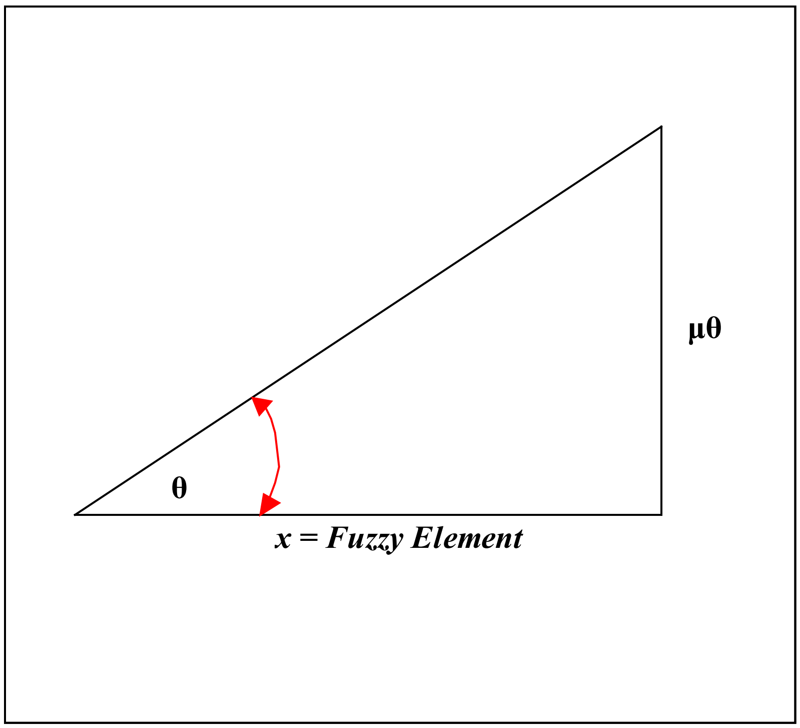


Figure 10. Calculation of Membership Value using the Angular Model.

For example, if weather condition is bad (*Negative*) an angle with **θ** = -∏/*4* or **θ** = *-45*^{o} is assigned to this linguistic term. Furthermore, an expert might state that weather has a *fairly effective* (*negatively effective*) affect on the overall project likelihood of delay. The linguistic terms can be captured using the Angular model as shown in Figures 11 and 12 next.

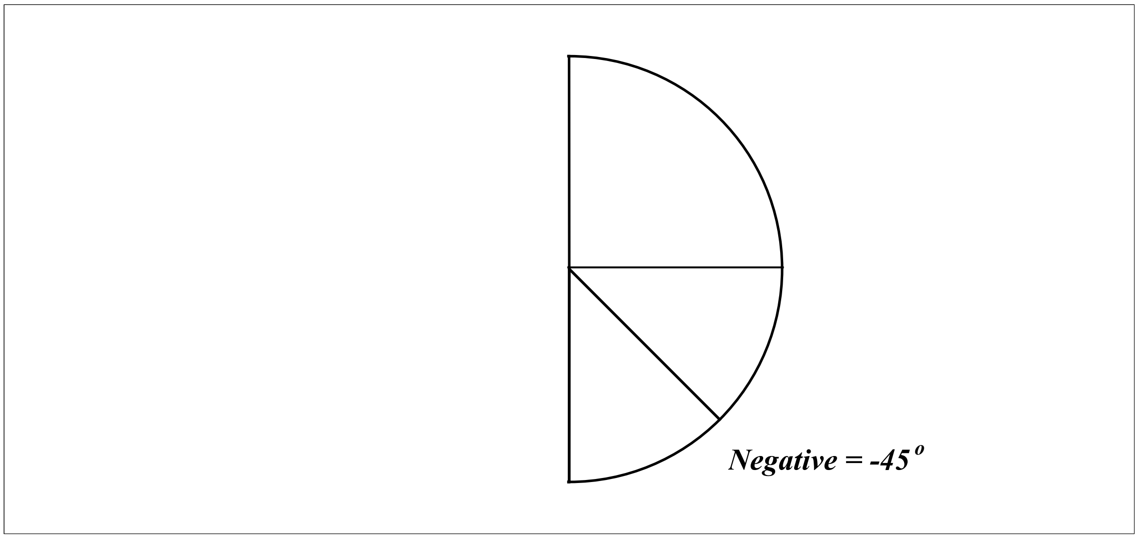


Figure 11. Weather Condition with (*negative or bad*) Linguistic Term using Angular Model.

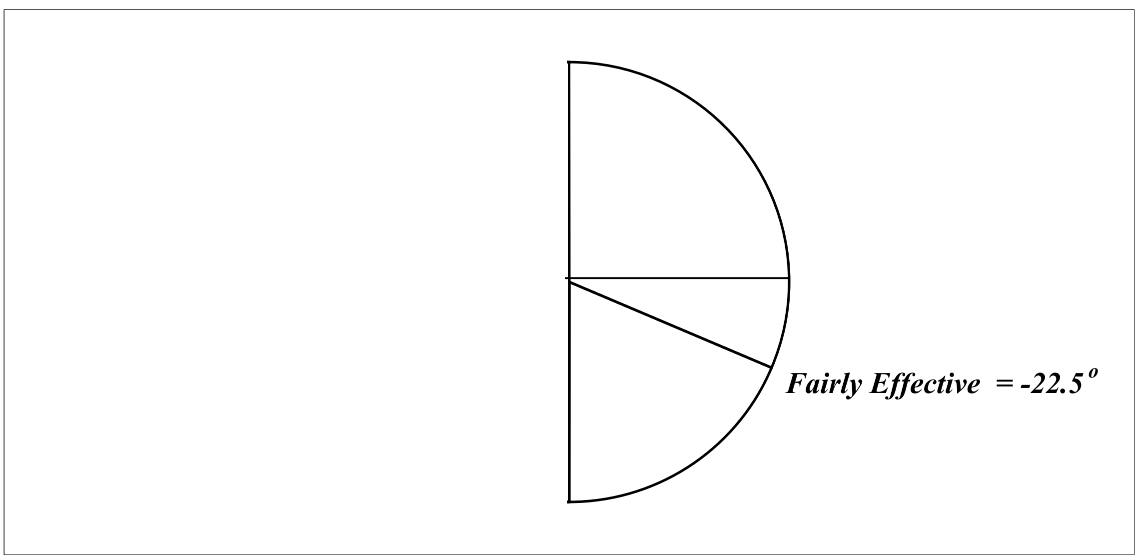


Figure 12. (*Fairly Effective)* Degree of Effectiveness for Weather Condition on Project Likelihood of Delay using Angular Model.

As an example to capture the weather condition and the degree of effectiveness of weather on the project delay, the membership functions of weather condition and effectiveness of weather on the likelihood of project delay are written as:

Weather condition: $\mu_\theta = x \tan(-45^o)$ $\mu_\theta = x * (-1)$

Effectiveness: $\mu_\theta = x \tan(-22.5^o)$ $\mu_\theta = x * (-0.4142)$

Hadipriono and Sun (1995) introduced the rating space concept based on the angular model introduced earlier by Hadipriono and Sun. In the rating space, the class of rating space R(r,X) consists of continuous functions with parameter r, that satisfies the following equation:

$$R(r,X) = rX \quad [4]$$

$$0 \leq X \leq 1; -\infty < r < \infty$$

Where X is the domain of the rating space and r is a rating value. The linguistic terms and the rating values are represented in the following table. Figure 13 provides definition of rating space.

Linguistic Term	**Rating Value [R]**
Very Negative	-2.414
Negative	-1
Fairly Negative	-0.414
Undecided	0
Fairly Positive	0.414
Positive	1
Very Positive	2.414

Table 1. Linguistic Values and Corresponding Rating Space.

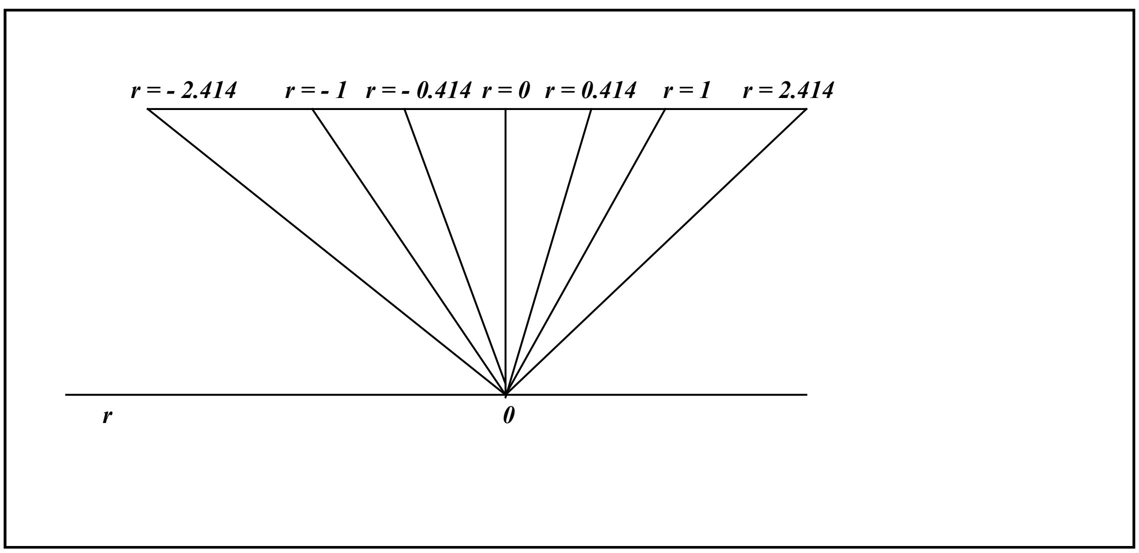


Figure 13. Definition of Rating Space.

For simplicity, we assume x = 1, the angular model representation of the linguistic terms (*negative* or *bad)*, weather condition and (*fairly effective*) level of effectiveness on the likelihood of project delay can be represented using Figures 14 and 15 as x = 1 in these figures.

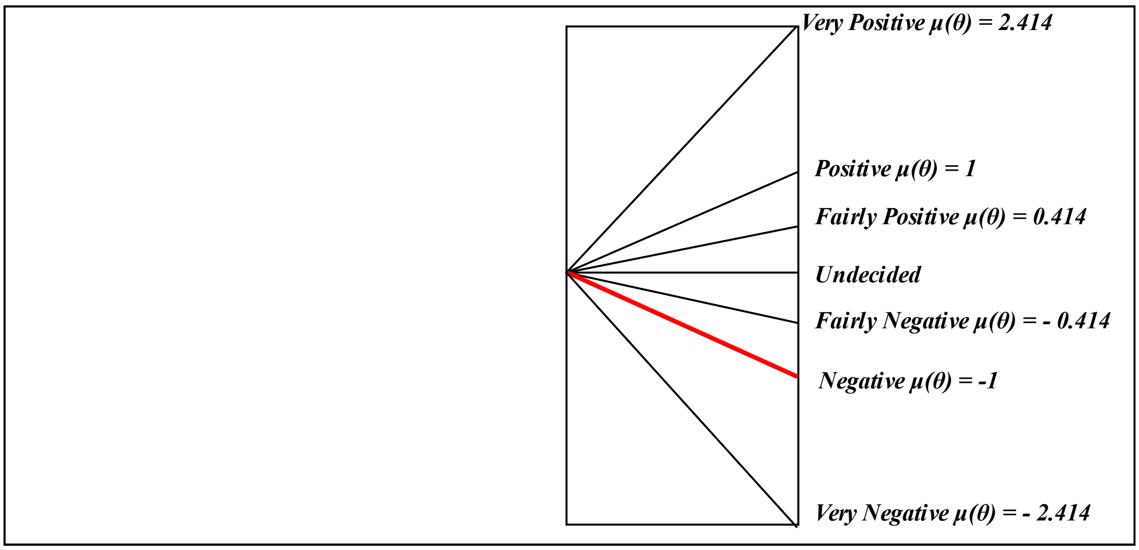


Figure 14. Weather Condition with (*negative or bad*) Linguistic Term with Assumption (x=1) using Rating Space Model Hadipriono and Sun (1995).

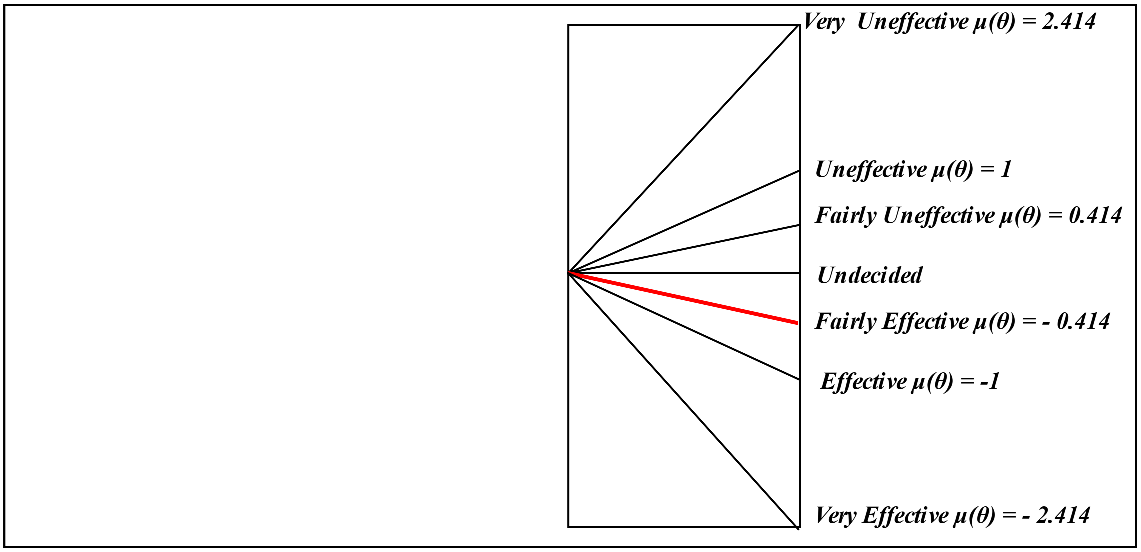


Figure 15. (*Fairly Effective)* Effectiveness for Weather Condition on Project Likelihood of Delay with Assumption (x=1) using Rating Space Model Hadipriono and Sun (1995).

Fuzzy multiplication is adopted to capture both cause of delay and effectiveness of the cause of delay on overall project delay. The likelihood of project delay as a result of (*bad weather*) condition, which (*fairly affects*) the likelihood of project delay is calculated using the following equation:

$$\mathrm{ATAN}[x\tan(\theta)x\tan(\theta)] = \mathrm{ATAN}[(1)\tan(-45)(1)\tan(-22.5)] = -22.5^{o} \qquad [5]$$

Figure 16 below provides the calculation of the likelihood of project delay as a result of (*bad weather*) condition, which (*fairly affects*) the likelihood of project delays.

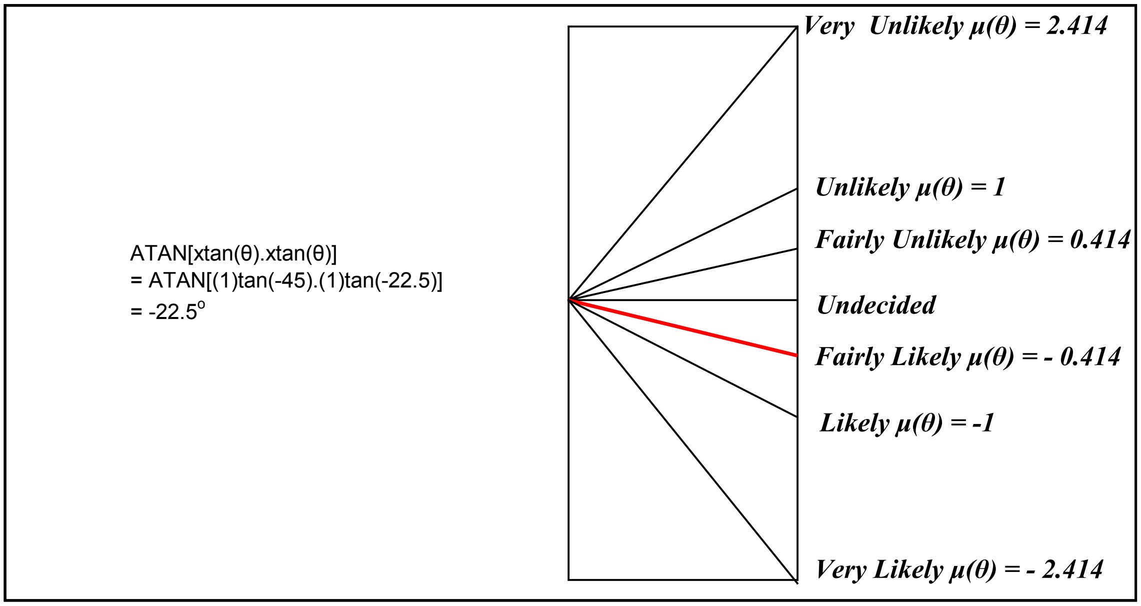


Figure 16. The Likelihood of Project Delay using Angular Model as a result of (*bad weather*) condition, which (*fairly affects*) the likelihood of project delays.

To capture the result of different causes of project delay, where the degree of effectiveness varies depending on the cause of project delay, a fuzzy set operation is implemented using the AND gate, the OR gate or the fuzzy mean gate. A detailed discussion of the fuzzy set operation using the angular model is represented later in this chapter.

3.2.2.4 Alpha Cut (α-cut) Method

Membership functions define the degree of participation of an observable element in the set, not the desirability or value of the information. Different factors contribute to overall project delay. Using the alpha cut associated with each factor the value of the factor is determined. Below that alpha cut, information is ignored unless the data above the alpha cut suggests that this information may be important. Then the alpha cut is lowered to increase the information bandwidth. "The α-cut of a fuzzy set A is the crisp set $^{\alpha}A$ that contains all elements of the universal set X whose membership grades in A are greater than or equal to the specific value of α." Klir and Yuan, (1995). Each fuzzy set, thus each fuzzy number can fully be represented by its α-cuts. α-cuts of each fuzzy number are closed intervals of real numbers. These two properties enable us to define arithmetic operations on their α-cuts.

The alpha-cut method can be applied to different fuzzy logic models. The triangular fuzzy set model differs from other fuzzy set models in that at any alpha (α) level, a closed interval represents the degree of belief in the linguistic terms shown. In translational fuzzy set models and Baldwin's fuzzy set models, a continuous monotonically increasing or decreasing function represents the fuzzy numbers. In angular fuzzy set models, membership values are represented by angles; therefore a new concept of α-cut method needs to be implemented to describe the degree of belief (the α level).

For example, if the weather condition is bad (*Negative*), Alpha-cut can give different results based on the fuzzy logic model the α-cut is performed on. In the following figures, the α-cut method is applied for negative or *bad* weather condition in both translational fuzzy set models, and triangular fuzzy set models. The Alpha-cut method is also applied for *Negative* or *bad* weather conditions in rotational fuzzy set models of both Baldwin's fuzzy set model and angular fuzzy set model.

Assuming that A is the fuzzy set of *bad* weather condition. A is a continuous fuzzy number which is described by the following translational fuzzy set:

Negative = [1/0, 0.8/0.1, 0.5/0.2, 0.1/0.3, 0/0.4,
0/0.5, 0/0.6, 0/0.7, 0/0.8, 0/0.9, 0/1] [6]

At any α level, a fuzzy number (the fuzzy element) that represents the degree of belief in representing the linguistic term *Negative* is quantified. The degree of belief is termed as "α level". For example, at α-level of 0.6, a fuzzy number [0.26, 0.34] is used to represent the linguistic term *Negative (or bad weather condition),* i.e., the degree to which the numbers from 0.26 to 0.34 may represent *negative (or bad weather condition)* is 0.6.

Figure 17 provides α-cut method for the *negative (or bad weather condition)* translational fuzzy set model.

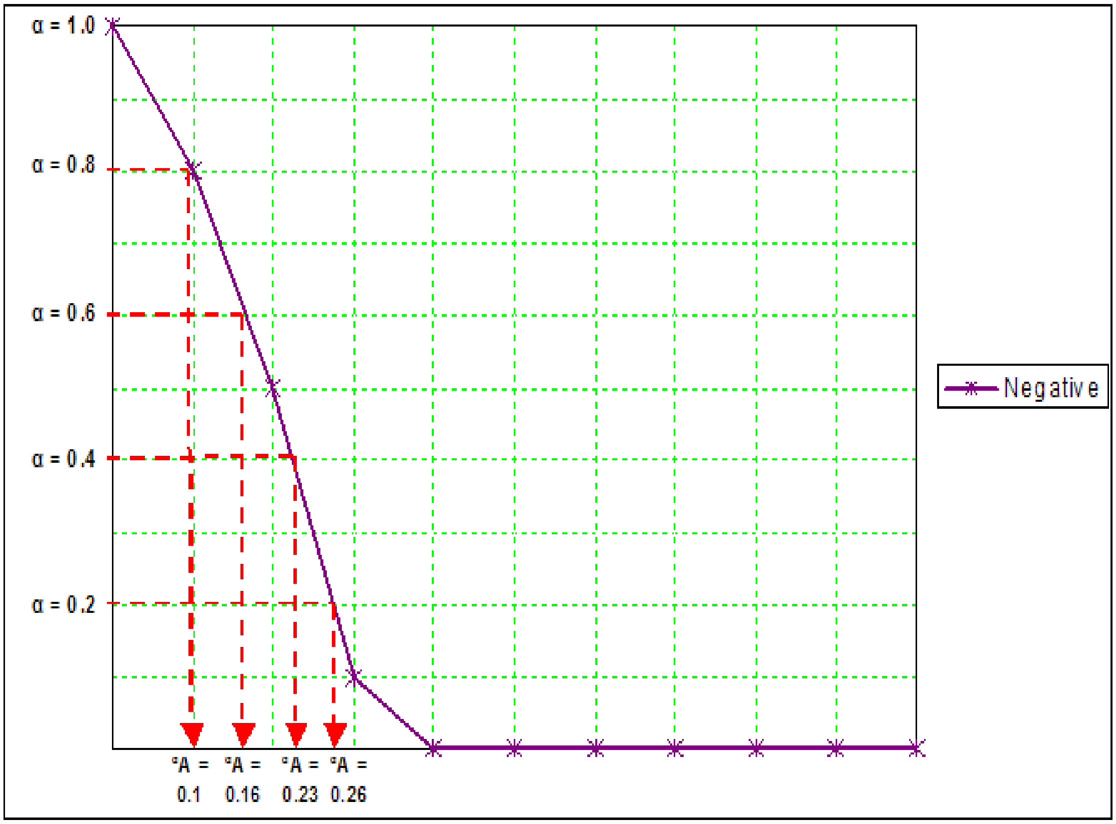


Figure 17. α-cut Method for *negative weather condition* using Translational Model.

Assuming that A is the fuzzy set of *bad* weather condition. A is a continuous fuzzy number which is described by the following triangular fuzzy set:

Negative = [0/0, 0/0.05, 0/0.1, 0/0.15, 0/0.2, 0.5/0.25, 1/0.3, 0.5/0.35, 0/0.4, 0/0.45, 0/0.5, 0/0.55, 0/0.6, 0/0.65, 0/0.7, 0/0.75, 0/0.8, 0/0.85, 0/0.9, 0/0.95, 0/1] [7]

$$A(x) = \begin{cases} 0 & \text{for } x \leq 0.2 \text{ and } x \geq 0.4 \\ 10x\text{-}2 & \text{for } x > 0.2 \text{ and } x < 0.3 \\ -10x + 4 & \text{for } x \geq 0.4 \end{cases} \qquad [8]$$

In triangular fuzzy sets where isosceles triangles are adopted, the properties of the fuzzy set can be captured by the base variables at α-cut = 0. The degree of belief is termed as "α level". For example, at α-level of 0.6, an interval of numbers [0.26, 0.34] is used to represent the linguistic term *Negative* (or *bad* weather condition*),* i.e., the degree to which to which the numbers from 0.26 to 0.34 may represent *negative* (or *bad* weather condition) is 0.6.

Figure 18 provides α-cut method for *negative (or bad weather condition)* triangular fuzzy set model.

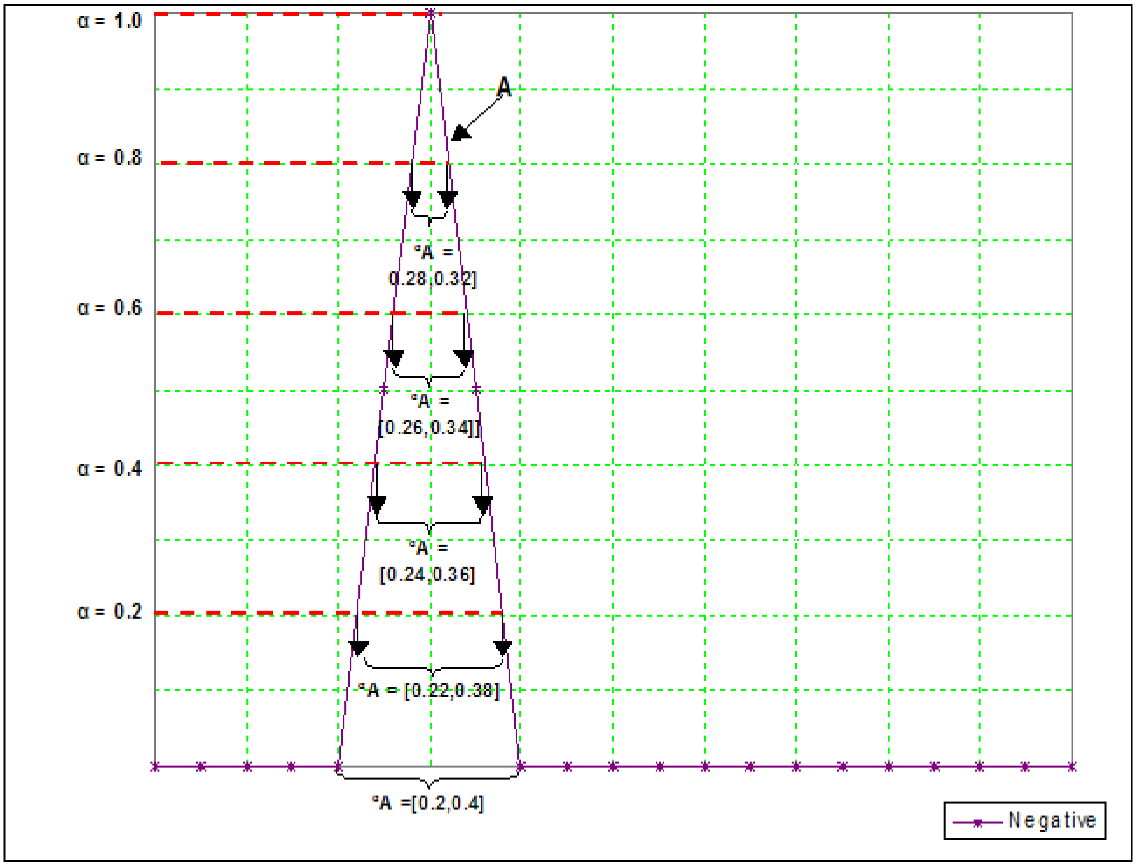


Figure 18. α-cut Method for *negative* weather condition using Triangular Model.

Assuming that A is the fuzzy set of *bad* weather condition. A is a continuous fuzzy number which is described by the following Baldwin's fuzzy set:

Negative = [0/0, 0.9/0.1, 0.8/0.2, 0.7/0.3, 0.6/0.4, 0.5/0.5, 0.4/0.6, 0.3/0.7, 0.2/0.8, 0.1/0.9, 0/1] [9]

At any alpha (α) level, the fuzzy element that represents the degree of belief in representing the linguistic term *Negative* is quantified. For example, at α-level of 0.6, a fuzzy number 0.4 is used to represent the linguistic term *Negative (or bad weather condition),* i.e., the degree to which the 0.4 may represent *negative (or bad weather condition)* is 0.6.

Figure 19 provides α-cut method for *negative (or bad weather condition)* Baldwin's fuzzy set.

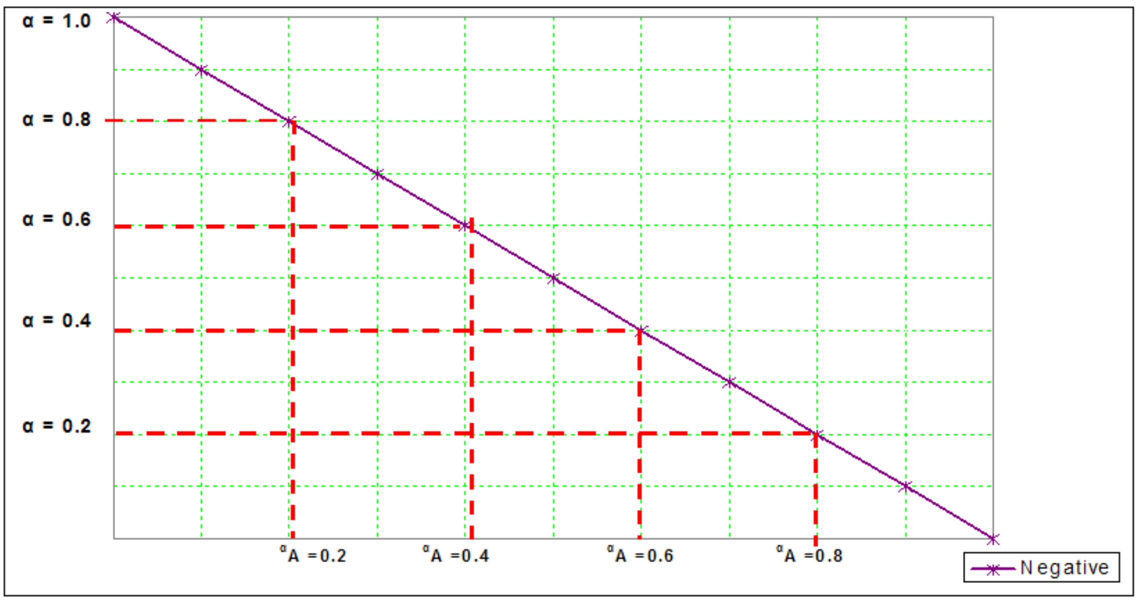


Figure 19. α-cut Method for *negative* weather condition using Baldwin's Model.

3.2.2.5 Fuzzy Arithmetic

In order to capture different causes of project delay and their degree of effect on the overall likelihood of project delay, the α-cut method is implemented on various fuzzy logic models. At each and every α level, fuzzy arithmetic can be implemented by multiplying two intervals since we want to capture the condition state (cause of delay) and the effectiveness of the cause of delay on the overall likelihood of project delay. Multiplication rule is applied on two intervals since multiplication is performed on infinite number of combination of pairs of crisp singletons from each of the two intervals and an interval is expected as a result.

Alpha-cut method can be applied to different fuzzy logic models. The triangular fuzzy set model differs from other fuzzy set models in that at any alpha level, a closed interval represents the degree of belief in representing the linguistic terms. In translational fuzzy set models and Baldwin's rotational fuzzy set models, a continuous monotonically increasing or decreasing function represents the fuzzy numbers. In angular fuzzy set models, membership values are represented by angles; therefore a new concept of α-cut method needs to be implemented to describe the degree of belief (the α level).

In triangular fuzzy sets, a closed interval that represents the degree of belief in representing the linguistic terms is determined for both the condition state (cause of delay) and the effectiveness of the cause of delay on the overall likelihood of project delay. For example, if weather condition is *bad* (*negative*) and this triggering cause of delay has a *fairly effective* (*negatively effective*) affect on the overall project likelihood of delay, then this information is captured using alpha-cut method to represent the degree of belief in representing the linguistic terms for both the cause of delay and the degree of effectiveness the cause has on the overall project delay. To capture information on the cause of delay and the degree of effectiveness the cause has on the overall project delay a fuzzy multiplication is suggested at each α level.

Figure 20 provides a fuzzy multiplication of *bad* (*negative*) weather, which has a *fairly effective* (*negatively effective*) affect on the overall project likelihood of delay using triangular fuzzy set.

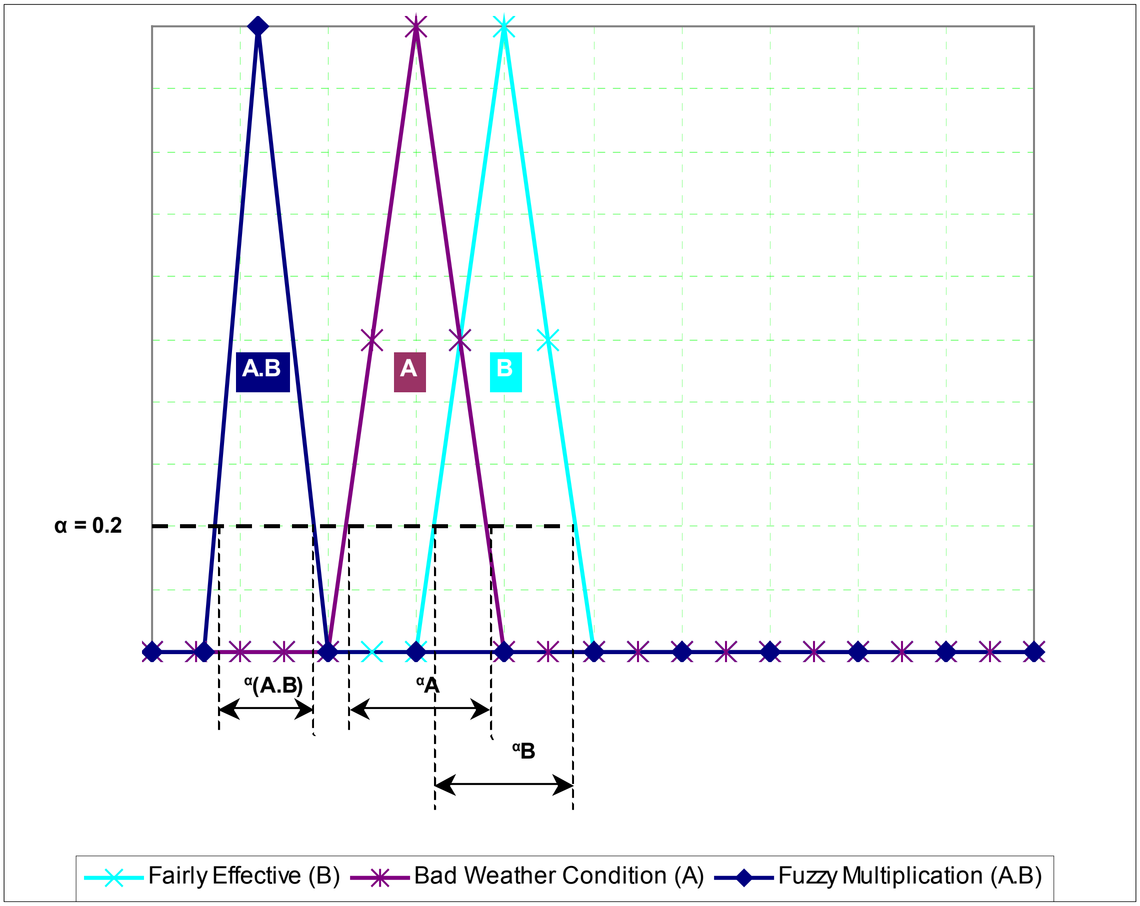


Figure 20. Fuzzy Arithmetic for the Triangular Fuzzy Sets.

In the case of fuzzy number where membership functions are monotonically increasing or decreasing, a fuzzy number that represents the degree of belief of linguistic terms is determined for both the condition state (cause of delay) and the effectiveness of the cause of delay on the overall likelihood of project delay. For example, if weather condition is *bad* (*negative*) and this triggering cause of delay has a *fairly effective* (*negatively effective*) affect on the overall likelihood of project delay, then this information is captured using alpha-cut method to represent the degree of belief in representing the linguistic terms for both the cause of delay and the degree of effectiveness the cause has on the overall project delay. To capture information on the cause of delay and the degree of effectiveness the cause has on the overall project delay, a fuzzy multiplication is suggested at each α level. Figure 21 provides fuzzy arithmetic obtained for translational fuzzy sets. Figure 22 provides fuzzy arithmetic obtained for the Baldwin’s fuzzy set model.

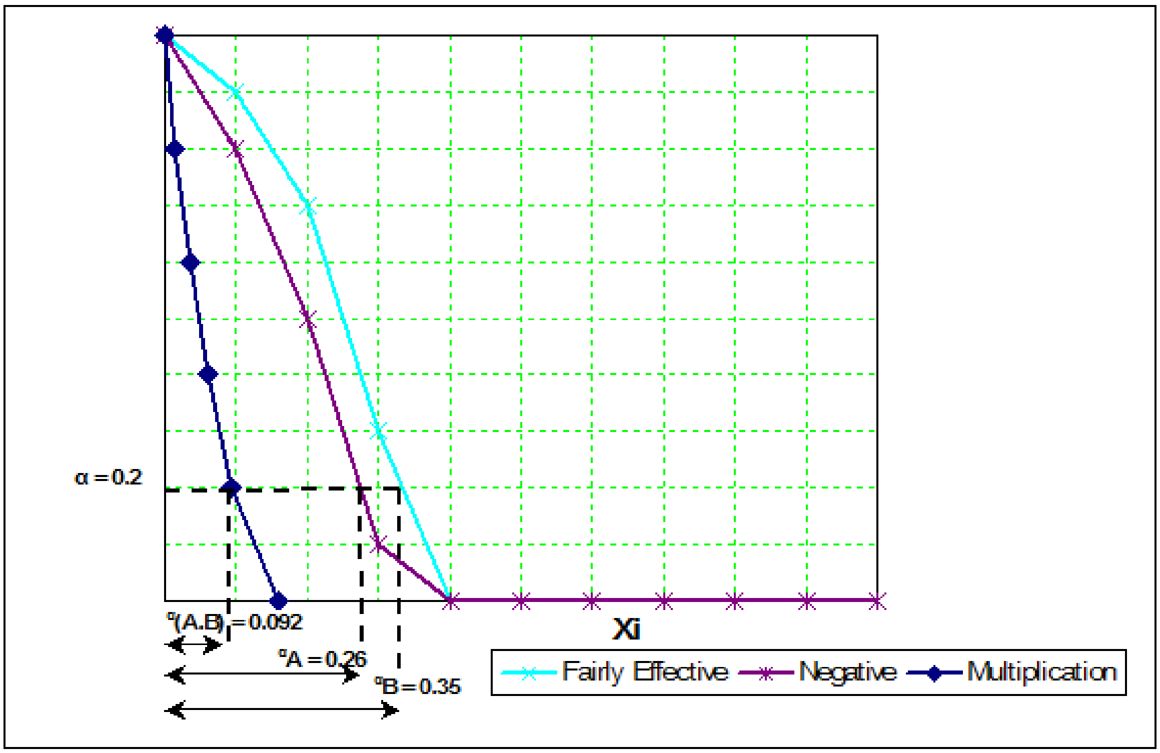


Figure 21. Fuzzy Arithmetic for the Translational Fuzzy Sets.

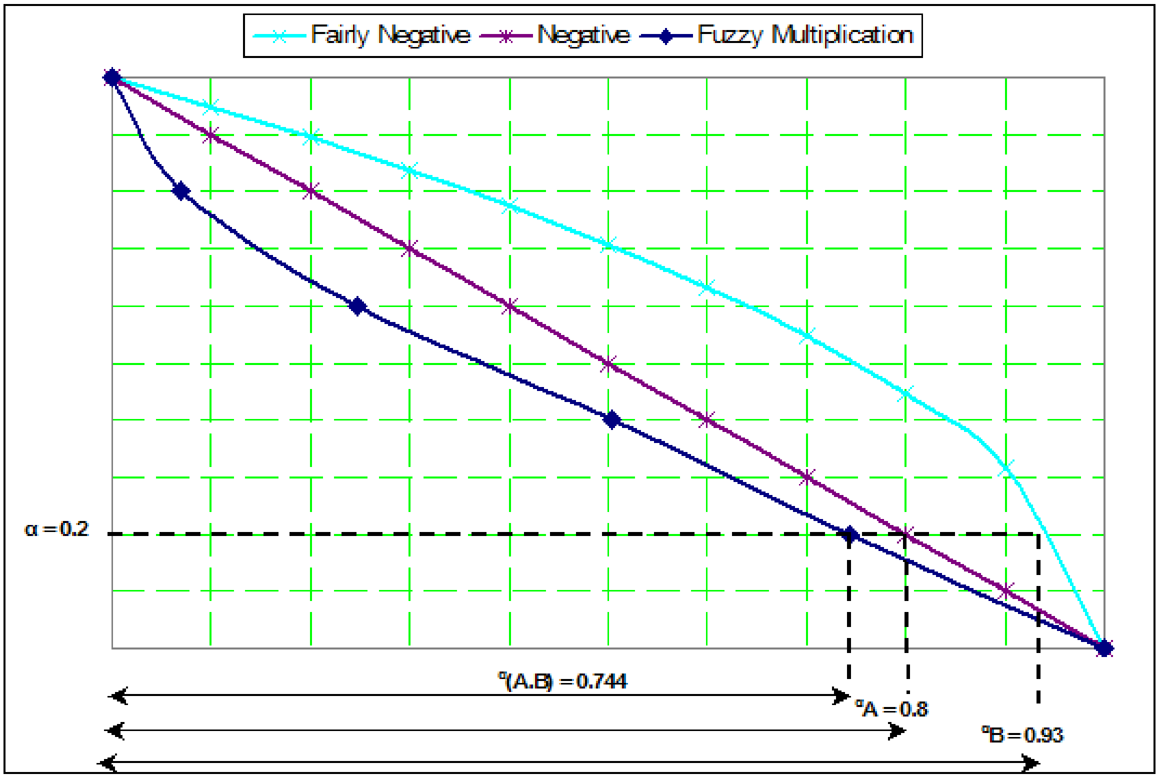


Figure 22. Fuzzy Arithmetic for Baldwin's Fuzzy Set Model.

3.2.2.6 Fuzzy Fault Tree Gates

Fault tree analysis (FTA) uses a top-down approach to generate a logic model that provides for both qualitative and quantitative evaluation of system reliability. The undesirable event at the system level is referred to as the top event. The top undesired event generally represents a system failure mode or hazard for which predictions are required. The lower level events in each branch of a fault tree are referred to as basic events. They represent internal (enabling), external (triggering), and human (procedural) failures for which the probability of failure is given based on historical data. In fuzzy fault trees, the likelihood of the top event is determined based on lower level events, which are the basic events that are determined based on experts' opinions and subjective judgments. Basic events are linked via logic symbols (gates) to one or more undesirable top events. In general, three fuzzy gates can be implemented to link basic events. Table 2 provides fuzzy gates and a detailed description of the AND, the OR and the Fuzzy Mean gates.

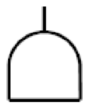
Symbol	Gate	Description
	And Gate	The AND gate is used to indicate that the output occurs if and only if all the input events occur. The output of an AND gate can be the top event or any intermediate event. The input events can be basic events, intermediate events (outputs of other gates), or a combination of both. There should be at least two input events to an AND gate.
	Or Gate	The OR gate is used to indicate that the output occurs if and only if at least one of the input events occur. The output of an OR gate can be the top event or any intermediate event. The input events can be basic events, intermediate events, or a combination of both. There should be at least two inputs to an OR gate.
	Fuzzy Mean Gate	Obtains the average value of all contributing events

Table 2. Fuzzy Gates Description.

3.2.2.7 Standard Fuzzy Set Operations

In general, standard fuzzy set operations are the standard intersection and the standard union. Furthermore, the weighted average or the fuzzy mean is another operation on fuzzy sets. The following section describes these fuzzy set operations in further details.

Standard Intersection $(A \cap B)(x) = \min[A(x), B(x)]$ [10]

Standard Union $(A \cup B)(x) = \max[A(x), B(x)]$ [11]

Weighted Average (Fuzzy Mean) $(A \sim B)(x) = [w_a.A(x),\ w_b.B(x)];$

$w_a + w_b = 1$ [12]

The intersection of two fuzzy sets, A and B, is specified by a binary operation on the unit interval; that is, a function of the form .

$$i: [0,1] \times [0,1] \rightarrow [0,1] \quad [13]$$

For each element x of the universal set, this function takes as its arguments the memberships of x in the fuzzy sets A and B, and yields the membership grade of the element in the set constituting the intersection of A and B.

$$(A \cap B)(x) = i[A(x), B(x)] \quad [14]$$

This operator, i, must have certain properties in order ensure that fuzzy sets produced by i are intuitively acceptable as meaningful fuzzy intersections of a given pair of fuzzy sets. The function i is independent of x; it depends only on the values of A(x) and B(x) fuzzy intersection can be represented by a Venn diagram as shown in Figure 23. Fuzzy intersection can be applied to different causes of project delay using four different fuzzy logic models. If experts are on the pessimistic side and think that different factors will all take place at the same time, a fuzzy AND operation is implemented to capture these different causes. Figure 24 provides implementation of fuzzy intersection using the translational fuzzy logic model, Figure 25 provides implementation of fuzzy intersection using the triangular fuzzy logic model, Figure 26 provides implementation of fuzzy intersection using Baldwin's rotational fuzzy logic model, and Figure 27 provides implementation of fuzzy intersection using angular fuzzy logic model.

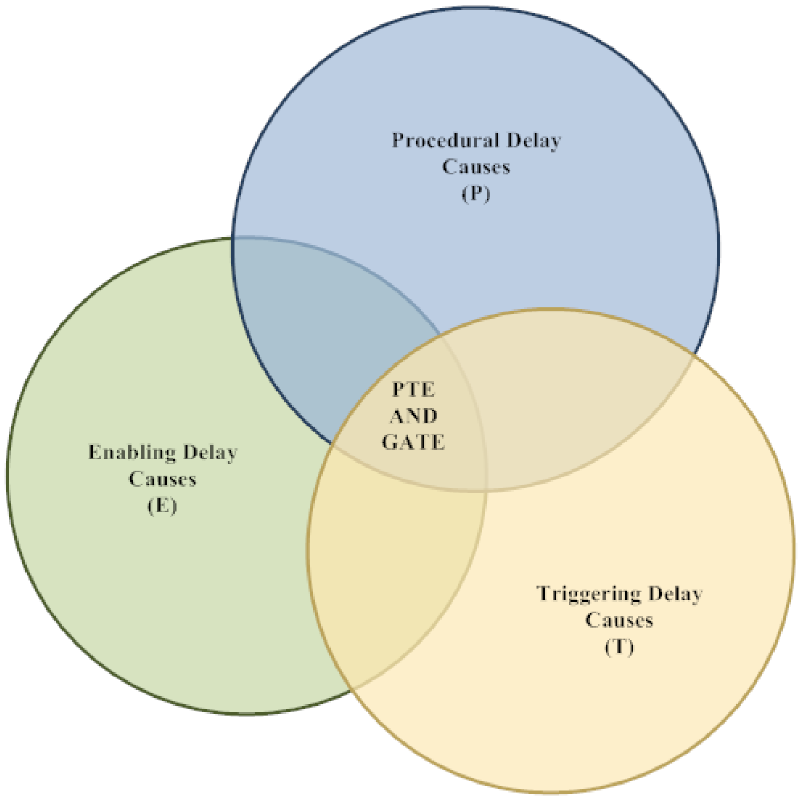


Figure 23. Venn Diagram for P∩T∩E.

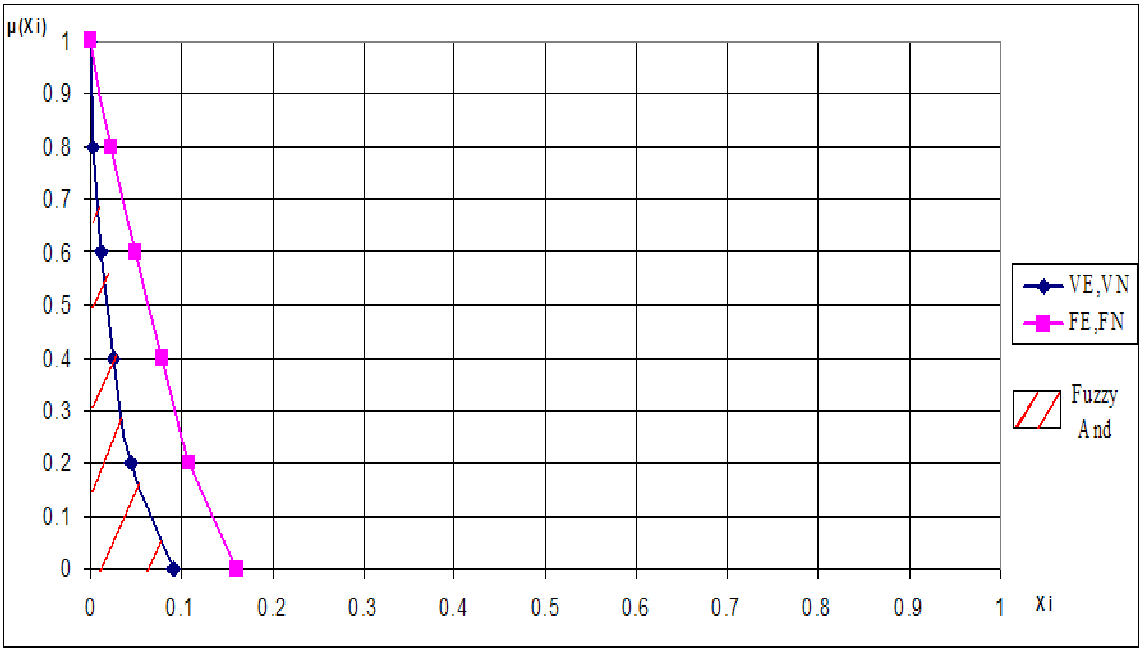


Figure 24. Fuzzy Intersection using Translational Model.

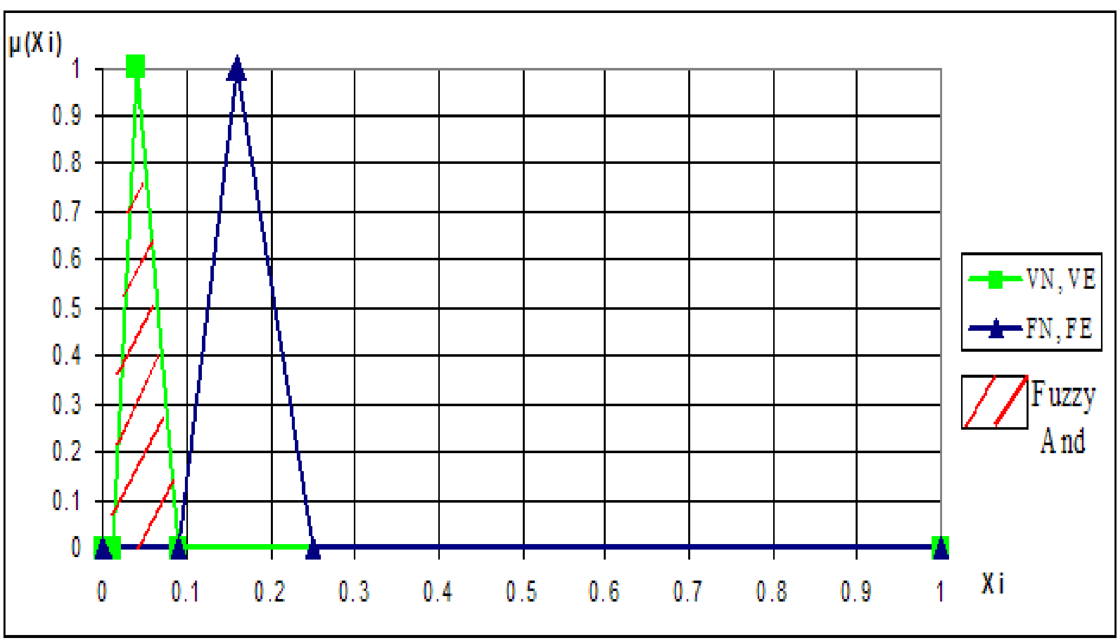


Figure 25. Fuzzy Intersection using Triangular Model.

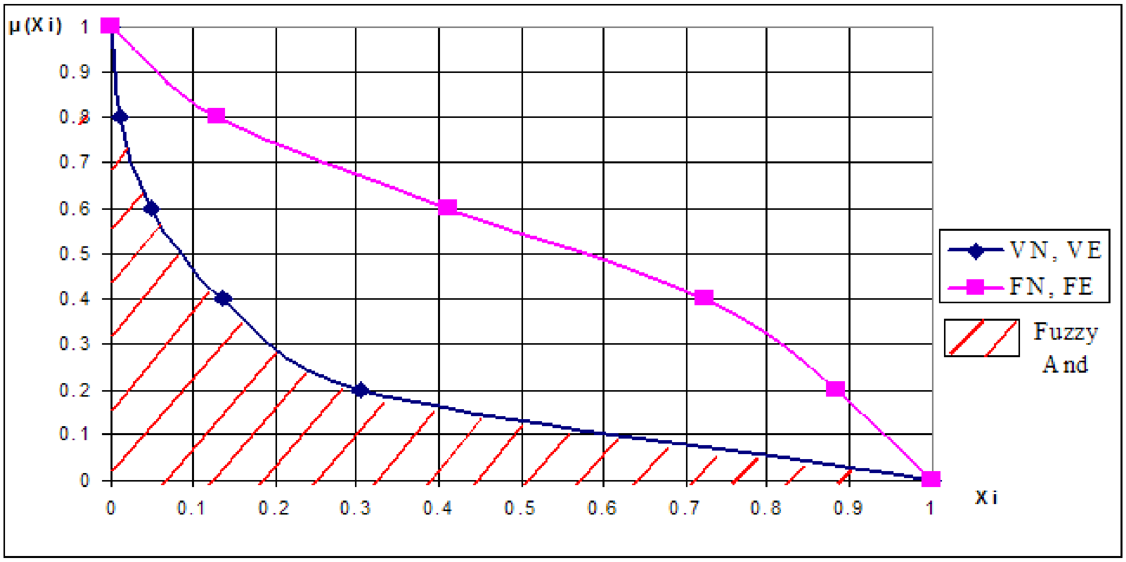


Figure 26. Fuzzy Intersection using Baldwin's Model.

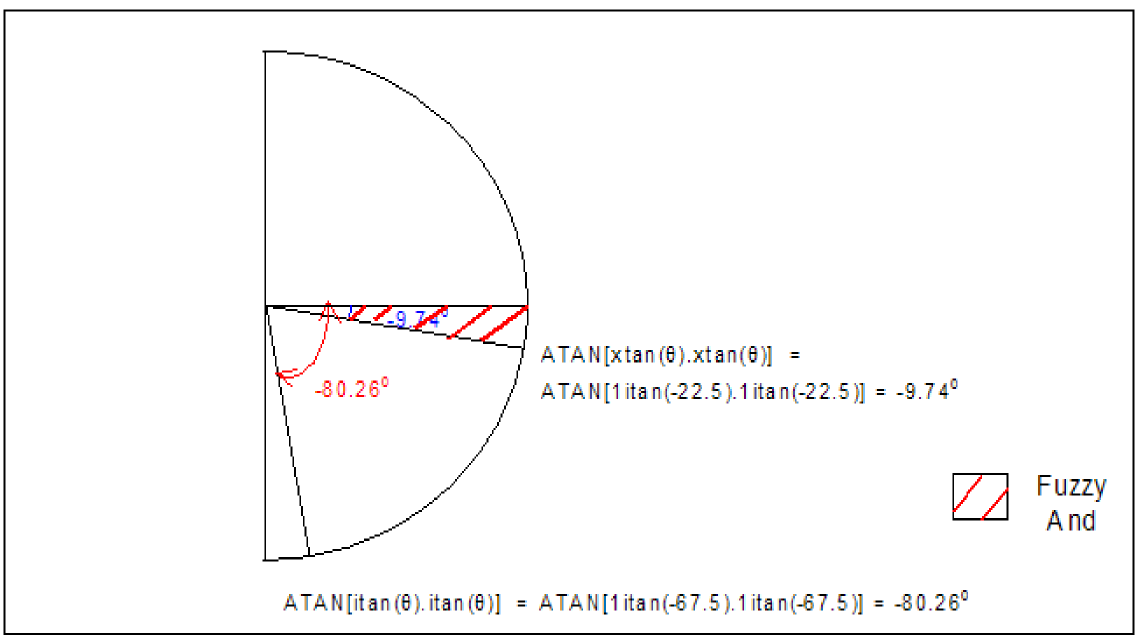


Figure 27. Fuzzy Intersection using Angular Model.

The general fuzzy union of two fuzzy sets A and B is specified by a function as the following equations show.

```
U: [0,1]x[0,1] -> [0,1]
```
[15]

or

```
(AUB)(x) = U [A(x),B(x)]
```
[16]

Fuzzy unions can be represented by a Venn diagram as shown in Figure 28. Fuzzy unions can be applied to different causes of project delay using four different fuzzy logic models. If experts are on the optimistic side and think that different factors will not all take place at the same time, but one factor or the other are likely to occur at a specific point of time, a fuzzy OR operation is implemented to capture these different causes. Figure 29 provides implementation of fuzzy union using the translational fuzzy logic model, Figure 30 provides implementation of fuzzy union using the triangular fuzzy logic model, Figure 31 provides implementation of fuzzy union using the Baldwin's fuzzy logic model, and Figure 32 provides implementation of fuzzy union using the angular fuzzy logic model.

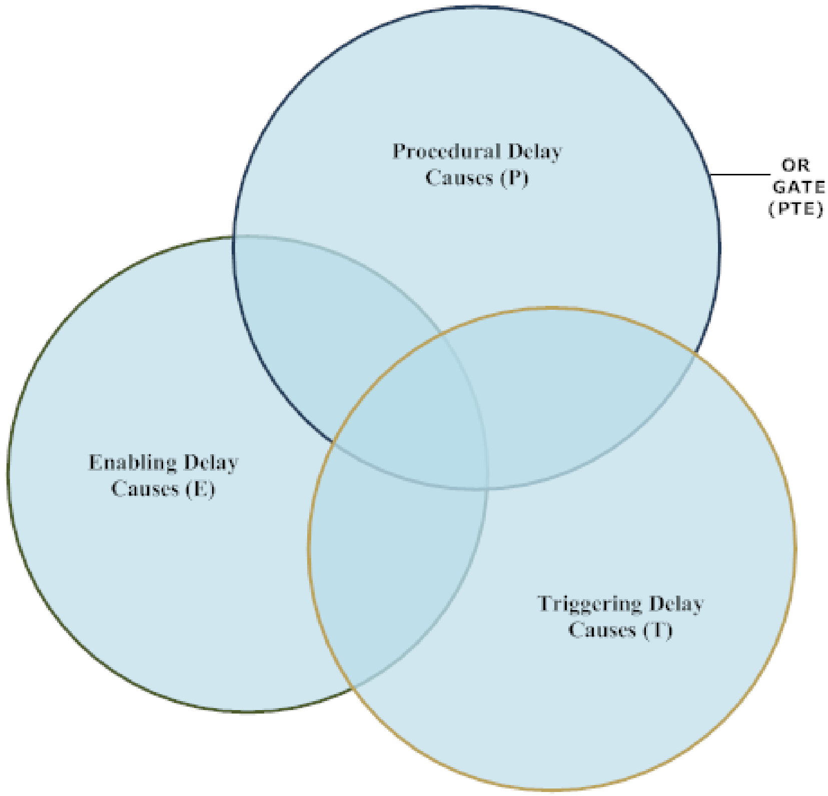


Figure 28. Venn Diagram for P∪T∪E (PTE).

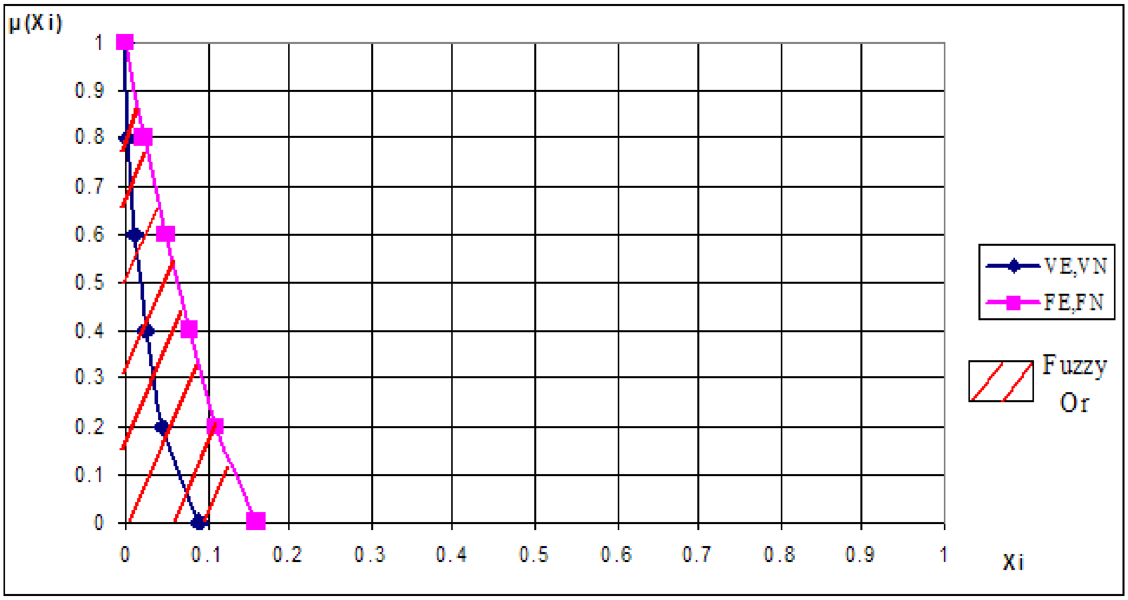


Figure 29. Fuzzy Union using Translational Fuzzy Logic Model.

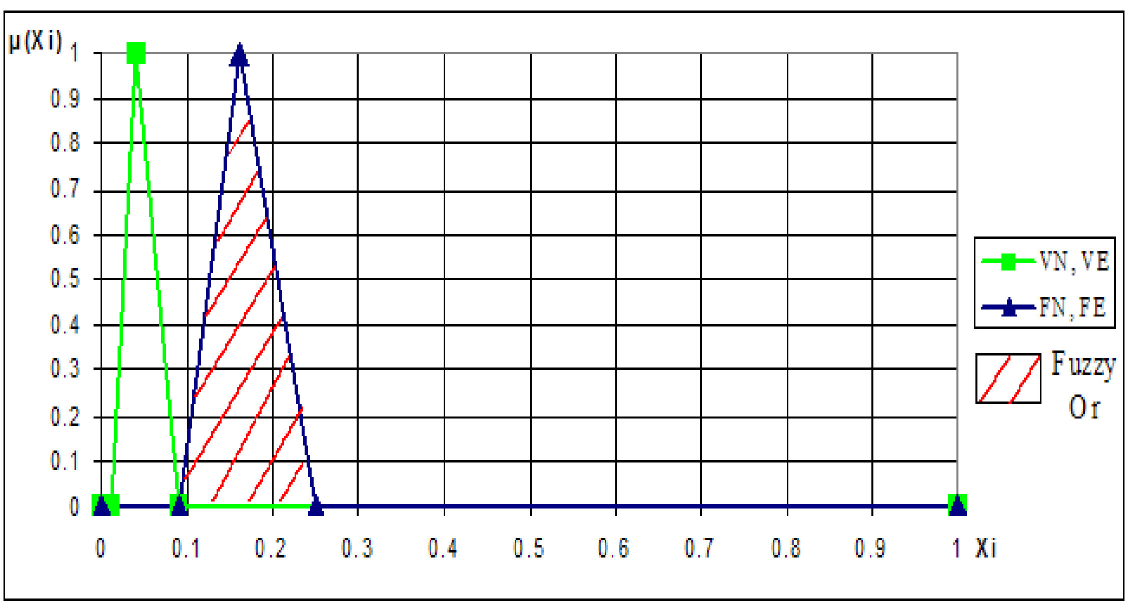


Figure 30. Fuzzy Union using the Triangular Model.

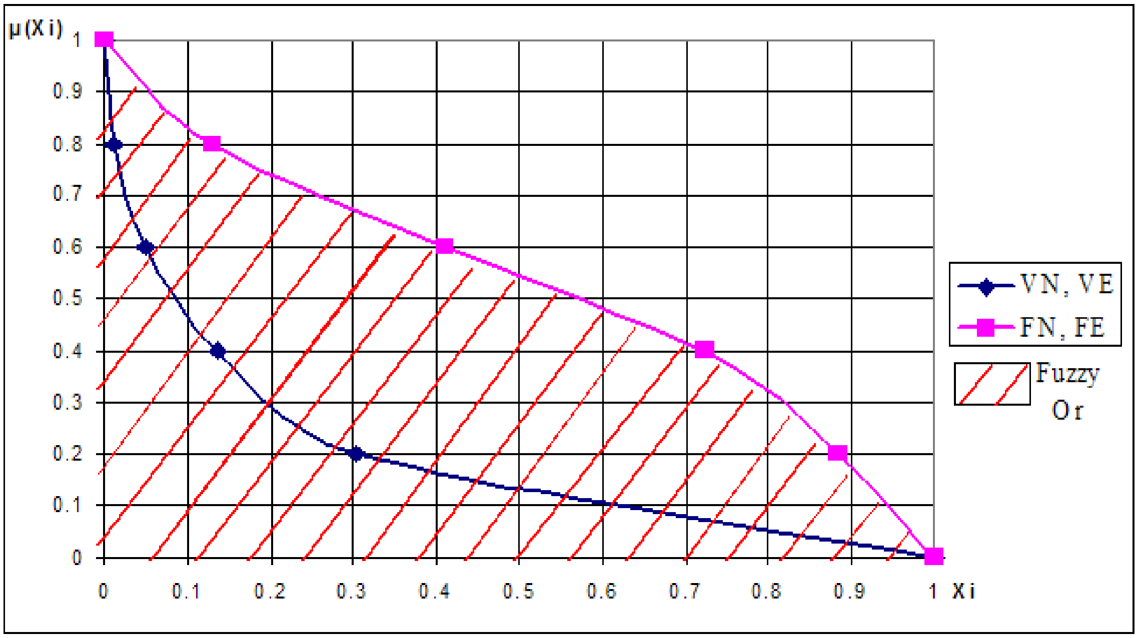


Figure 31. Fuzzy Union using Baldwin's Model.

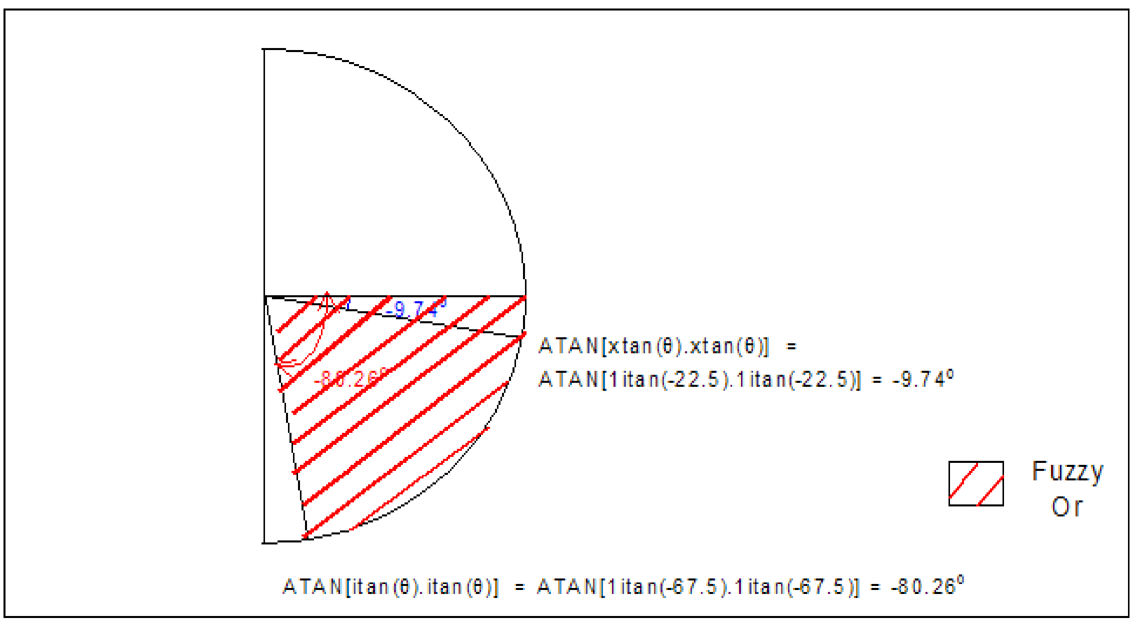


Figure 32. Fuzzy Intersection using Angular Model.

The weighted average or the fuzzy mean is captured using the weighted average equation:

$$(A\sim B)(x) = [w_a.A(x),\ w_b.B(x)];\ w_a + w_b = 1 \qquad [17]$$

Fuzzy mean can be applied to different causes of project delay using four different fuzzy logic models. If experts consider the average of different factors that contribute to project delay, a fuzzy mean operation is implemented to capture these different causes. Figure 33 provides implementation of fuzzy mean using the translational fuzzy logic model, Figure 34 provides implementation of fuzzy mean using the triangular fuzzy logic model, Figure 35 provides implementation of fuzzy mean using Baldwin's fuzzy logic model and Figure 36 provides implementation of fuzzy mean using angular fuzzy logic model.

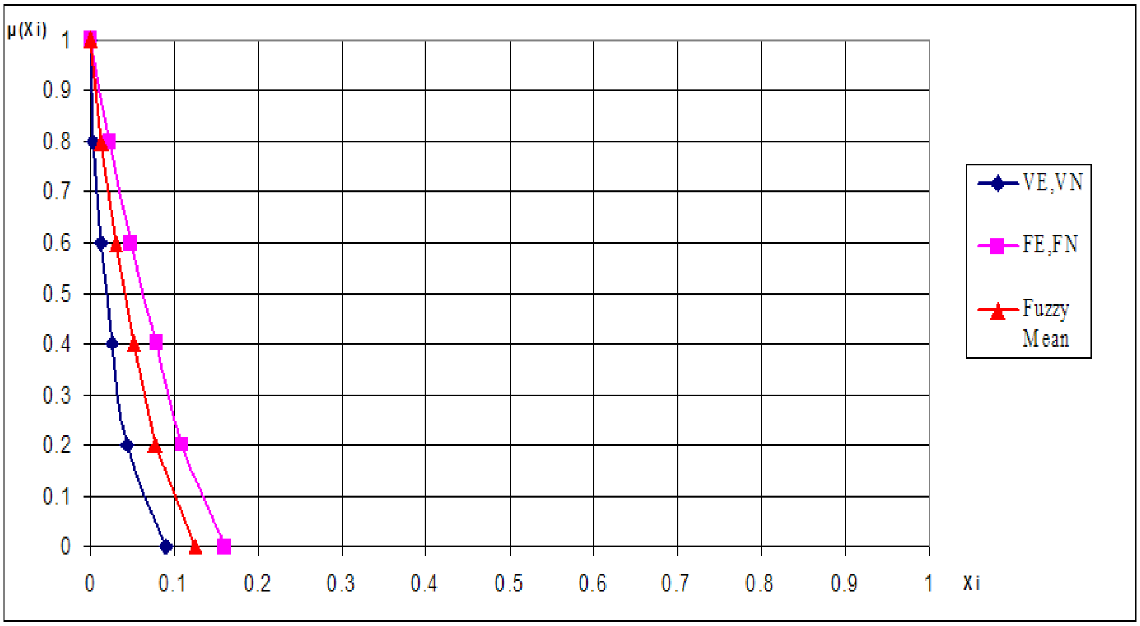


Figure 33. Fuzzy Mean of Translational Model.

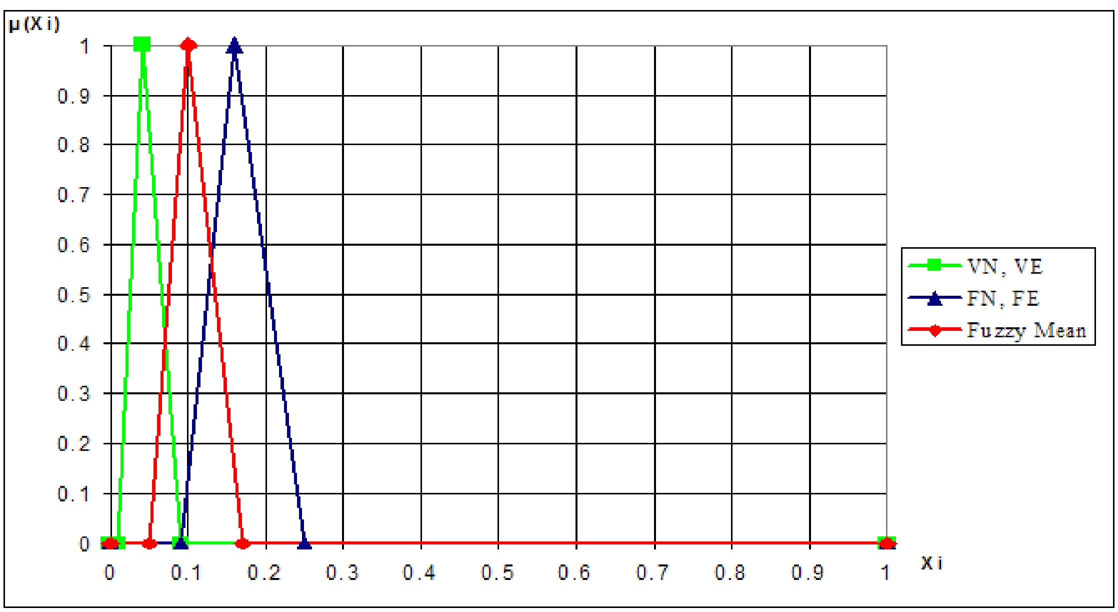


Figure 34. Fuzzy Mean of Triangular Model.

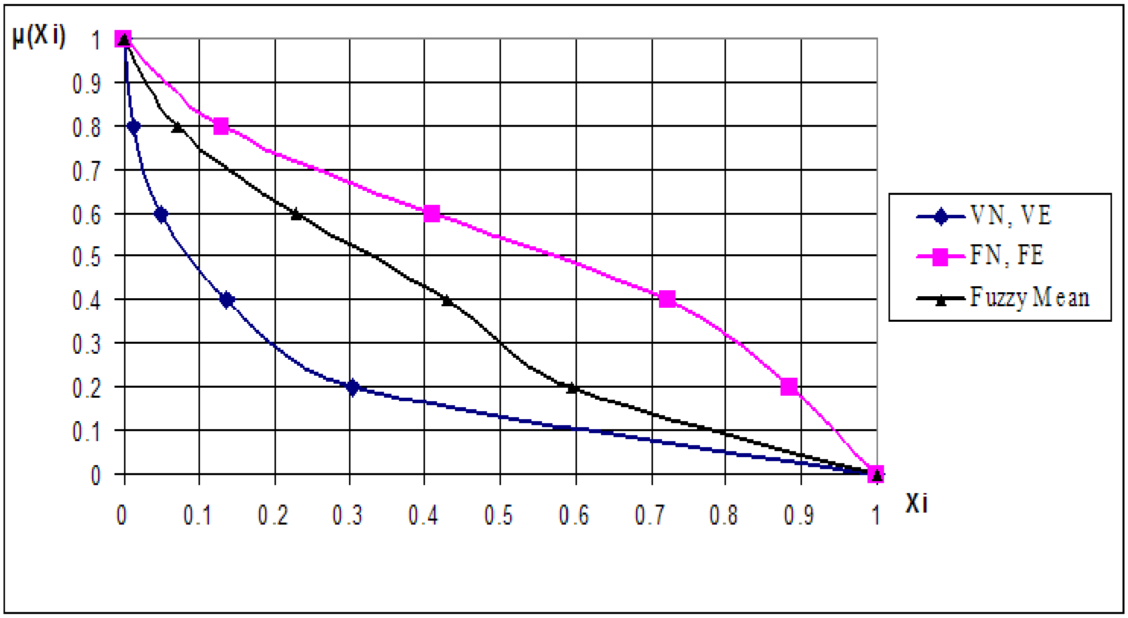


Figure 35. Fuzzy Mean of Baldwin's Model.

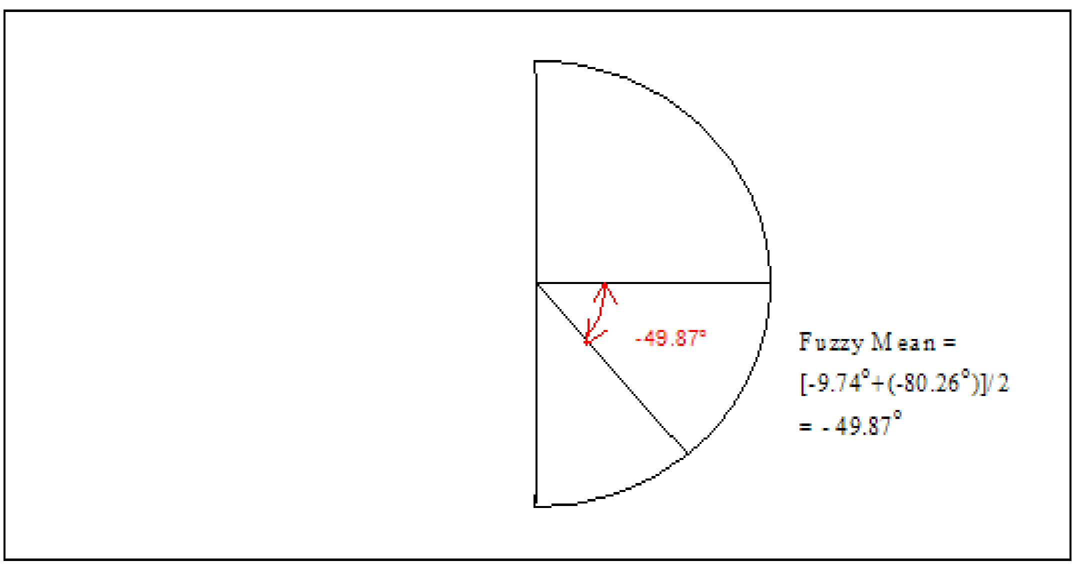


Figure 36. Fuzzy Mean of Angular Model.

3.2.2.8 Defuzzification

Transformation from a fuzzy set to a crisp number is called a defuzzification. It is not a unique operation as different approaches are possible. According to Hellendoorn and Thomas (1993) seven methods are proposed:

1. Max membership principle
2. Centroid method
3. Weighted average method
4. Mean max membership
5. Center of sum
6. Center of largest area
7. First (or last) of maxima

3.2.2.8.1 Max Membership Principle

The max membership principle method is limited to peaked output functions. The following expression represents the max membership principle.

$$\mu_c(x^*) \geq \mu_c(x) \text{ for all } x \in X \quad [18]$$

Where x^* is the defuzzification value. This principle is exemplified in Figure 37 in which the corresponding element for the maximum membership equals to 0.5.

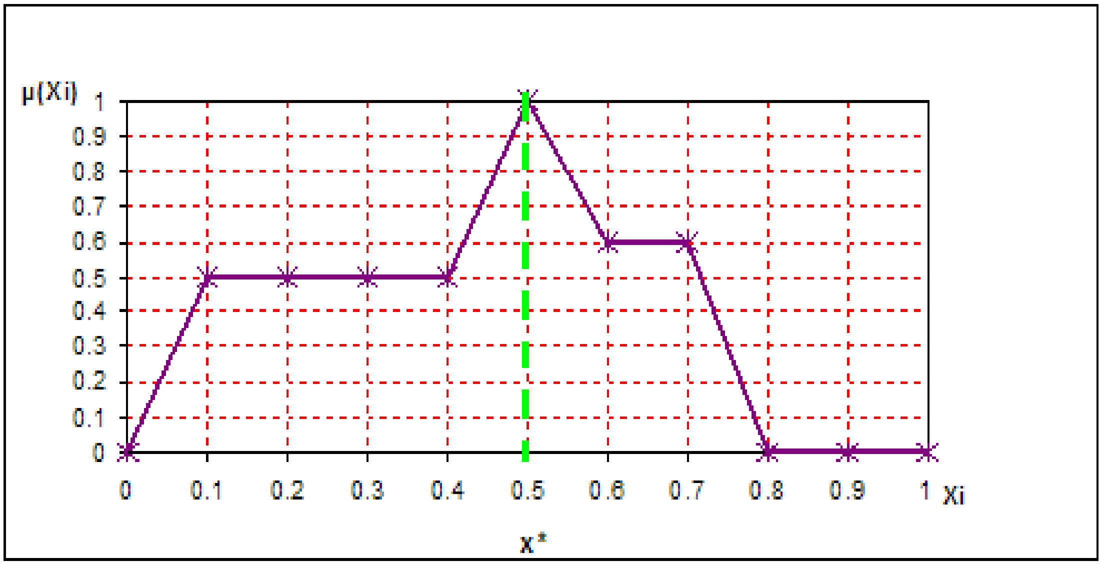


Figure 37. Max Membership Defuzzication Method.

3.2.2.8.2 Centroid Method

The centroid method or the center of gravity or the center of area is the most prevalent and physically appealing of all defuzzification methods Sugeno (1985), Lee (1990). The following expression represents the centroid method.

$$x^* = \int \mu_c(x).x\, dx \,/\, \int \mu_c(x)\, dx \qquad [19]$$

Where x^* is the defuzzification value. This principle is illustrated in Figure 38. Here the corresponding element for the centroid equals to 0.424.

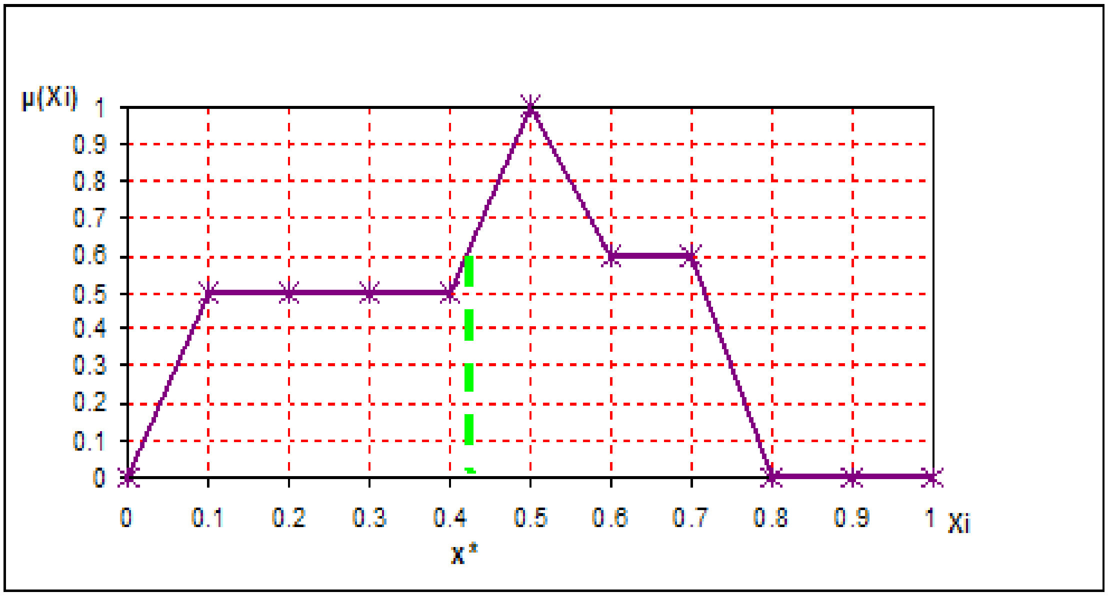


Figure 38. Centroid Defuzzification Method.

3.2.2.8.3 Weighted Average Method

The weighted average method is a defuzzification method that is most frequently used in fuzzy application due to its computational efficiently Ross (2004). The following expression represents the weighted average method.

$$x^* = \sum \mu_c(\bar{x}).x \ / \sum \mu_c(\bar{x}) \qquad [20]$$

Where x^* is the defuzzification value, $\bar{x}$ is the centroid of the contributing membership functions A, B, and C. The weighted average value is 0.463. This value is the average of membership functions A, B, and C shown in Figures 39, 40, and 41. Figure 42 shows the membership function of x* and the weighted average centroid value calculated.

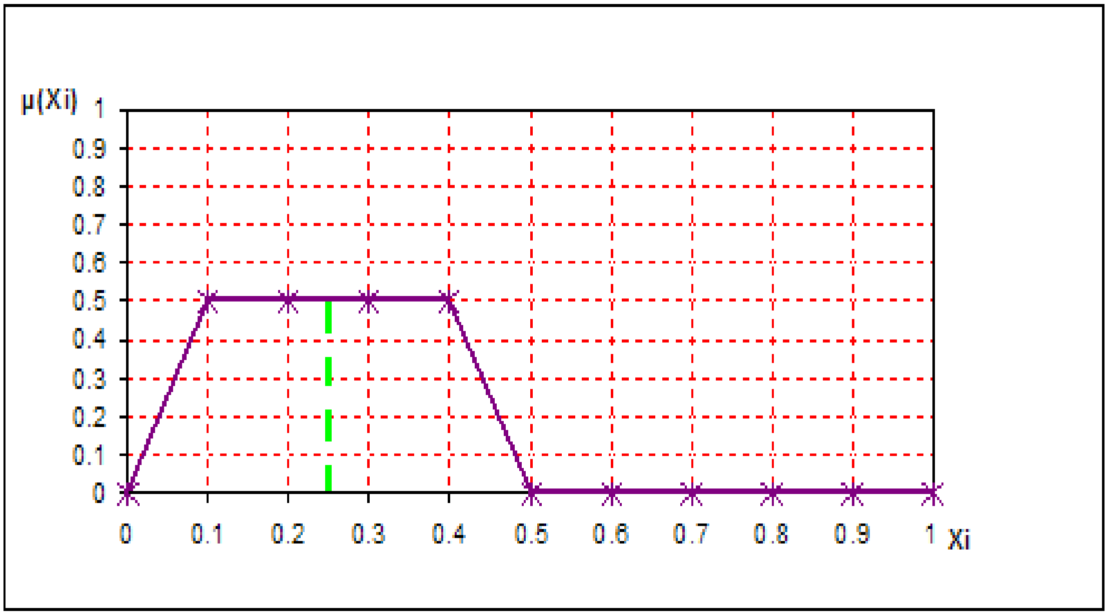


Figure 39. Membership Function A and the Corresponding Centroid.

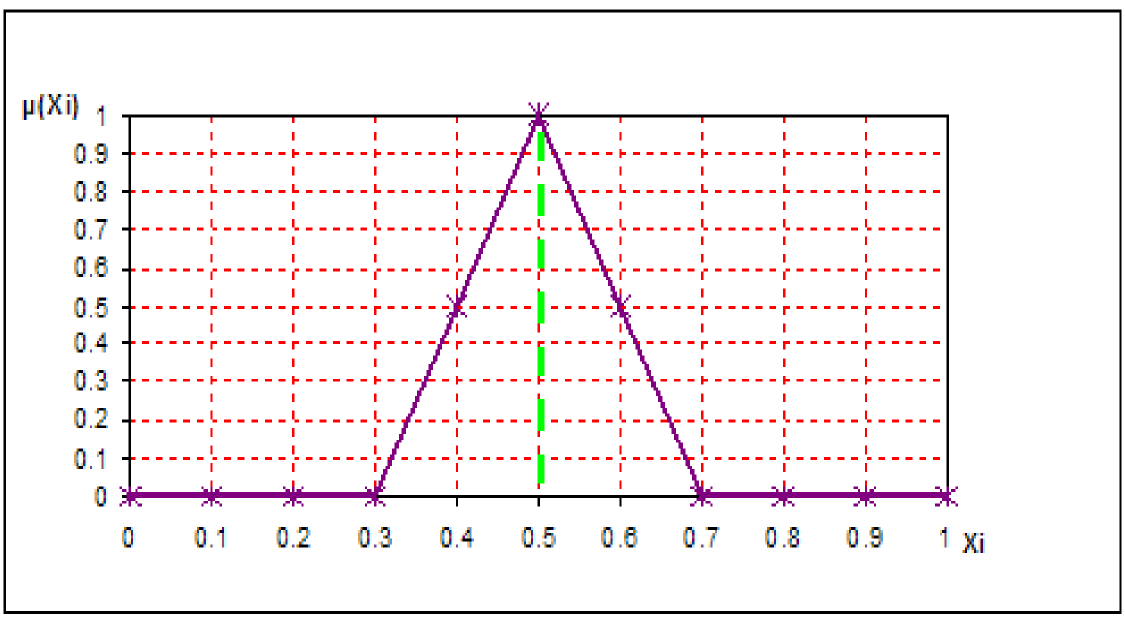


Figure 40. Membership Function B and the Corresponding Centroid.

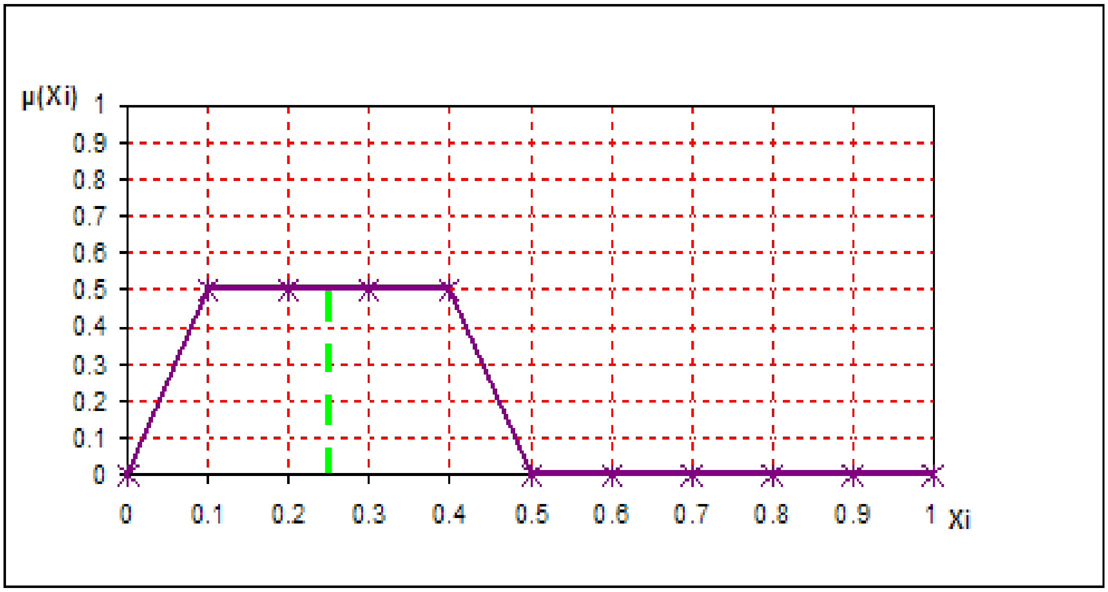


Figure 41. Membership Function C and the Corresponding Centroid.

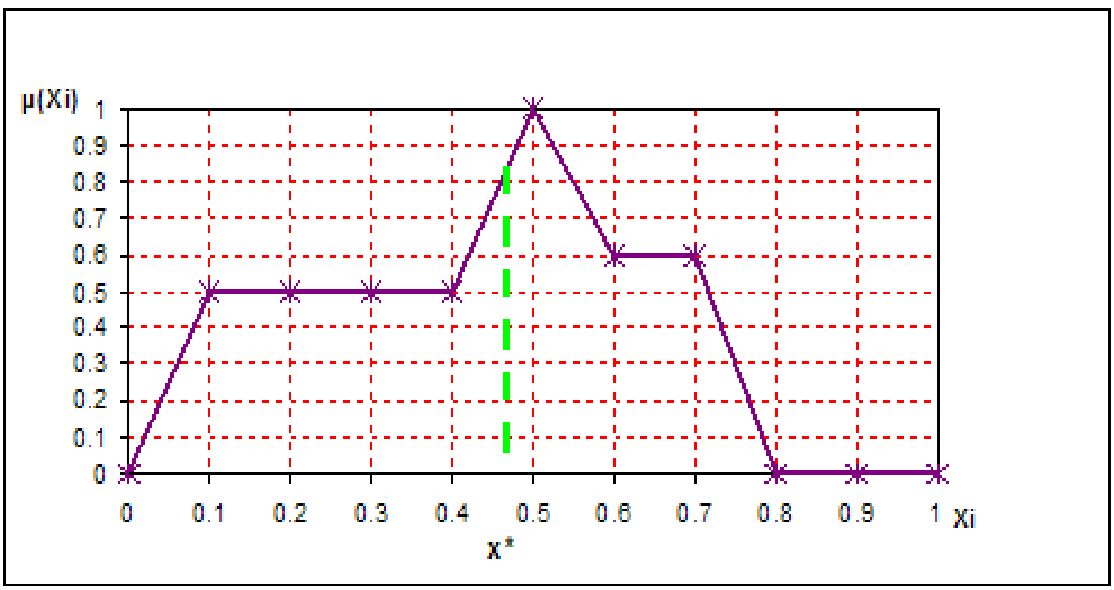


Figure 42. Weighted Average Method.

3.2.2.8.4 Mean Max Membership

In case the maximum membership is a plateau (instead of a single point), the mean of maximum membership function is calculated using the following equation Sugeno (1985), Lee (1990).

$$x^{*} = (a + b) / 2 \qquad [21]$$

Where x^{*} is the defuzzification value. The mean max membership method is represented in Figure 43 where a and b are shown.

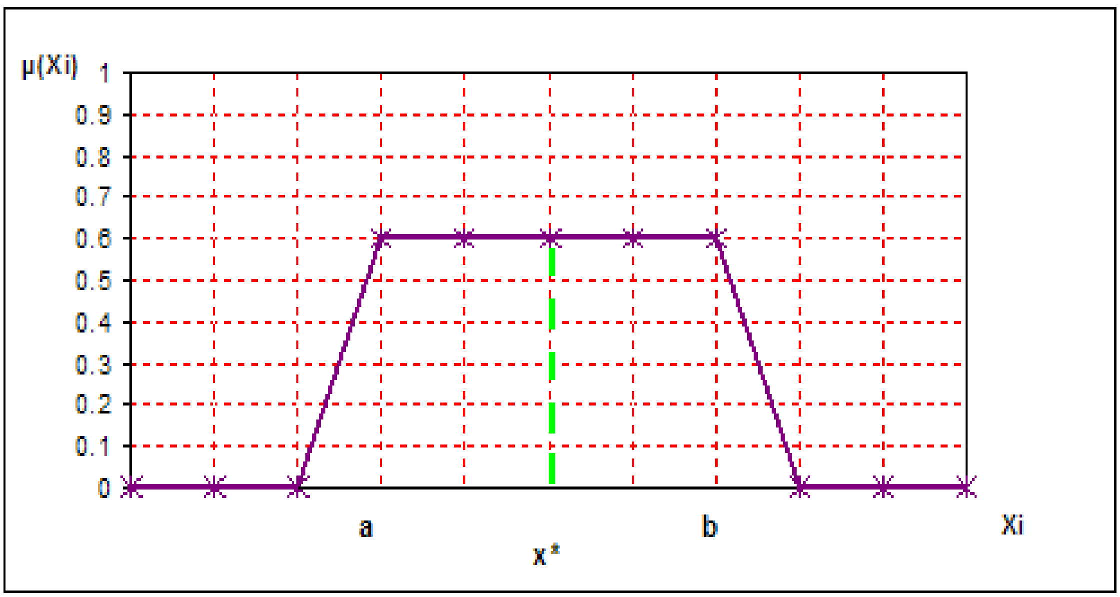


Figure 43. Mean Max Defuzzification Method.

3.2.2.8.5 Center of Sums

In the center of sums method, the contribution of the area of each fuzzy set individually is considered. Mathematically, the center-of-gravity takes the union of the fuzzy sets, however, the center of sums takes the sum of the fuzzy sets Ross (2004). The defuzzification value is calculated based on the following equation:

$$x^* = \int_x \sum \mu_c(x).x \, dx \, / \int \mu_c(x) \, dx \qquad [22]$$

Where x^* is the defuzzification value. The corresponding element for the center of sums equals to 0.4. This value is the average of membership functions A, B, and C shown in Figures 44, 45, and 46. The center of sums principle is depicted in Figure 47.

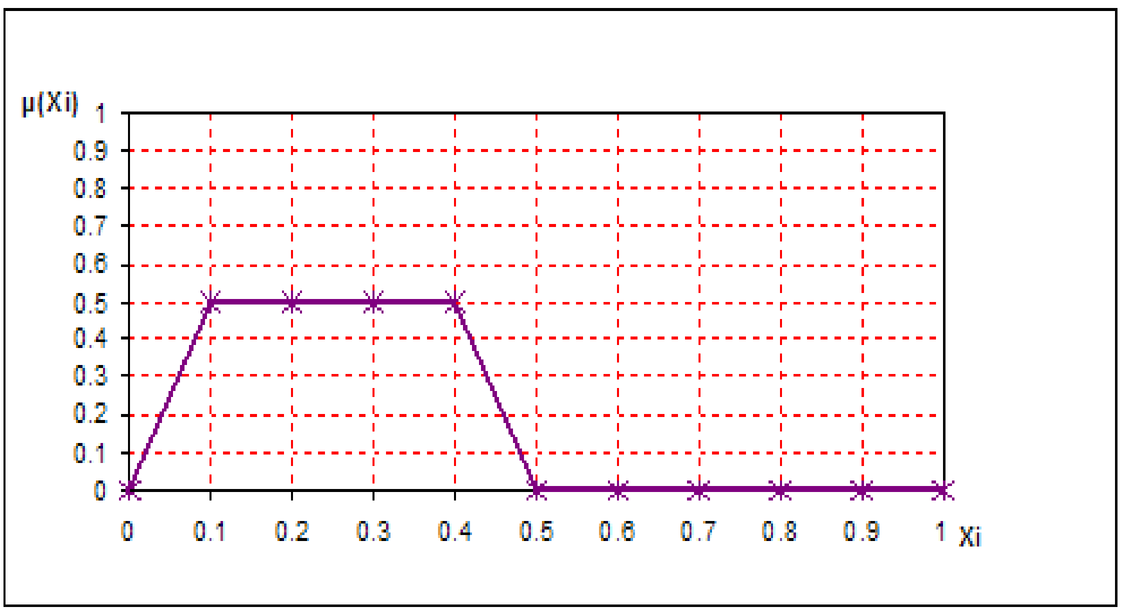


Figure 44. Membership Function A.

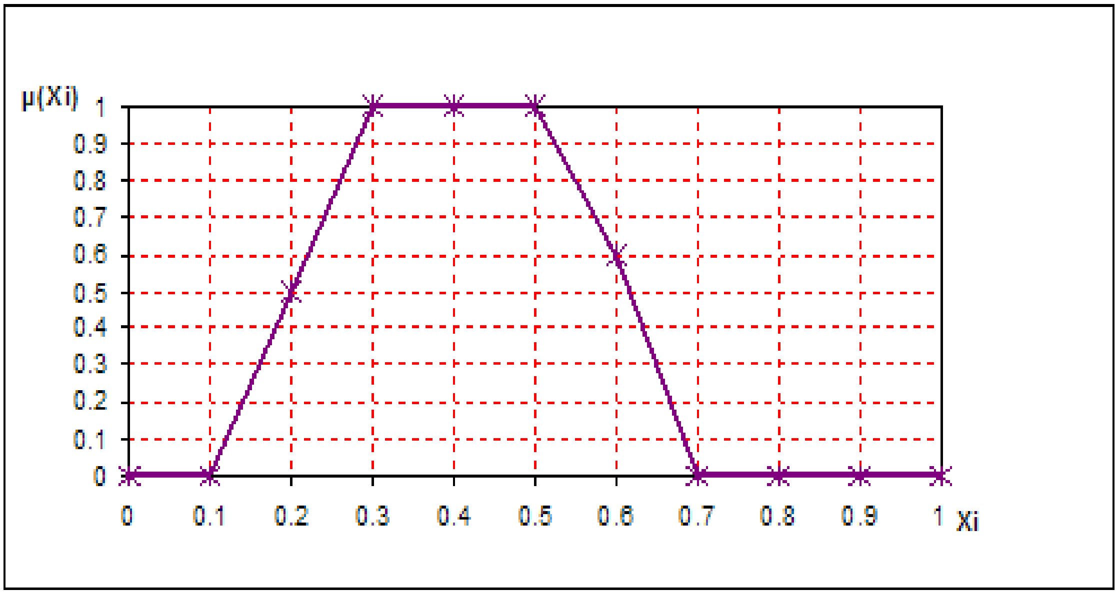


Figure 45. Membership Function B.

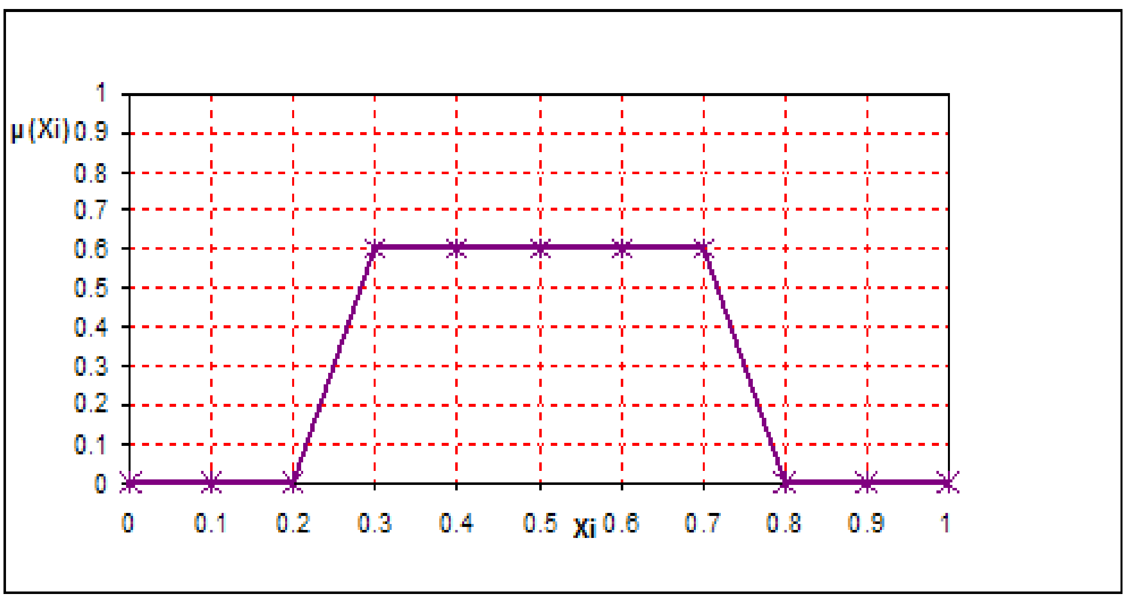


Figure 46. Membership Function C.

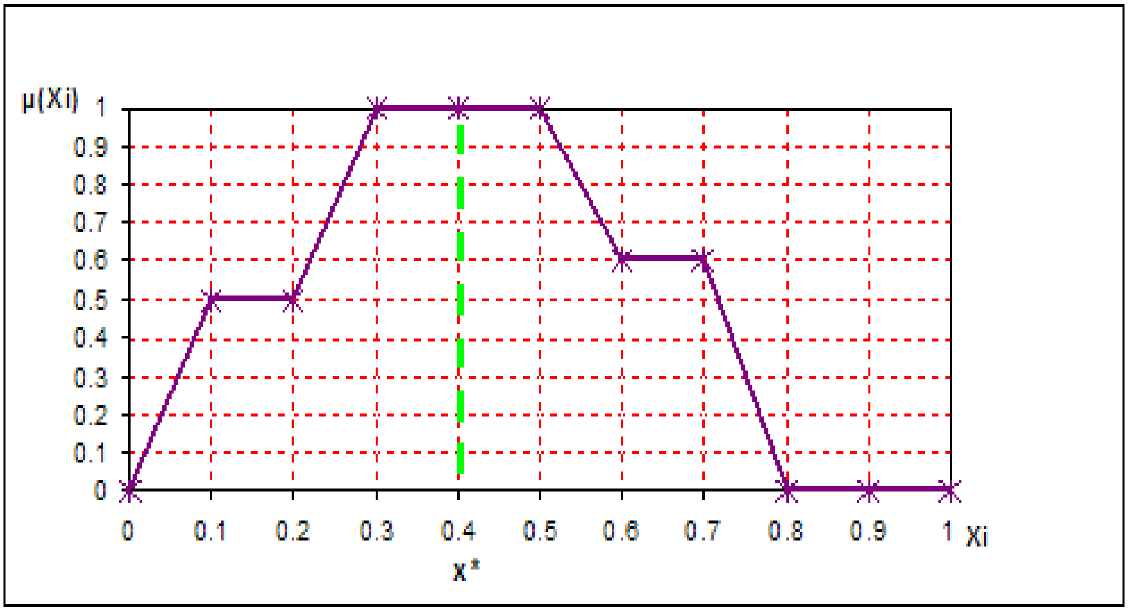


Figure 47. Center of Sums Defuzzification Method.

3.2.2.8.6 Center of Largest Area

In case the fuzzy set has two convex subregions, or more. The defuzzification value is calculated using the centroid method for the largest convex subregion. The result is shown graphically in Figure 48. The defuzzification value is calculated based on the centroid Equation 19, which yields 0.424.

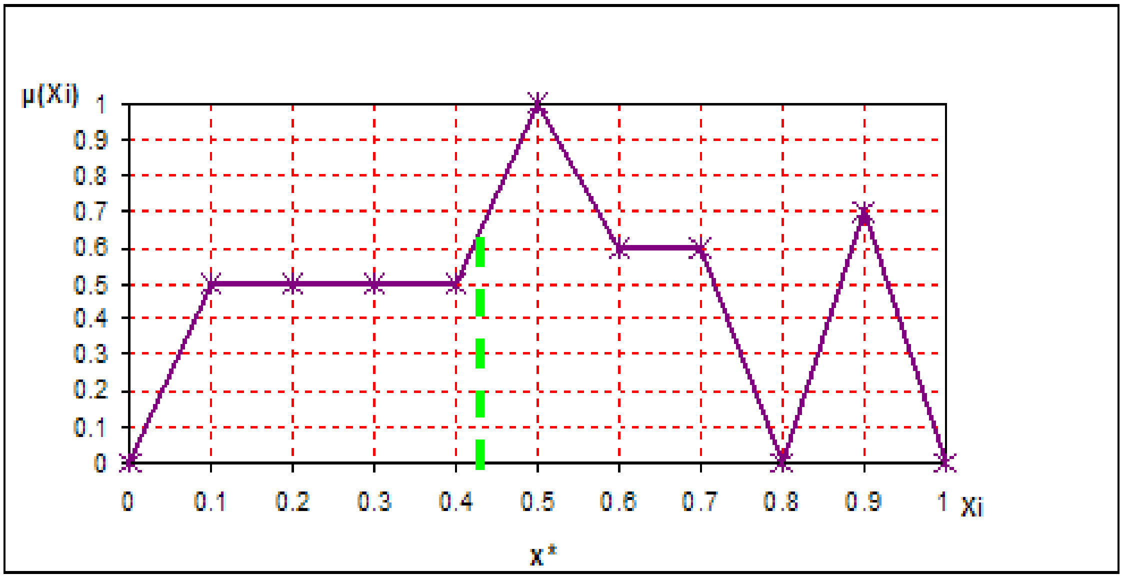


Figure 48. Center of Largest Area Defuzzification Method.

3.2.2.8.7 First (or Last) of Maxima

This method uses the union of the fuzzy sets and takes the smallest value of the domain with maximal membership degree for the first of maxima. In the last of maxima method, the union of the fuzzy sets is calculated and the largest value of the domain with maximal membership degree is calculated. Figures 49, and 50 show the first of maxima and the last of maxima methods.

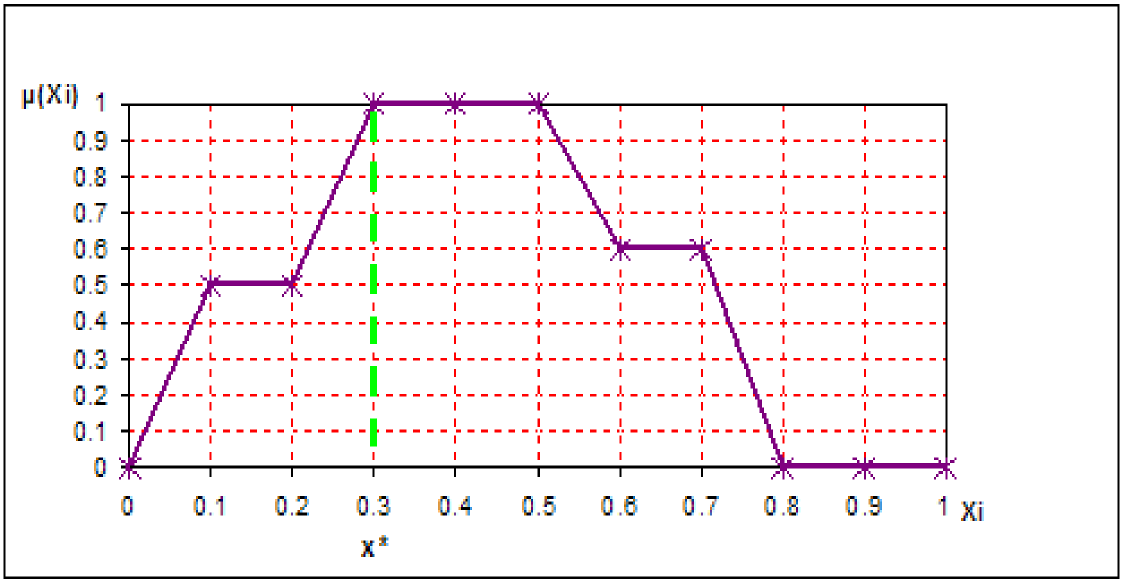


Figure 49. First of Maxima Defuzzification Method.

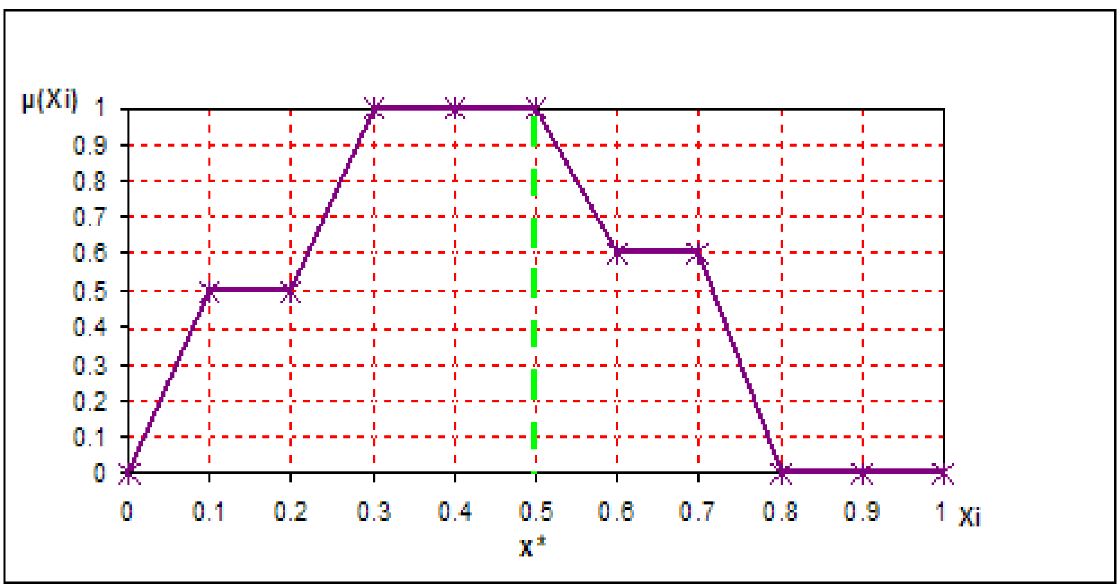


Figure 50. Last of Maxima Defuzzification Method.

In order to select a method among the seven different methods, Hellendoorn and Thomas (1993) identified five criteria to select a method. These criteria are continuity, disambiguity, plausibility, computational simplicity and the weighting method. Continuity means that the method should be consistent and small changes made to the input should not result in dramatic changes in the output. Disambiguity refers to that the defuzzification method should always result in a unique value. In the center of largest area method, changes take place only if the largest area is no longer the largest among the subareas. Plausibility refers to that the defuzzification method is supposed to be in the middle of the domain and the defuzzification value should have a high degree of membership. In the centoid method, plausibility criteria is not present since the centroid method is concerned with the value that divides the area under the membership function into two equal areas. Computational simplicity refers to how simple the method is. Among the different defuzzification methods, max membership principle, mean max membership, and the first of maxima method are computationally simple. The fifth criteria in selecting a defuzzification method is the weighting method. In both the centroid method and the weighted average methods, the weights are individual membership values. In the center of sums method, the weights are the areas of the respective membership functions.

Among the different defuzzification methods, the weighted average method is selected as a defuzzification method that is used in this research. This selection is due to the fact that different fuzzy logic models are implemented to model project delay. Among these different models, there is a need to implement a method that is applicable to the for different fuzzy logic models. The methods that are based on the maximum membership values (max membership principle, mean max membership, first and last of maxima) are excluded due to the fact that in the triangular fuzzy logic model, equal triangles do not produce a membership function with maximum area. The center of largest are is excluded due to the fact that this method is restricted to outputs of membership functions with a minimum of two convex subregions. For simplicity and due to the fact that the weighted average method is the most widely used Ross (2004) we would implement the weighted average method.

Figure 51 provides weighted average method calculated using fuzzy AND for the translational fuzzy logic model. Figure 52 provides weighted average method calculated using fuzzy OR for the translational fuzzy logic model. Figure 53 provides weighted average method calculated using fuzzy MEAN for the translational fuzzy logic model. Figure 54 provides weighted average method calculated using fuzzy AND for the triangular fuzzy logic model. Figure 55 provides weighted average method calculated using fuzzy OR for the triangular fuzzy logic model. Figure 56 provides the weighted average method calculated using fuzzy MEAN for the triangular fuzzy logic model. Figure 57 provides weighted average method calculated using fuzzy AND for the Baldwin's fuzzy logic model. Figure 58 provides weighted average method calculated using fuzzy OR for the Baldwin's fuzzy logic model. Figure 59 provides the weighted average method calculated using fuzzy MEAN for Baldwin's fuzzy logic model.

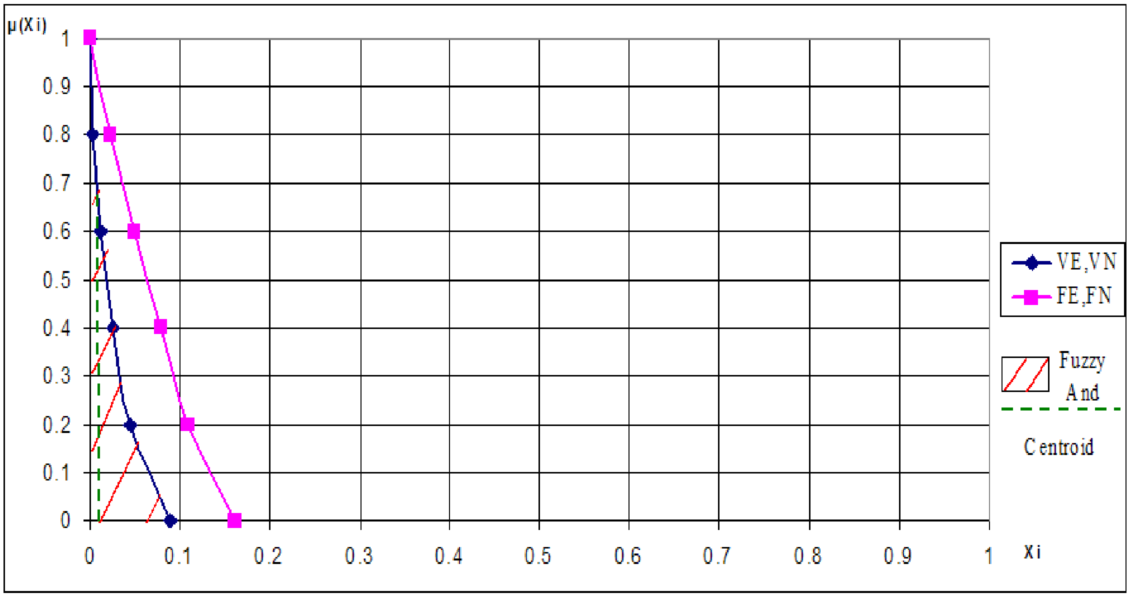


Figure 51. Weighted Average Calculated using Fuzzy AND for the Translational Model.

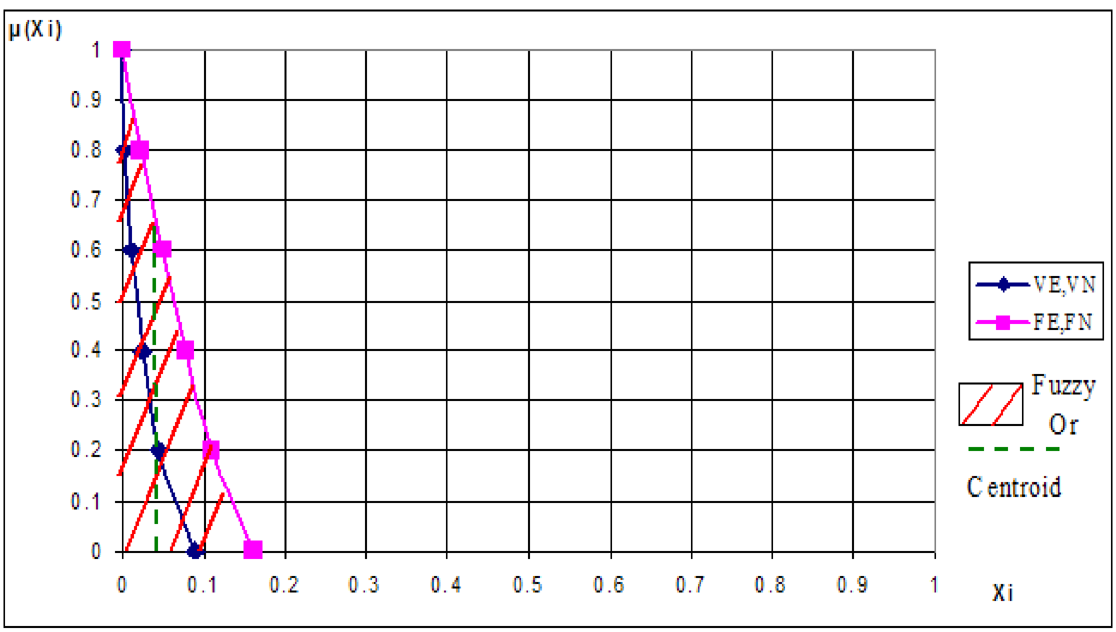


Figure 52. Weighted Average Calculated using Fuzzy OR for the Translational Model.

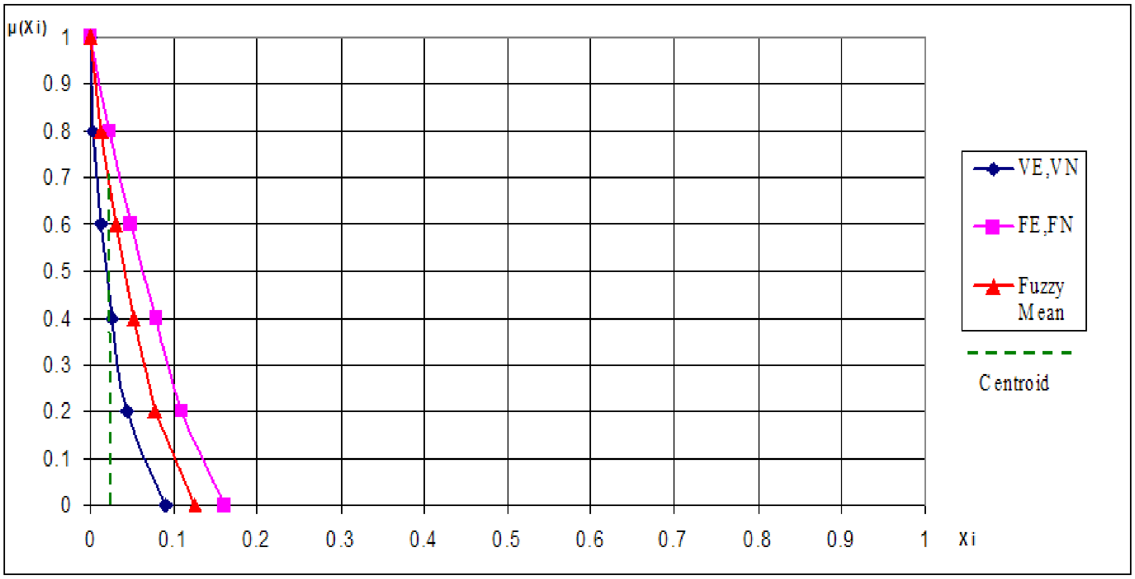


Figure 53. Weighted Average Calculated using Fuzzy Mean for Translational Model.

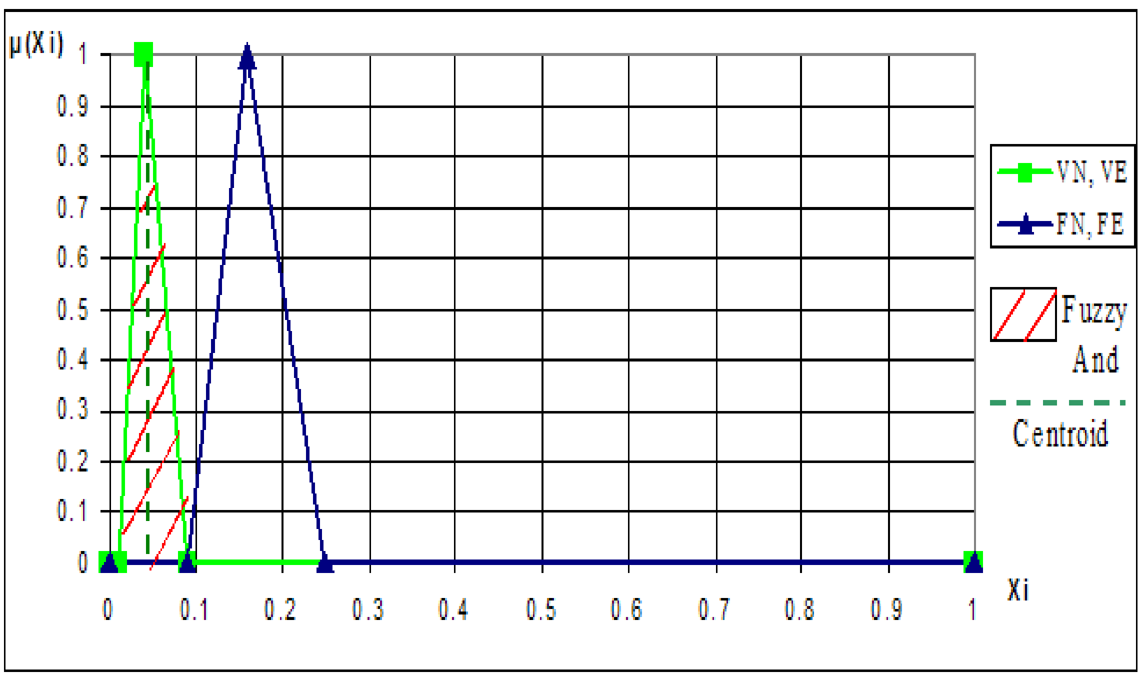


Figure 54. Weighted Average Calculated using Fuzzy AND for the Triangular Model.

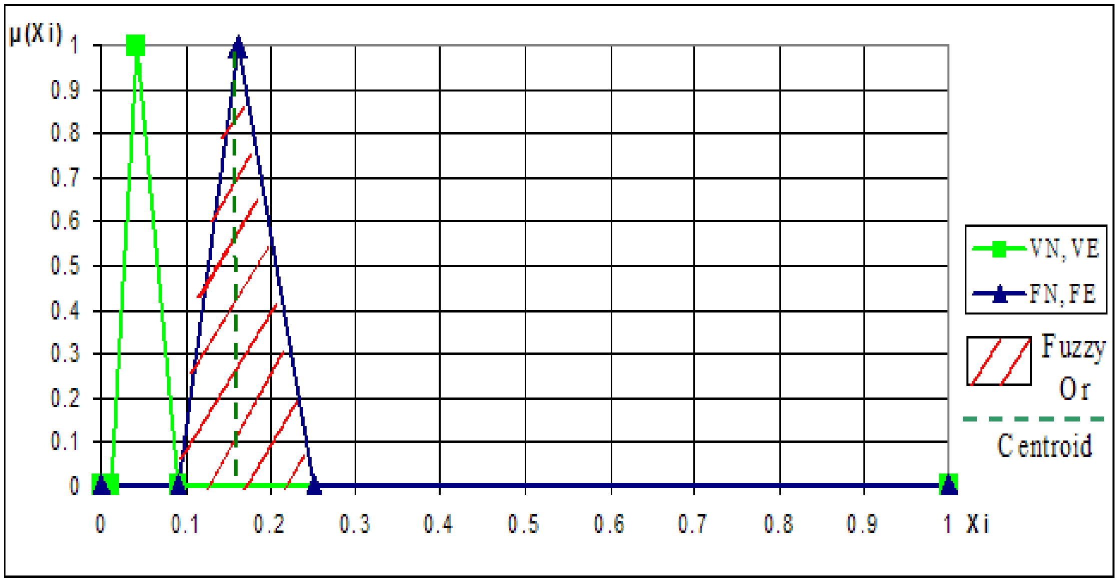


Figure 55. Weighted Average Calculated using Fuzzy OR for the Triangular Model.

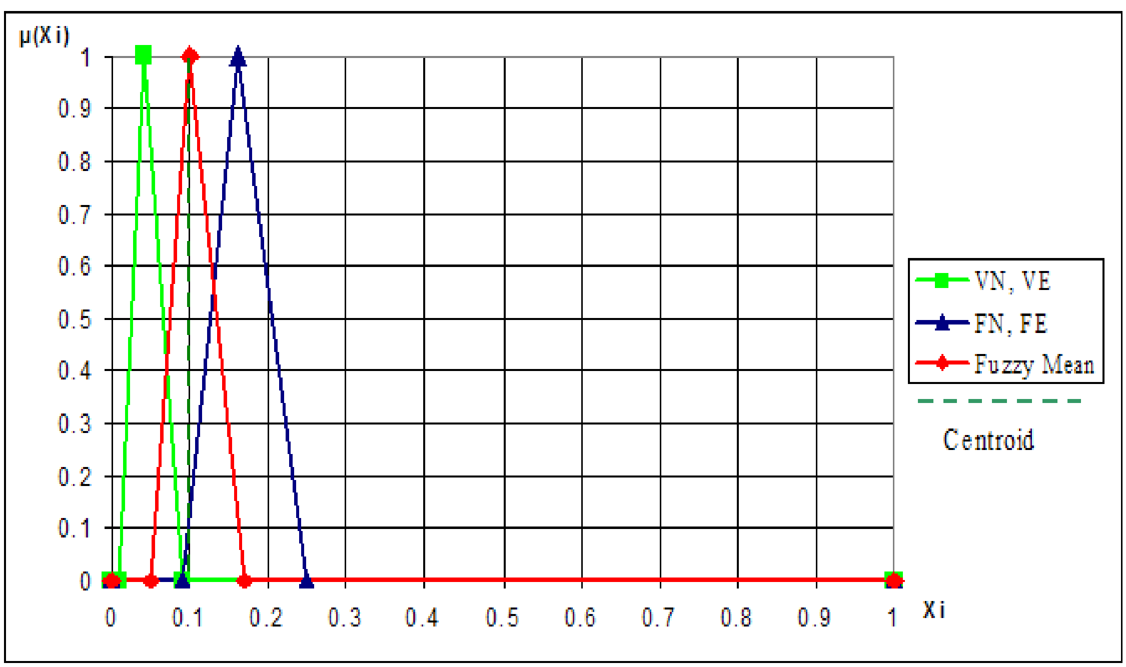


Figure 56. Weighted Average Calculated using Fuzzy Mean for the Triangular Model.

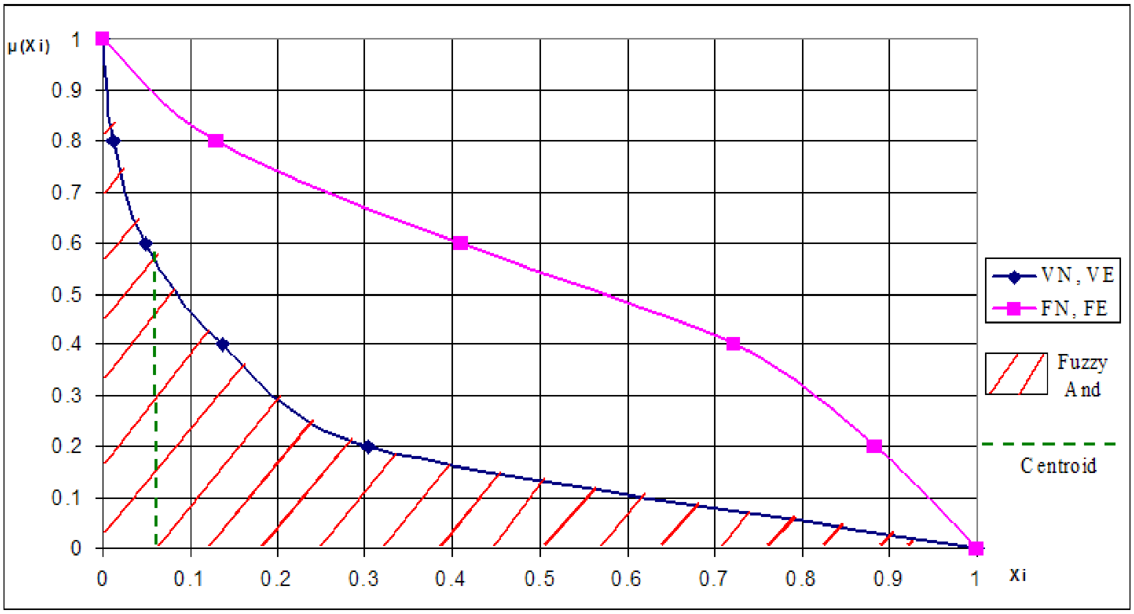


Figure 57. Weighted Average Calculated using Fuzzy AND for Baldwin's Model.

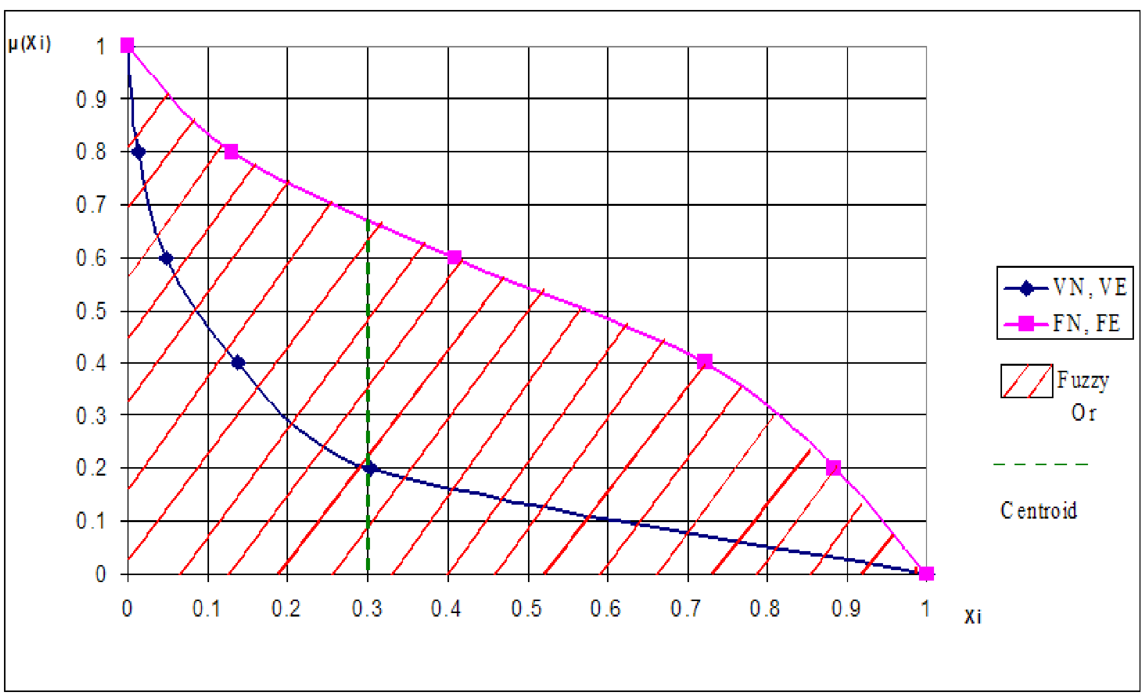


Figure 58. Weighted Average Calculated using Fuzzy OR for Baldwin's Model.

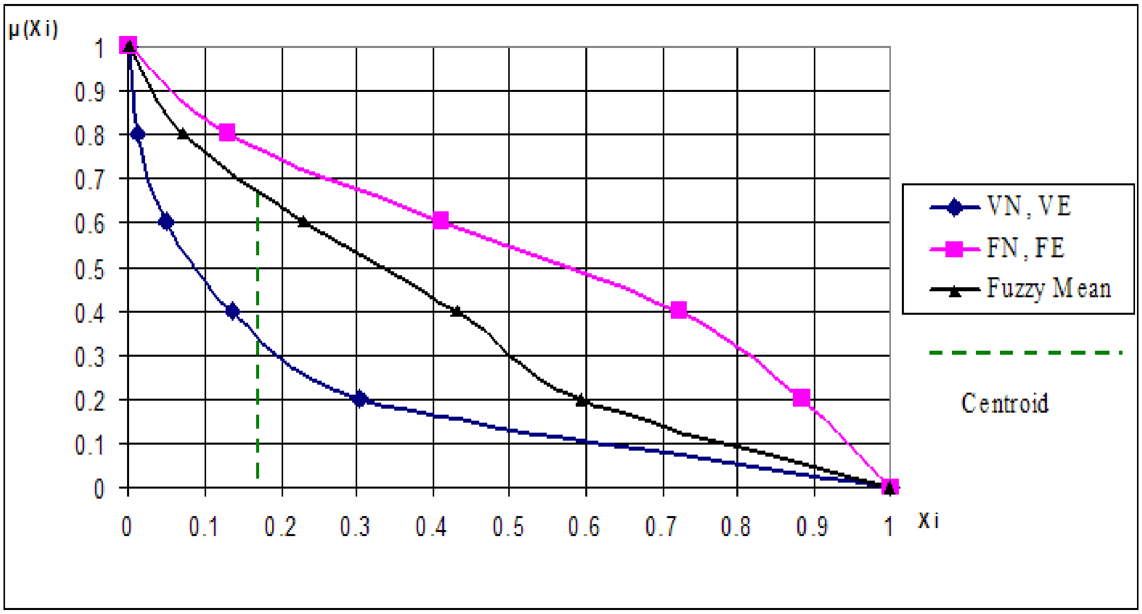


Figure 59. Weighted Average Calculated using Fuzzy Mean for Baldwin's Model.

Chapter 4

PROJECT DELAY ANALYSIS USING PROBABILISTIC FAULT TREE ANALYSIS

4.1 Introduction

A probabilistic approach can be implemented to analyze delays using the probabilistic fault tree analysis. Fault tree analysis involves specifying a top event to analyze project delay, followed by identifying all of the associated elements in the system that could cause the top event to occur. Fault trees provide a convenient representation of the combination of events resulting in the occurrence of the top undesired event.

Fault tree analyses are generally performed graphically using a logical structure of AND, OR, and INHIBIT gates. Basic events may occur together in order for that top event to occur. In this case, these events would be arranged under an AND gate, meaning that all of the basic events would need to occur to trigger the top event. If the basic events would trigger the top undesired event by the occurrence of this basic event alone, then basic events would be grouped under an OR gate. If the basic event (event A) triggers the top undesired event if the occurrence of the event is conditioned on the occurrence of another event a conditional failure occurs. In such conditional occurrence of events, an INHIBIT gate is used.

Fault trees are a deductive method that can analyze an unfavorable outcome using conditional probability theory. Probabilities are assigned to the fault tree branches and branches with the highest probability of occurrence are managed to control the probability of occurrence.

4.2 Probabilistic Fault Tree Analysis Gates

Basic events can be linked together using three different gates. These gates are the AND gate, the OR gate, and the INHIBIT gate. In the AND gate, the top undesired event occurs if and only if all basic events occur. For example, if a triggering event and an enabling event and a procedural event all need to occur simultaneously for a project delay to occur, the AND gate is used as a logical structure to link the three basic events as shown in Figure 60. The probability of project delay to occur is the probability of the top undesired event. In this research, the event tree is used for planning purposes, instead of for diagnostic; hence, the assumption is that project delay has not yet occurred (planners do not know the outcome of the top event). Under the assumption that all events are statistically independent, the probability of the top undesired event can be calculated as follows:

$$P(Top) = P(A) \cap P(B) \cap P(C) = P(A).P(B).P(C) \quad [23]$$

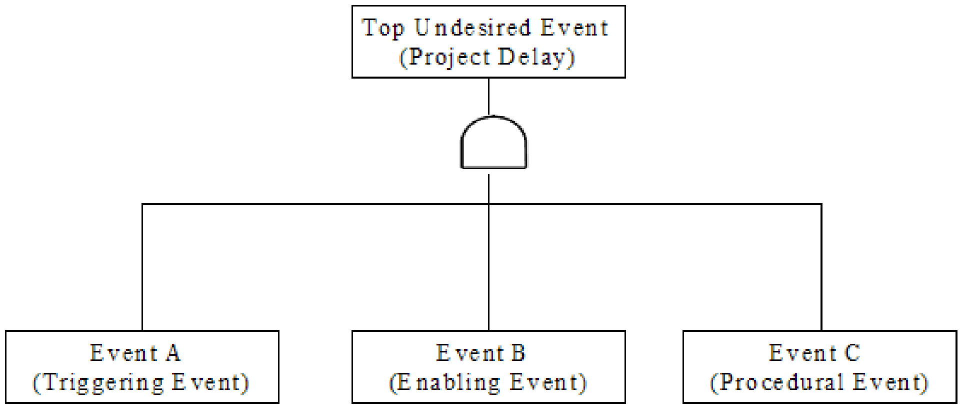


Figure 60. Basic Events Linked using the AND Gate.

If the occurrences of project delay takes place when the triggering event or the enabling event or the procedural event occur, i,e. the project is delayed if at least one of the basic events occurs, the OR gate is used as a logical structure to link the three basic events as shown in Figure 61. The probability of project delay is the probability of the top undesired event. Under the assumption that all events are statistically independent, the probability of the top undesired event (project delay) can be calculated as follows:

$$P(Top) = P(A) \cup P(B) \cup P(C)$$

$$= P(A)+P(B)+P(C)-P(A \cap B)-P(A \cap C)-P(B \cap C)+P(A \cap B \cap C) \quad [24]$$

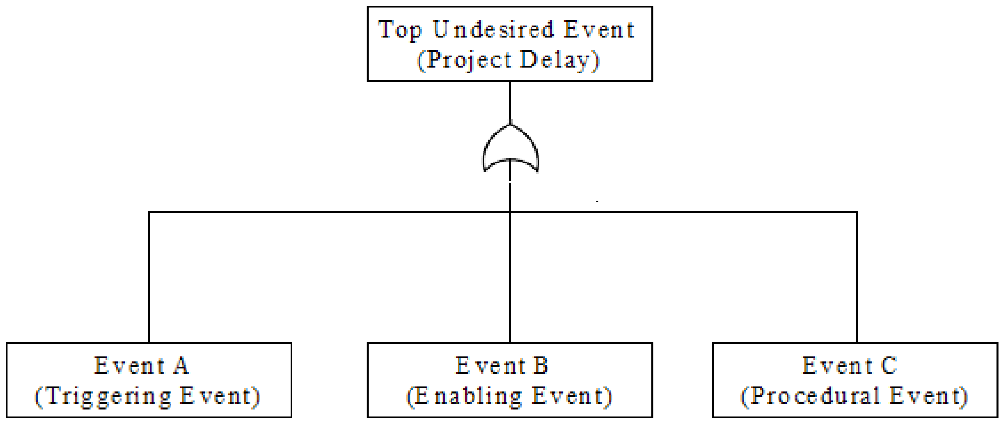


Figure 61. Basic Events Linked using the OR Gate.

If a basic event trigger the top undesired event (project delay) if the occurrence of the basic event is conditioned on the occurrence of another event, a conditional failure occurs. In such conditional occurrence of events, an INHIBIT gate is used. In case an INHIBIT gate is used to link basic events, the top undesired event occurs if all basic events occur and an additional conditional event occurs. The INHIBIT gate logical structure is represented in Figure 62. Under the assumption that all events are statistically independent, the probability of the top undesired even project delay is calculated as follows:

$$P(Top) = \quad P(A) \cdot P(B/A) \qquad [25]$$

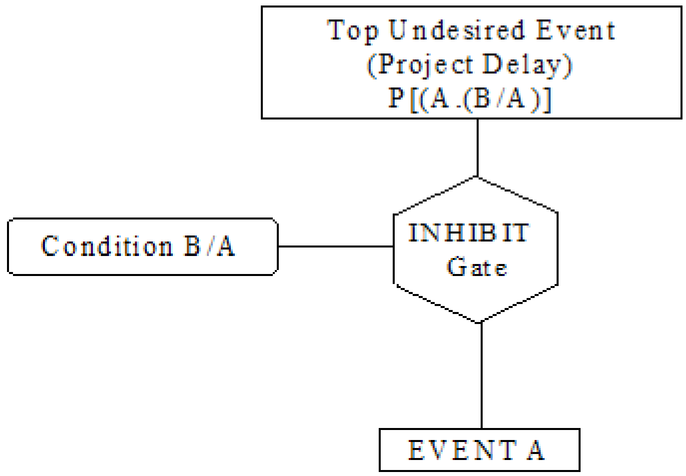


Figure 62. Basic Events Linked using the INHIBIT Gate.

4.3 Probabilistic Fault Tree Analysis Model

In general, causes of delay are classified into three categories, procedural, triggering, and enabling. The likelihood of project delay is the top undesired event whose occurrence probability is calculated using a probabilistic value. In the probabilistic fault tree analysis model, different factors that contribute to project delay are assumed to be independent. The degree of effectiveness each factor has on the overall likelihood of project delay is quantified using a probabilistic value that range between 0 and 1. Triggering delay causes are further divided into weather conditions, unforeseen conditions and natural disasters. Triggering delay causes are further classified into material related causes, worker related causes and equipment related causes. Procedural delay causes are further divided into managerial causes, legal causes, financial causes and operational causes.

Each cause of delay affects the overall project delay with a certain degree of effectiveness. If, for example, weather conditions are expected to be bad and the probability of bad weather conditions (usually probability of rain) can be determined from historical data, this factor is conditioned on the degree of effectiveness of the bad weather condition on overall project delay. If, for example, work is undertaken in a closed environment, weather in such case is conditioned on the effectiveness of weather on overall project delay and this factor is not considered in the analysis. An INHIBIT gate is used to condition each factor on the effectiveness of the factor on the project delay. Two gates are implemented to link basic events, these events are the AND gate and the OR gate. Figure 63 and Table 3 show the logic implemented in constructing the probabilistic fault tree analysis.

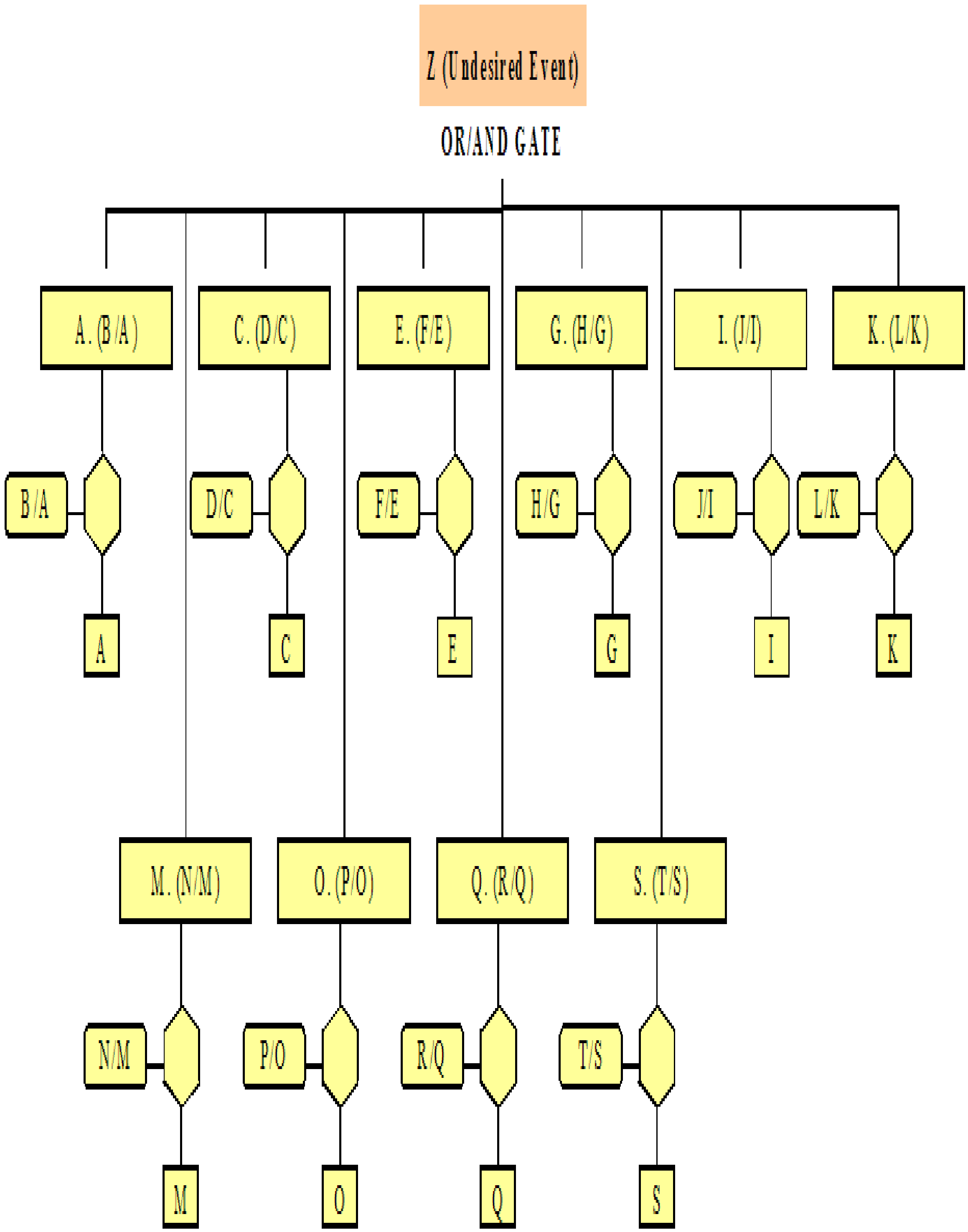


Figure 63. Probabilistic Fault Tree Logic.

SYMBOL	DESCRIPTION
A	Weather Condition
C	Unforseen Condition
E	Natural Disaster
G	Material Causes
I	Worker Related Causes
K	Equipment Related Causes
M	Managerial Causes
O	Legal Causes
Q	Financial Causes
S	Operational Causes
B/A	Effectiveness of Weather Condition on Project Delay
D/C	Effectiveness of Unforseen Condition on Project Delay
F/E	Effectiveness of Natural Disaster on Project Delay
H/G	Effectiveness of Material Causes on Project Delay
J/I	Effectiveness of Worker Related Causes on Project Delay
L/K	Effectiveness of Equipment Related Causes on Project Delay
N/M	Effectiveness of Managerial Causes on Project Delay
P/O	Effectiveness of Legal Causes on Project Delay
R/Q	Effectiveness of Financial Causes on Project Delay
T/S	Effectiveness of Operational Causes on Project Delay

Table 3. Probabilistic Fault Tree Legend.

A computer model of probabilistic fault tree analysis has been constructed using Visual Basic. The computer model calculates the probability of the top undesired event (project delay) as a result of different factors. Triggering, enabling and procedural factors have been implemented to quantify the likelihood of the top undesired event (project delay). Two logical gates (AND and OR gates) have been implemented to link the basic events of project delay. Figures 64 and 65 show the probabilistic fault tree computer model using the two logical gates (the AND and the OR gates).

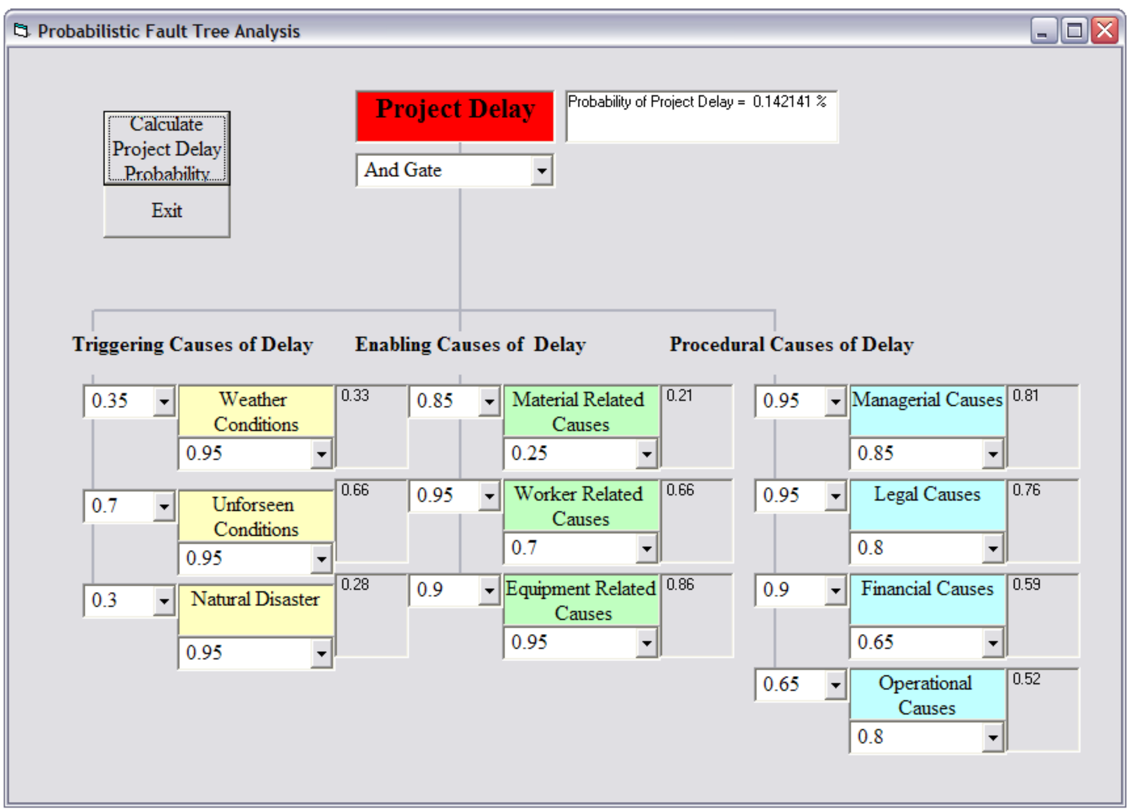


Figure 64. Probabilistic Fault Tree using AND Gate.

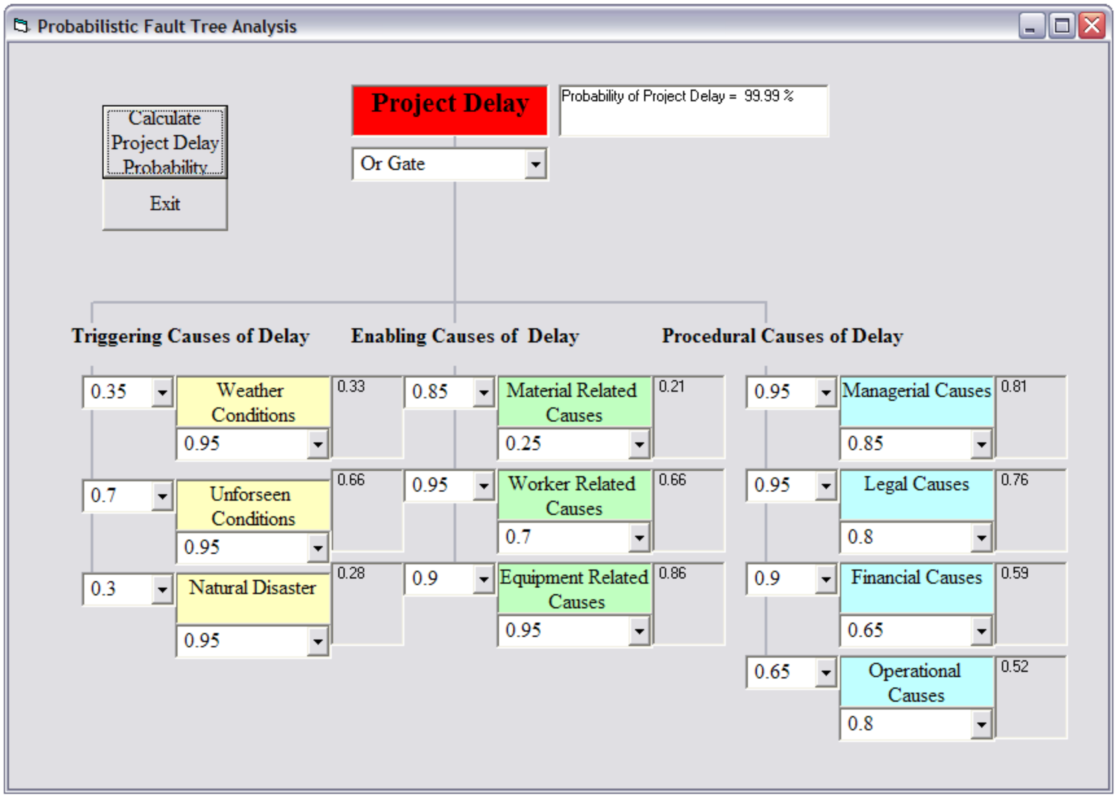


Figure 65. Probabilistic Fault Tree using OR Gate.

Implementation of a probabilistic approach to model project delay is questionable due to many reasons. First, the probabilistic fault tree analysis is based on historical data and one might argue that construction projects are different from one another and because they are performed in an open system where an uncontrollable environment comes into play. Second, the assumption in building the probabilistic fault tree is that all basic events are independent. Different factors that contribute to project delay are in fact statistically dependent; for example, weather condition can affect other factors performance such as productivity of workers and availability of material. Such correlation is routinely neglected in probabilistic fault tree analysis. Furthermore, at construction sites, probabilistic values are often expressed in linguistic terms, such as *likely*, *unlikely*, etc. These expressions are important yet difficult to define quantitatively. Discussion of a method of delay analysis more suited to construction facilities is presented in the following chapters.

Chapter 5

FUZZY MODELS

5.1 Introduction

Fuzzy sets can be employed to transform linguistic expressions such as *unlikely*, *likely* and *very likely* into quantitative terms. Fuzzy set analysis has been widely used in the civil engineering area Blockley (1980), Hadipriono (1985). Notwithstanding this use, its application in the area of project delay due to different causes is still limited. Different causes of delay are usually measured quantitatively and qualitatively. Quantitative measurements of causes of delay are related to direct measurements of the cause condition. For example, material availability can be measured quantitatively using planned schedule, earned value techniques and planning requirements of material logs and associated management information systems which provide direct measurements of material availability on site. In construction, specifications and standards can provide the basis for quantitative measurements of performance. Historical data about the material availability time requirement of past empirical and analytical measurements is the basis for obtaining quantitative measurements of material availability.

On the other hand, qualitative measurements of different causes of delay can be expressed in linguistic terms. Contract documents, such as specifications, contain qualitative expressions that are described linguistically. Additionally, quality control measurements during construction are usually expressed in linguistic terms. For example, it would be imprudent for a manager to precisely estimate the time needed for a specific material to be on site. In practice, managers use their subjective judgment, which is imprecise yet useful, to estimate time required for material to be available on site. They may think or express such judgment in terms of *very available, available*, or *fairly available.* Such linguistic terms, though not easily defined, are essential to construction. Furthermore, when assessing the likelihood of project delay as a result of material availability or unavailability and its impact on the project planned schedule, one would not necessarily use numerical probabilistic values, but rather use subjective expressions such expressions as *low, high*, or *very high*. These linguistic values can be represented by fuzzy sets.

Fuzzy set theory is based on a membership function that lies over a range of numbers between 0 and 1. Assigning quantitative values to linguistic terms is the first step in using fuzzy set theory. Fuzzy logic operates on a concept of membership such as the availability of material on site. If in an expert judgment material is *unavailable* the term *unavailable* can be translated as a membership of the set of material availability, and can be written symbolically as μ*(unavailable*), where μ is the membership function that has a value between 0 and 1. The fuzzy concept of material availability can be further extended into *very unavailable*, *unavailable*, *fairly unavailable*, *fairly available*,

available, and *very available*. Similarly, fuzzy logic can be applied to the likelihood of delay concept of membership value. For example, if the likelihood of delay is *high (negative)*, this term is a member of the likelihood of delay set and can be written symbolically as μ(*high*), where μ is a membership function that returns a value between 0 and 1.

Fuzzy set models may take different shapes. However, all fuzzy set models relate the membership value μ_x (i) to the fuzzy element x_i. In this research four fuzzy set models are introduced and all these models have three characteristics: positive, negative, and neutral. Examples of terms denoting positive characteristics are *unlikely* delay, and *positive* weather conditions. On the other hand, terms such as *likely* project delay and *very negative* weather conditions have negative characteristics. Terms such as *fair*, *medium*, and *moderate* have neutral characteristics. In constructing and using fuzzy set models, consistency of these values is essential for the analysis.

Fuzzy set models can be classified into translational and rotational models. In translational models, subjective judgments are captured with membership functions where linguistic values change when shifted horizontally. Most of the literature introduces triangular and bell shaped translational models. The hedges such as *not very*, *fairly*, and *very* are determined by following Zadeh's classification of membership functions as follows:

$$\mu_{not\ likely}(p) = 1 - \mu_{likely}(p) \qquad [26]$$

$$\mu_{unlikely}(p) = \mu_{likely}(1-p) \qquad [27]$$

Where *p* is the probability value in an interval of [0,1]. Furthermore, the hedges *fairly* and *very* are defined by membership functions as follows:

$$\mu_{very\ likely}(p) = [\mu_{likely}(p)]^{2} \qquad [28]$$

$$\mu_{fairly\ likely}(p) = [\mu_{likely}(p)]^{0.5} \qquad [29]$$

In rotational models, subjective judgments are captured with ramp membership functions, which are linear or non-linear functions and connect two rotational points. The hedges such as *not very*, *fairly*, and *very* are determined using Zadeh's hedging classification shown in Equations [26], [27], [28], and [29].

5.2 Fuzzy Set Rotational Models

In rotational models, subjective judgments are captured with ramp membership functions, which are linear or nonlinear functions and connect two rotational points. Two fuzzy set models that are rotational in their nature are Baldwin's rotational model and the fuzzy set angular model.

5.2.1 Baldwin's Model

Fuzzy set Baldwin's model relates the membership values $\mu(x_i)$ to the fuzzy element x_i. Characteristically, a rotational model represents a linguistic value that is represented by a line that connects one or two rotational points at the end of the line. These models are called ramp functions. The following fuzzy sets provide membership values for different fuzzy rotational sets including both positive and negative fuzzy sets:

Very Negative = [1/0, 0.81/0.1, 0.64/0.2, 0.49/0.3, 0.36/0.4, 0.25/0.5, 0.16/0.6, 0.09/0.7, 0.04/0.8, 0.01/0.9, 0/1] [30]

Negative = [1/0, 0.9/0.1, 0.8/0.2, 0.7/0.3, 0.6/0.4, 0.5/0.5, 0.4/0.6, 0.3/0.7, 0.2/0.8, 0.1/0.9, 0/1] [31]

Fairly Negative = [1/0, 0.95/0.1, 0.89/0.2, 0.84/0.3, 0.77/0.4, 0.71/0.5, 0.63/0.6, 0.55/0.7, 0.45/0.8, 0.32/0.9, 0/1] [32]

Fairly Positive = [0/0, 0.32/0.1, 0.45/0.2, 0.55/0.3, 0.63/0.4, 0.71/0.5, 0.77/0.6, 0.84/0.7, 0.89/0.8, 0.95/0.9, 1/1] [33]

Positive = [0/0, 0.1/0.1, 0.2/0.2, 0.3/0.3, 0.4/0.4, 0.5/0.5, 0.6/0.6, 0.7/0.7, 0.8/0.8, 0.9/0.9, 1/1] [34]

Very Positive = [0/0, 0.01/0.1, 0.04/0.2, 0.09/0.3, 0.16/0.4, 0.25/0.5, 0.36/0.6, 0.49/0.7, 0.64/0.8, 0.81/0.9, 1/1] [35]

Figure 66 provides fuzzy set Baldwin's model constructed using subjective assessment of linguistic values.

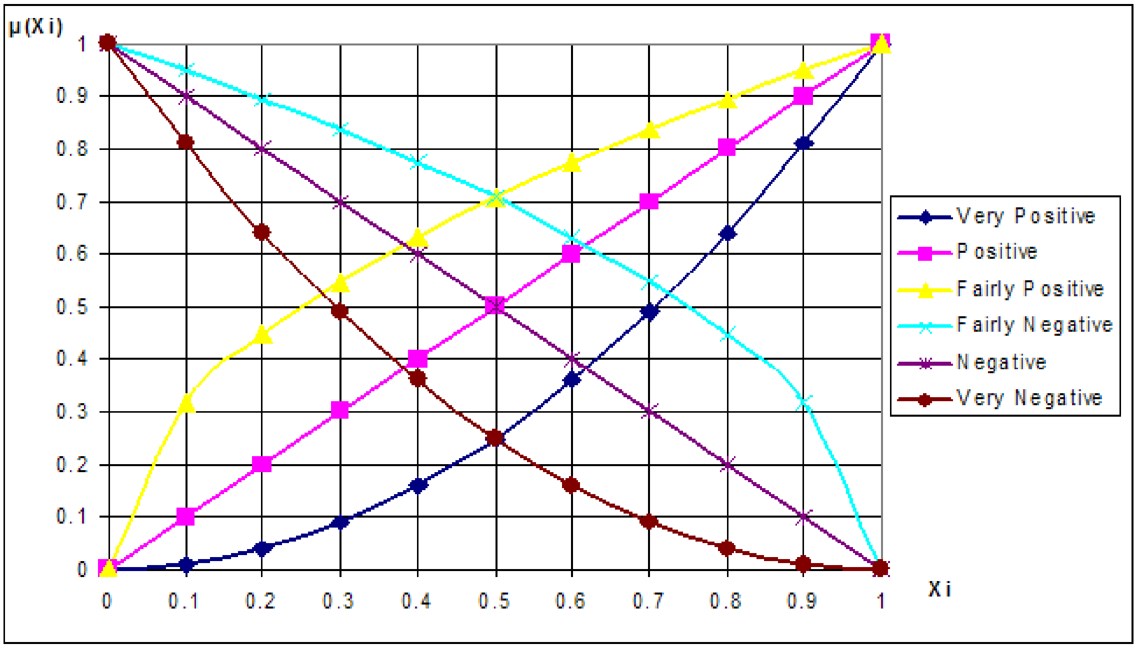


Figure 66. Baldwin's Model.

5.2.2 Fuzzy Set Angular Model

Angular models with rotational characteristics have been developed by Hadipriono and Sun (1990). In the angular model, linguistic values are represented with angles; consequently each value has a different angle. Hence the membership value is a function of an angle Θ. The angular model is represented by a half circle with an angle that rotates between +∏/2 and -∏/2. The *undecided* linguistic value is represented by a horizontal line with the angle Θ =0. The angle of Θ = ∏/2 represents the linguistic value of *absolutely positive*, or no risk. The line corresponding to the linguistic term *absolutely negative* is opposite to the *absolutely low* line with an angle of *Θ* = -∏/2. Negative terms such as *fairly negative, negative*, and *very negative* indicate negative conditions of different causes of project delay. These positive values are represented by lines with angles ranging between Θ = 0 and Θ = ∏/*2*. Negative linguistic terms such as *fairly negative, negative* and *very negative* which describe the negative causes of project delay are represented by angles below the horizontal *undecided* line. Effectiveness of different causes of project delay is captured by negative values of linguistic terms such as *fairly effective, effective*, and *very effective*. Negative linguistic terms such as *fairly effective, effective* and *very effective* are represented by angles below the horizontal ‘ undecided’ line. Angular models can be used more conveniently than other models. Also, interpretation of results represented by linguistic values can be performed easily. Linguistic terms and their positive or negative ratings are represented by the angular model shown in Figure 67.

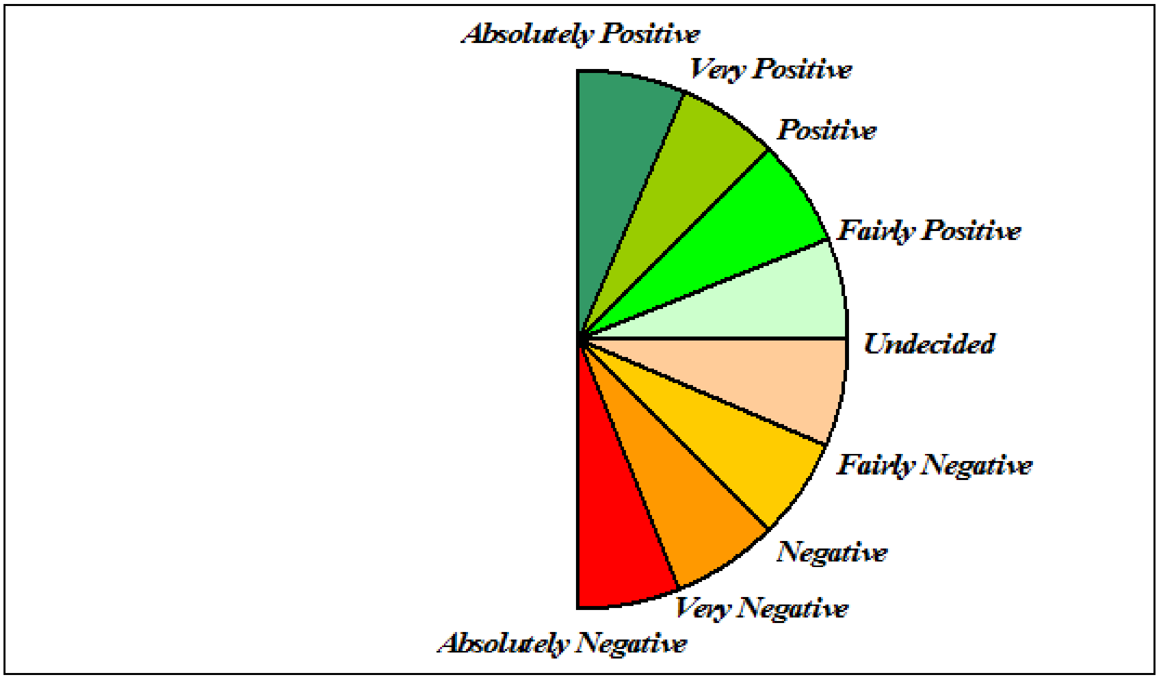


Figure 67. Linguistic Values Represented by the Angular Model.

Table 4 provides linguistic terms and their values in terms of angles and Figure 68 illustrates the linguistic terms and their values representation using the angular model.

Linguistic Term	**Angle (Θ in degrees)**
Absolutely Negative	-90°
Very Negative	-67.5°
Negative	-45°
Fairly Negative	-22.5°
Undecided	0°
Fairly Positive	22.5°
Positive	45°
Very Positive	67.5°
Absolutely Positive	90°

Table 4. Linguistic Terms and their Values in Terms of Angles for Angular Model.

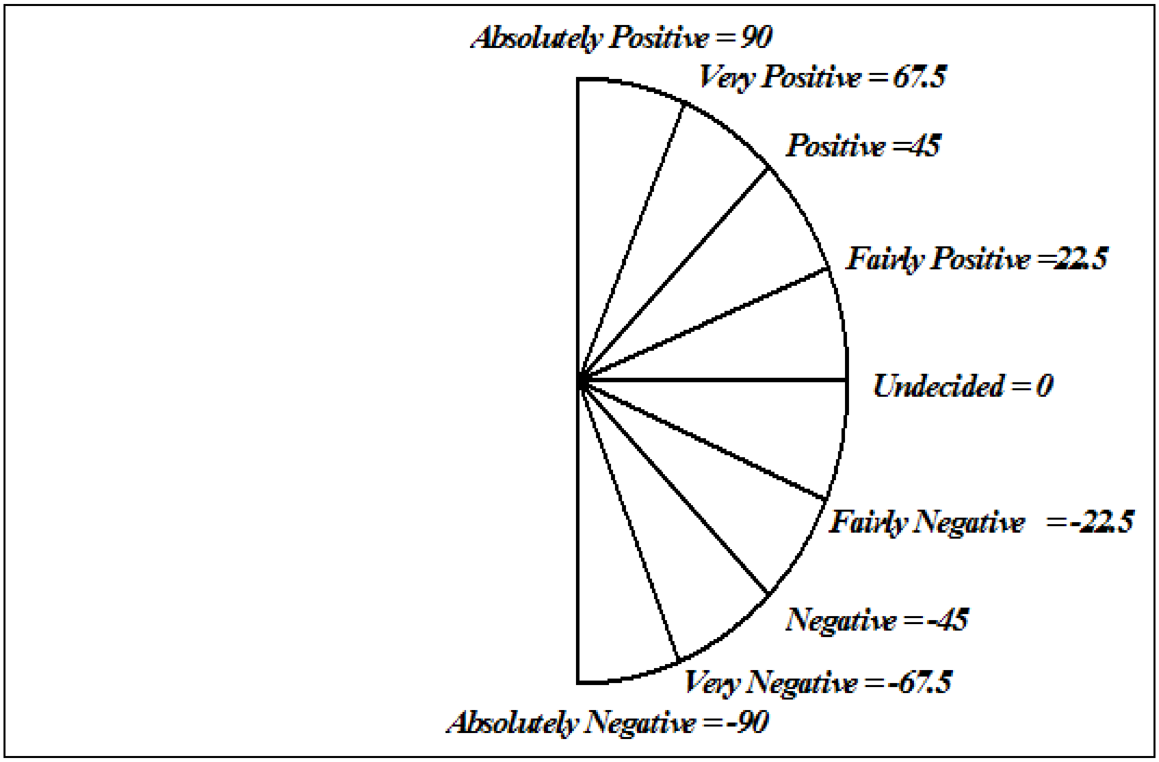


Figure 68. Linguistic Terms and their Values Using Angular Model.

5.3 Fuzzy Set Translational Models

In translational models, subjective judgments are captured with membership functions where linguistic values change when shifted horizontally. The two translational models discussed in this research are fuzzy set triangular model and the translational model.

5.3.1 Fuzzy Set Translational Model

The fuzzy set translational model relates the membership values $\mu(x_i)$ to the fuzzy element x_i. In the translational fuzzy set model, the linguistic value is represented by fuzzy set relation that shifts horizontally. Figure 69 provides a fuzzy set translational model constructed using subjective assessment of linguistic values. The following fuzzy sets provide membership values for different fuzzy translational sets including both positive and negative fuzzy sets:

Very Negative = [0/0, 0.64/0.1, 0.25/0.2, 0.01/0.3, 0/0.4, 0/0.5, 0/0.6, 0/0.7, 0/0.8, 0/0.9, 0/1] [36]

Negative = [0/0, 0.8/0.1, 0.5/0.2, 0.1/0.3, 0/0.4, 0/0.5, 0/0.6, 0/0.7, 0/0.8, 0/0.9, 0/1] [37]

Fairly Negative = [0/0, 0.9/0.1, 0.7/0.2, 0.3/0.3, 0/0.4, 0/0.5, 0/0.6, 0/0.7, 0/0.8, 0/0.9, 0/1] [38]

Fairly Positive = [0/0, 0/0.1, 0/0.2, 0/0.3, 0/0.4, 0/0.5,
0/0.6, 0.3/0.7, 0.7/0.8, 0.9/0.9, 0/1] [39]

Positive = [0/0, 0/0.1, 0/0.2, 0/0.3, 0/0.4, 0/0.5,
0/0.6, 0.1/0.7, 0.5/0.8, 0.8/0.9, 0/1] [40]

Very Positive = [0/0, 0/0.1, 0/0.2, 0/0.3, 0/0.4, 0/0.5,
0/0.6, 0.01/0.7, 0.25/0.8, 0.64/0.9, 0/1] [41]

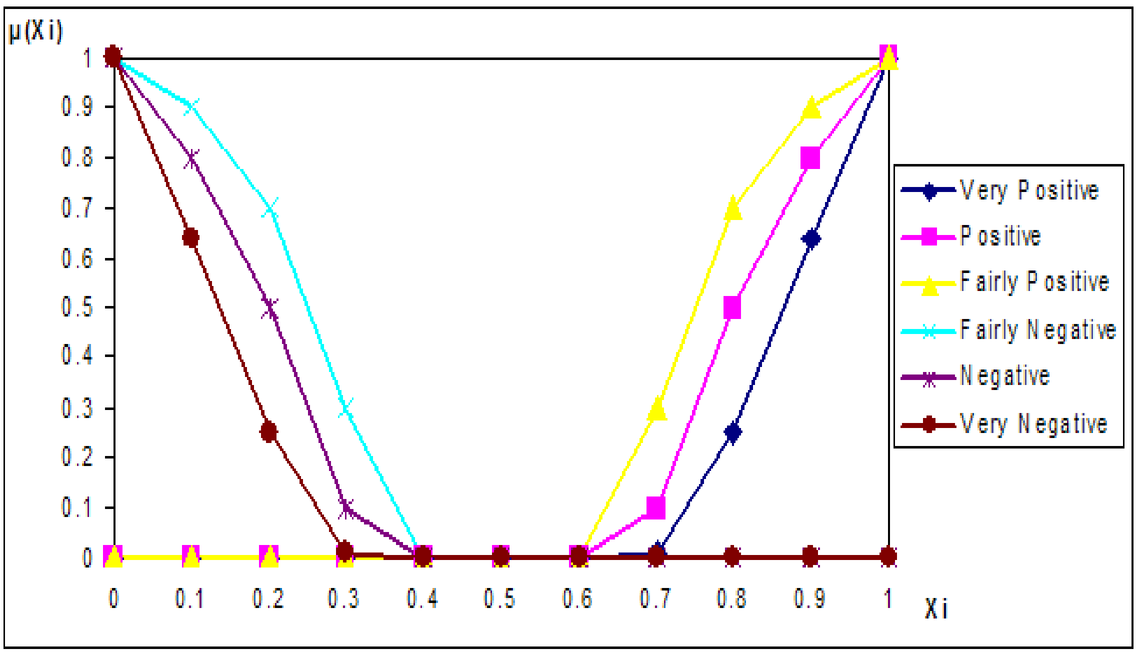


Figure 69. Fuzzy Set Translational Model.

5.3.2 Fuzzy Set Triangular Model

The fuzzy set translational model relates the membership values $\mu(x_i)$ to the fuzzy element x_i. In the translational fuzzy set model, linguistic value is represented by a fuzzy set relation that shifts horizontally. Figure 70 provides a fuzzy set triangular model constructed using subjective assessment of linguistic values. The following fuzzy sets provide membership values for fuzzy triangular model including both positive and negative fuzzy sets:

Very Negative = [0/0, 0/0.05, 0/0.1, 0.5/0.15, 1/0.2, 0.5/0.25, 0/0.3, 0/0.35, 0/0.4, 0/0.45, 0/0.5, 0/0.55, 0/0.6, 0/0.65, 0/0.7, 0/0.75, 0/0.8, 0/0.85, 0/0.9, 0/0.95, 0/1] [42]

Negative = [0/0, 0/0.05, 0/0.1, 0/0.15, 0/0.2, 0.5/0.25, 1/0.3, 0.5/0.35, 0/0.4, 0/0.45, 0/0.5, 0/0.55, 0/0.6, 0/0.65, 0/0.7, 0/0.75, 0/0.8, 0/0.85, 0/0.9, 0/0.95, 0/1] [43]

Fairly Negative = [0/0, 0/0.05, 0/0.1, 0/0.15, 0/0.2, 0/0.25, 0/0.3, 0.5/0.35, 1/0.4, 0.5/0.45, 0/0.5, 0/0.55, 0/0.6, 0/0.65, 0/0.7, 0/0.75, 0/0.8, 0/0.85, 0/0.9, 0/0.95, 0/1] [44]

Fairly Positive = [0/0, 0/0.05, 0/0.1, 0/0.15, 0/0.2, 0/0.25, 0/0.3, 0/0.35, 0/0.4, 0.5/0.45, 1/0.5, 0.5/0.55, 0/0.6, 0/0.65, 0/0.7, 0/0.75, 0/0.8, 0/0.85, 0/0.9, 0/0.95, 0/1] [45]

Positive = [0/0, 0/0.05, 0/0.1, 0/0.15, 0/0.2, 0/0.25, 0/0.3, 0/0.35, 0/0.4, 0/0.45, 0/0.5, 0.5/0.55, 1/0.6, 0.5/0.65, 0/0.7, 0/0.8, 0/0.75, 0/0.85, 0/0.9, 0/0.95, 0/1] [46]

Very Positive = [0/0, 0/0.05, 0/0.1, 0/0.15, 0/0.2, 0/0.25, 0/0.3, 0/0.35, 0/0.4, 0/0.45, 0/0.5, 0/0.55, 0/0.6, 0.5/0.65, 1/0.7, 0.5/0.75, 0/0.8, 0/0.85, 0/0.9, 0/0.95, 0/1] [47]

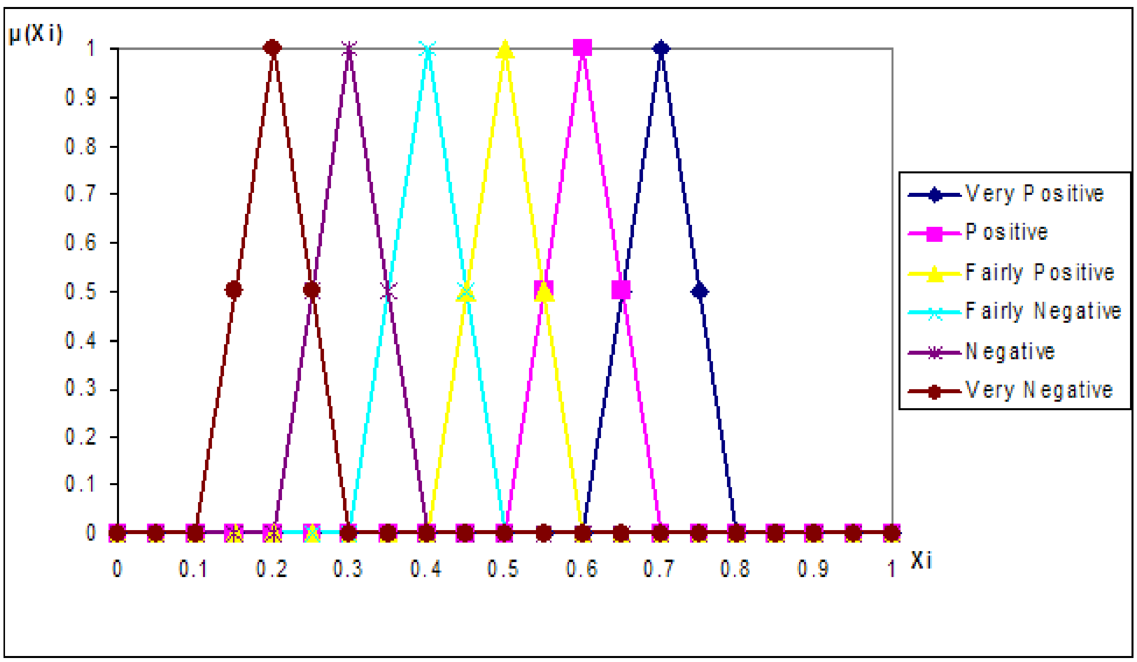


Figure 70. Fuzzy Set Triangular Model.

For example, if weather conditions are *bad,* the linguistic term *Negative* or *bad* is a linguistic value that is represented by fuzzy set depending on the fuzzy model adopted. The fuzzy models in translational fuzzy set model and triangular fuzzy set model can provide a fuzzy membership function depending on the model being implemented. Furthermore, *Negative* or *bad* weather condition can be represented using rotational fuzzy set models of both Baldwin's rotational fuzzy set model and angular fuzzy set model. Figure 71 provides fuzzy membership function for translational fuzzy set model. Figure 72 provides fuzzy membership function for triangular fuzzy set model. Figure 73 provides fuzzy membership function for Baldwin's fuzzy set model. Figure 74 provides fuzzy membership function for angular fuzzy set model.

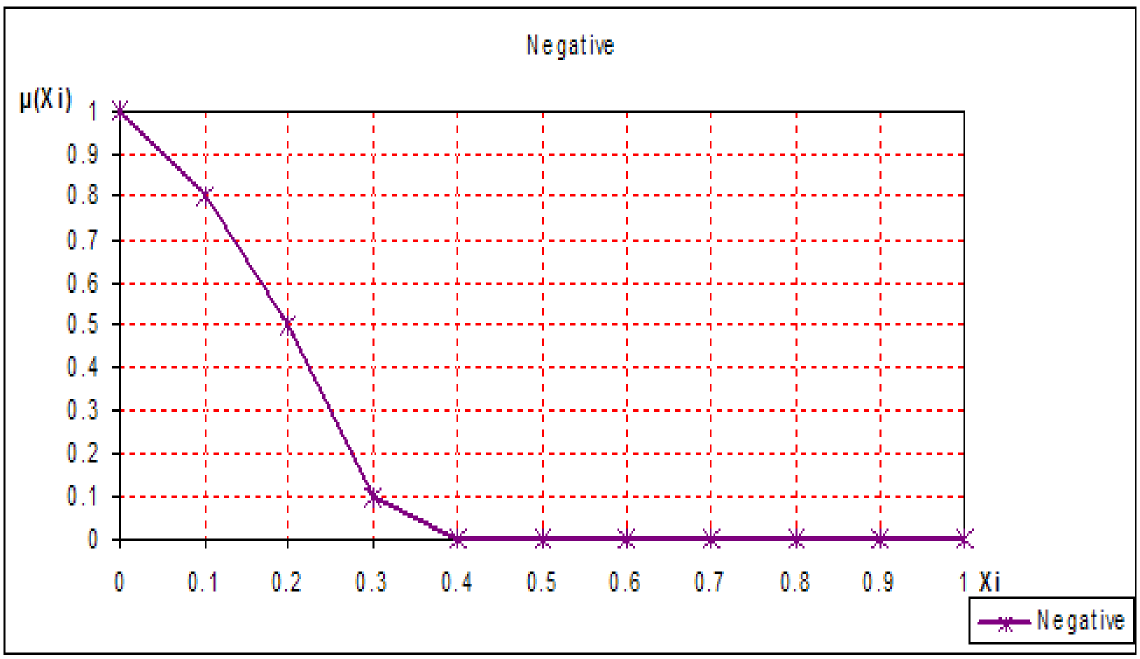


Figure 71. Fuzzy Membership Function for Translational Fuzzy Set Model.

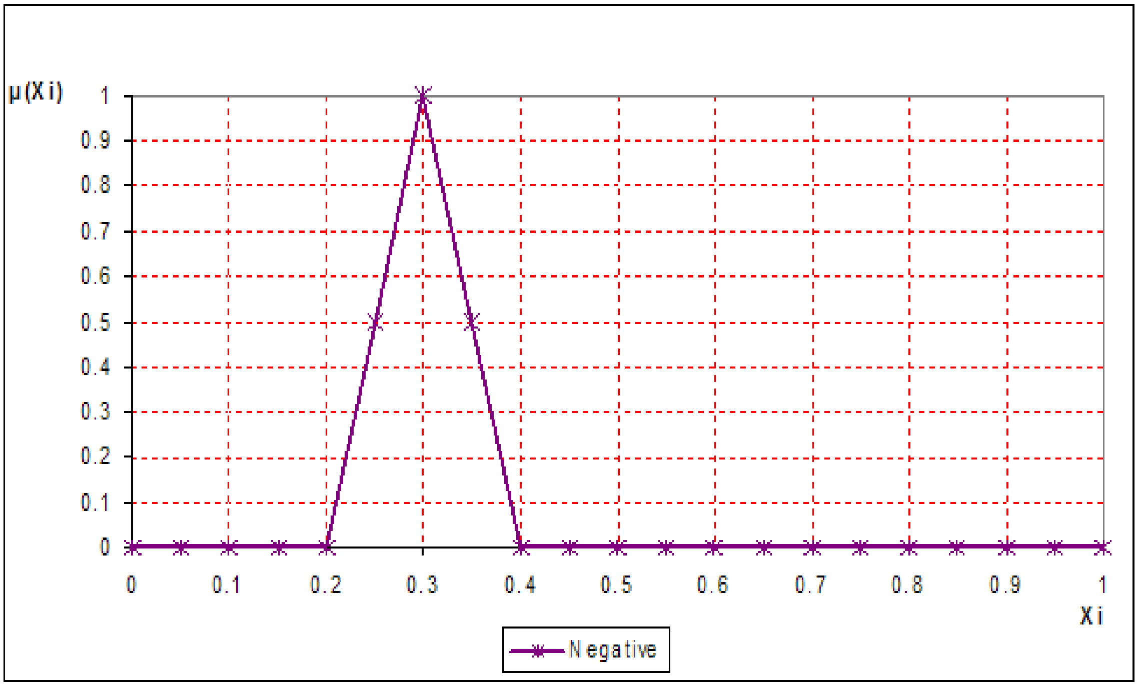


Figure 72. Fuzzy Membership Function for Triangular Fuzzy Set Model.

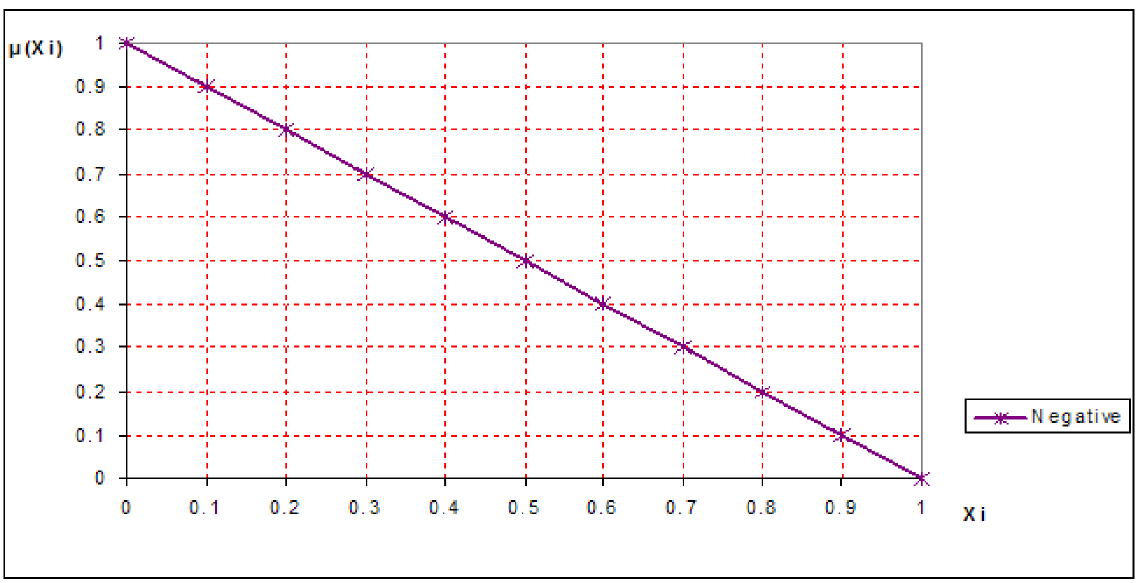


Figure 73. Fuzzy Membership Function for Baldwin's Fuzzy Set Model.

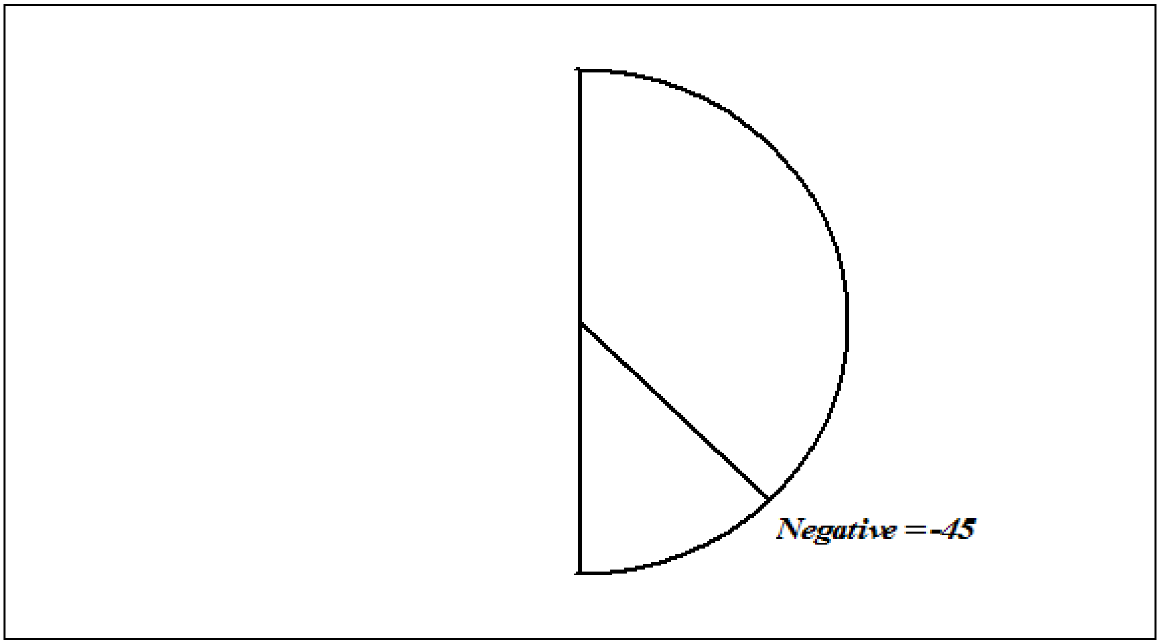


Figure 74. Fuzzy Membership Function for Angular Fuzzy Set Model.

Chapter 6

FUZZY FAULT TREE ANALYSIS

6.1 Introduction

Traditional fault tree analyses use single probability to represent each basic event. However, it is unrealistic to evaluate the occurrence of a top event by using a crisp value without considering inherent uncertainty and imprecision each basic event has. Furthermore, the unprecedented nature of projects results in a new set of governing factors for each and every project undertaken. The unprecedented nature of projects makes the implementation of probability theory unrealistic. This is basically due to the fact that probability theory is based on historical data but implementation of historical data in unprecedented projects is questionable. Probabilistic values are often expressed by experts' subjectively using linguistic terms. Quantification of such expressions is hard using probability theory. Therefore, the fuzzy set theory can be used to deal with this kind of phenomenon. Fuzzy fault tree algorithm is developed by the lambda-cut method.

Fuzzy set theory was developed specifically to deal with uncertainties that are not statistical in nature Klir and Yuan (1995). The definition of a fuzzy set can be stated as follows: If X is a collection of objects denoted generically by x, then a fuzzy set A in X is defined as a set or ordered pairs [$A = \{(x, \mu A(x))$ where $\mu A(x)$ is a membership function for the fuzzy set A]. The membership function maps each element of X to a membership value between 0 and 1. Different fuzzy members can be used. Several fuzzy operations, such as union and intersection, can be used to manipulate relationships between fuzzy numbers. Among these operations, a-cut is an important concept in the fuzzy logic.

Based upon the first decomposition theorem of fuzzy set theory, any fuzzy set can be associated to a collection of crisp sets known as α-cut. The α-cut provides a useful way for resolving a membership function in terms of constituent crisp sets, as well as for synthesizing a membership function out of crisp sets. Based upon the α-cut concept, fuzzy numbers are implemented to determine the condition of different causes that contribute to project delay. Furthermore, the α-cut concept is implemented to determine the degree of effectiveness if each factor's contribution to overall project delay. We assign weighted input values to the corresponding effectiveness before every gate operation. Suppose that input A with effectiveness E1 is noted as A_{E1}. Then the corresponding membership values for the weighted value W at $\mu_w(x_W) = \mu_A(x_A) = \mu_{E1}(x_{E1}) = \alpha$ is obtained as

$$x_W = x_A * x_{E1} \qquad [48]$$

or

$$\mu_w^{-1}(\alpha) = \mu_A^{-1}(\alpha) * \mu_E^{-1}(\alpha), \qquad \forall\ \alpha :[0,1] \qquad [49]$$

Where x_W, x_A and x_{E1} are the fuzzy elements of W, A and E1 respectively; * is an arithmetic product; the subscript of membership value μ represents the corresponding fuzzy set; and $\mu^{-1}(\alpha)$ is an inverse membership function of the corresponding fuzzy set.

When an input value of a gate has a *negative* basic term then the effectiveness should have a negative characteristic. The fuzzy fault tree model suggested to analyze project delay is assumed to model negative conditions. If management anticipates negative conditions, then this would lead to the fault tree analysis. Therefore, only negative characteristics of causes of project delay and accordingly negative characteristics of effectiveness are considered for the analysis.

Fuzzy operation of minimum (min) and maximum (max) were introduced by Zadeh as AND and OR operators. An AND operation is used for an intersection in set theory. The fuzzy AND operation takes into consideration the minimum membership value of the input values. The fuzzy OR operation takes into consideration the maximum membership value of the input values. In both the AND and the OR operations only one input could affect the output. Another operation suggested in this study is the Fuzzy Mean operation. Since a Boolean linguistic value is a multi-valued expression, we can implement an operation where all inputs affect the output. A Fuzzy Mean is an operation that can manipulate the average of more than one input value. Thus the mean operator output value is between those of AND and OR.

6.2 The Software Program

Computer software has been developed using Visual Basic to assess the likelihood of project delay. The software uses the linguistic variables that describe causes of project delay and the effectiveness of each cause on the overall project delay. A fuzzy fault tree approach has been employed to obtain results. The methodology used in the calculation of the likelihood of delay has been discussed in prior sections of this dissertation. The fuzzy fault tree is designed to model negative causes of project delay. In case a positive condition of causes of delay is encountered in a given project for example, if weather condition is good or if the delay cause does not affect the overall project delay, then this delay cause is excluded from the analysis. The user selects the state of the bottom events, which describe different causes of delay including triggering delay causes, enabling delay causes and procedural delay causes. The various states of the delay cause are: *very negative*, *negative* and *fairly negative*. The user also needs to select the degree of effectiveness of each contributing cause of delay on the overall project delay.

The fuzzy fault tree computer program starts with a welcome screen where there is three selection choices. The user could get information on how to use the computer program, can enter the program or can exit by clicking on one of the three buttons shown in Figure 75 below.

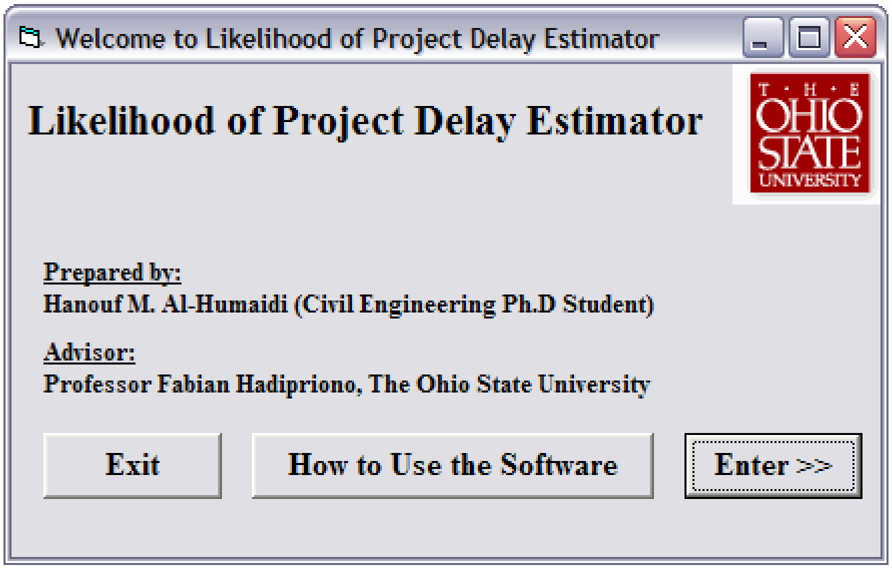


Figure 75. The Computer Program Welcome Screen.

If the user selects the "How to Use the Software" button, the software directs the user to screen shown in Figure 76. In this screen steps on how to use the software are provided to the user. If the user selects the "Enter" button, the user is directed to another screen shown in Figure 77. This screen is the fuzzy fault tree screen.

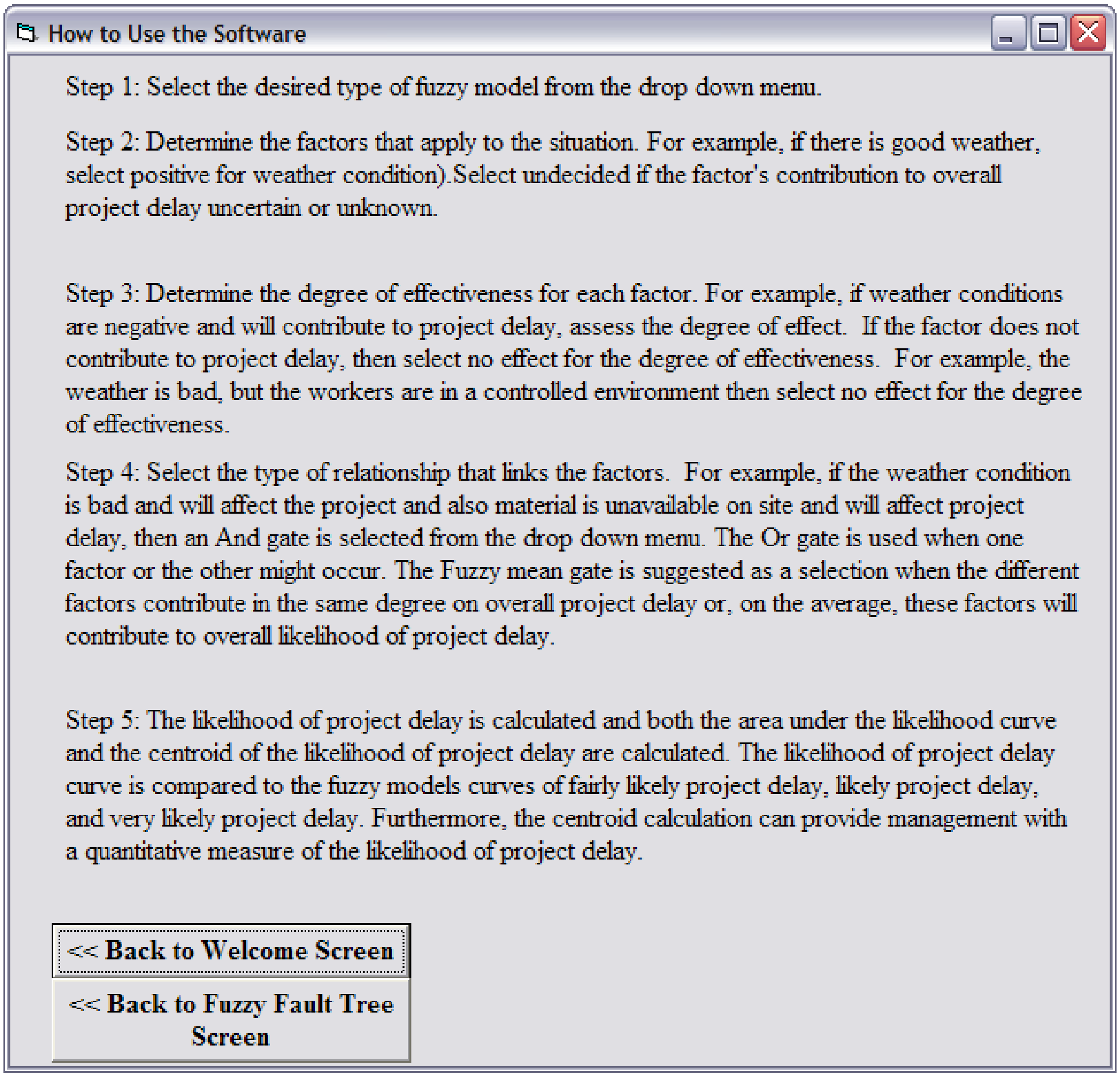


Figure 76. The “How to Use the Software” Screen.

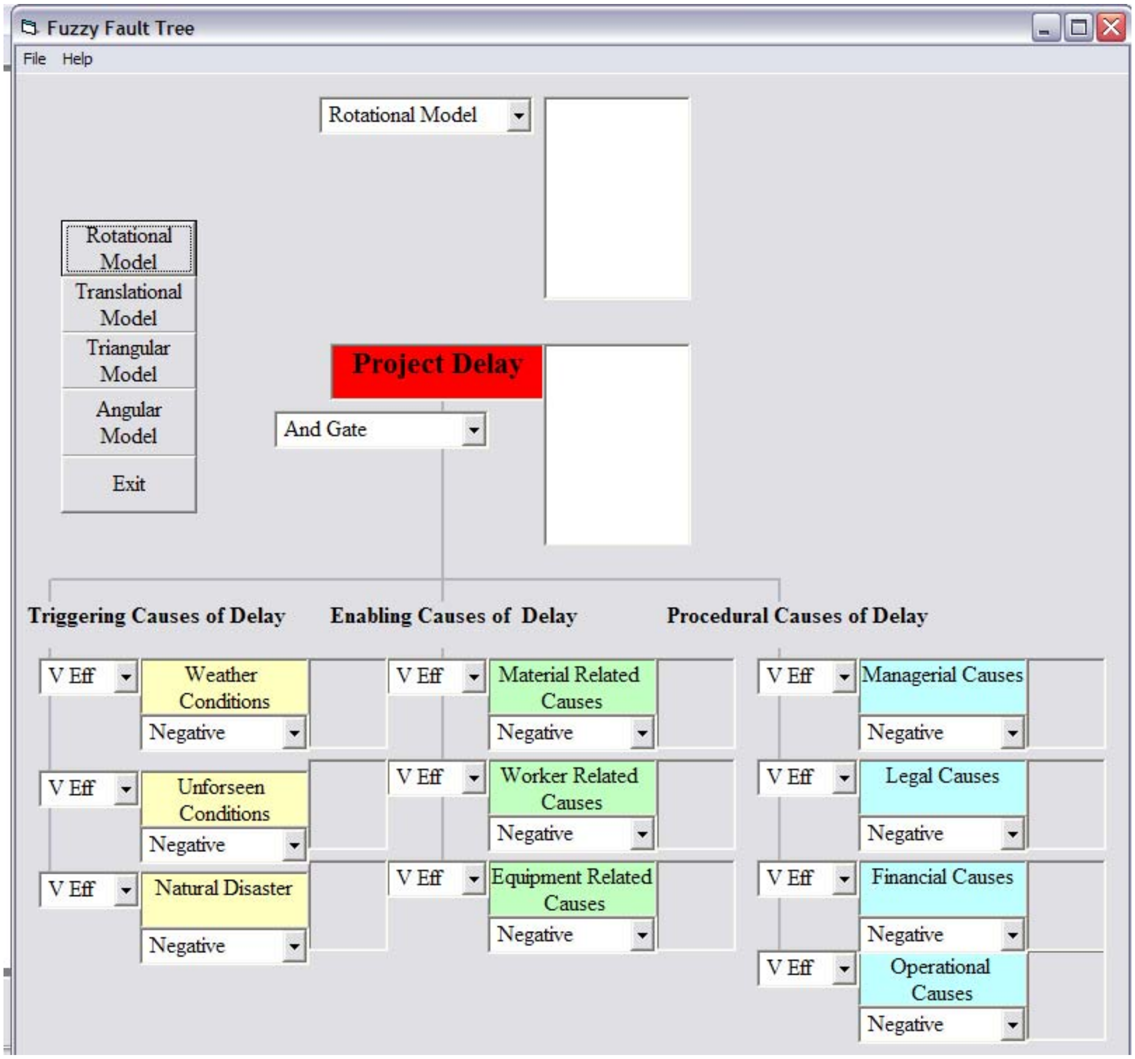


Figure 77. The Fuzzy Fault Tree Screen.

Two menus have been provided to users. These menus are the File menu and the Help menu. In the File menu, the user can save the set of selections and the results into a text file go back into the welcome screen or exit the program. In the "Help" menu, the user can select to get information on the project delays, causes of project delay, fuzzy logic models, fault tree analysis, likelihood of project delay, notations and abbreviations or information on how to use the software. Figures 78 and 79 show the "Help" and the

“File” menus. Figure 80 provides the project delays screen. Figure 81 provides the causes of project delay information screen. Figure 82 provides the fuzzy logic models screen. Figure 83 provides the fault tree analysis information screen. Figure 84 provides the likelihood of project delay information screen. Figure 85 provides notations and abbreviations information screen. The How to Use the Software information screen is shown earlier in Figure 65.

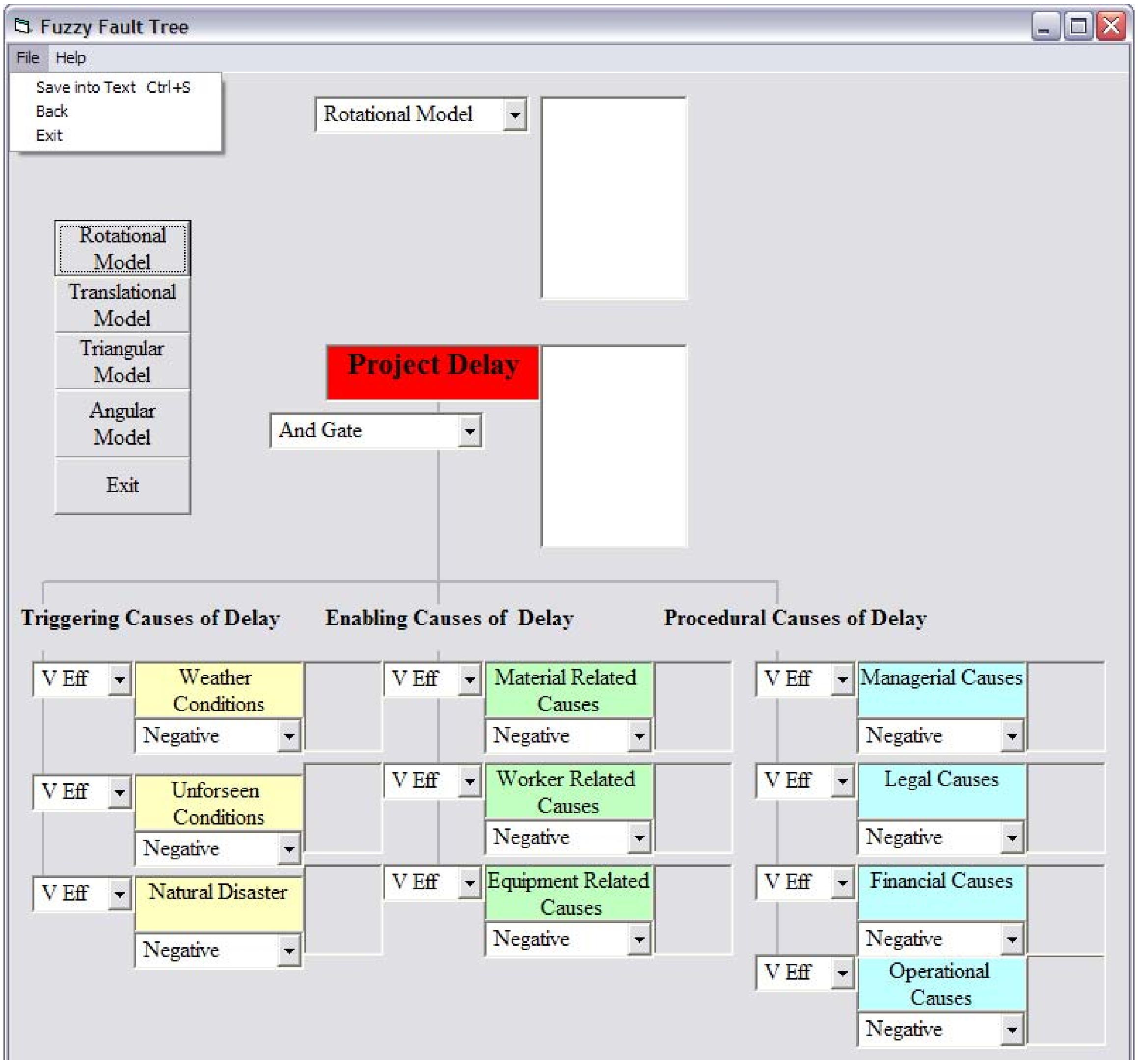


Figure 78. The Help Menu.

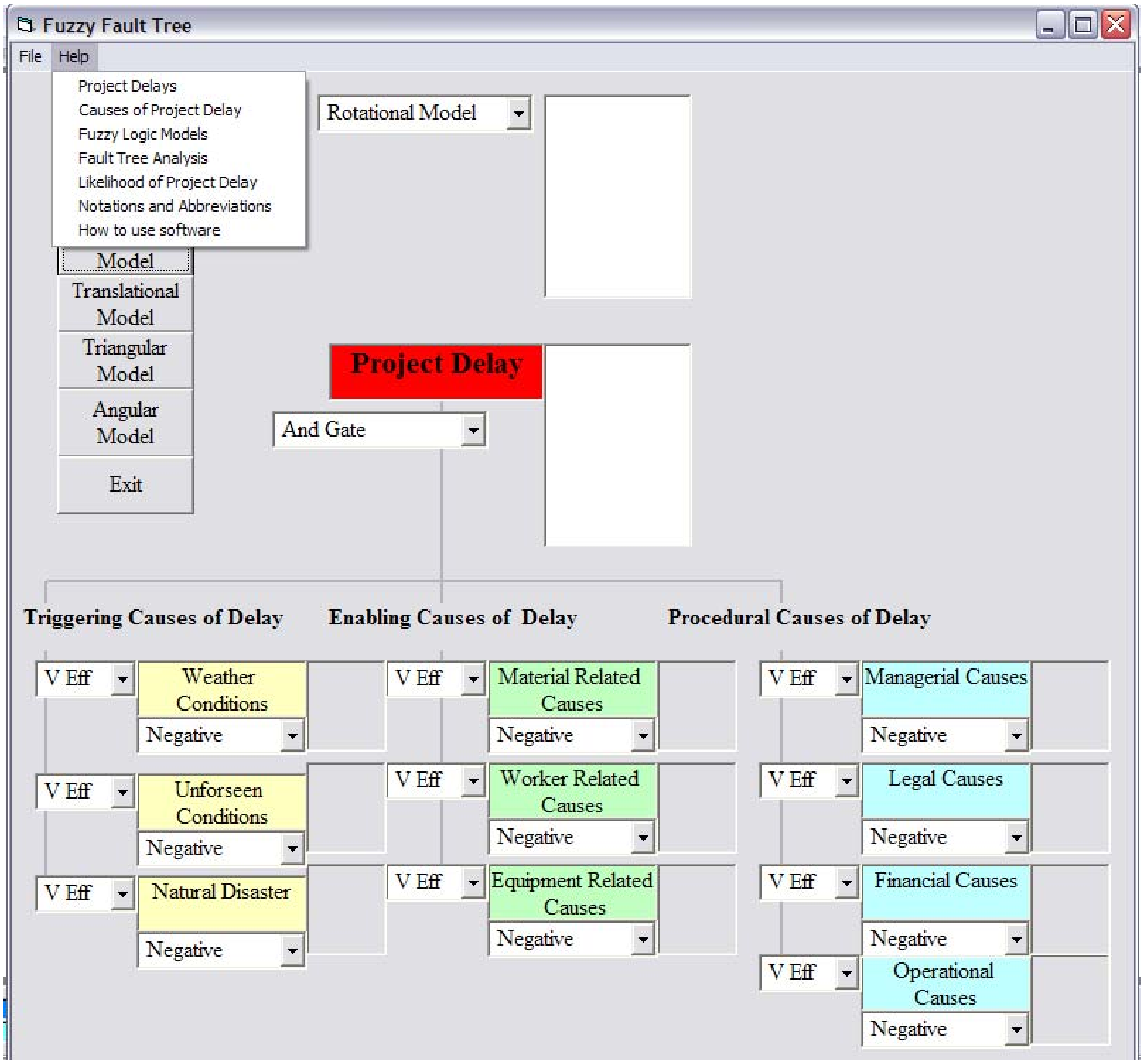


Figure 79. The File Menu.

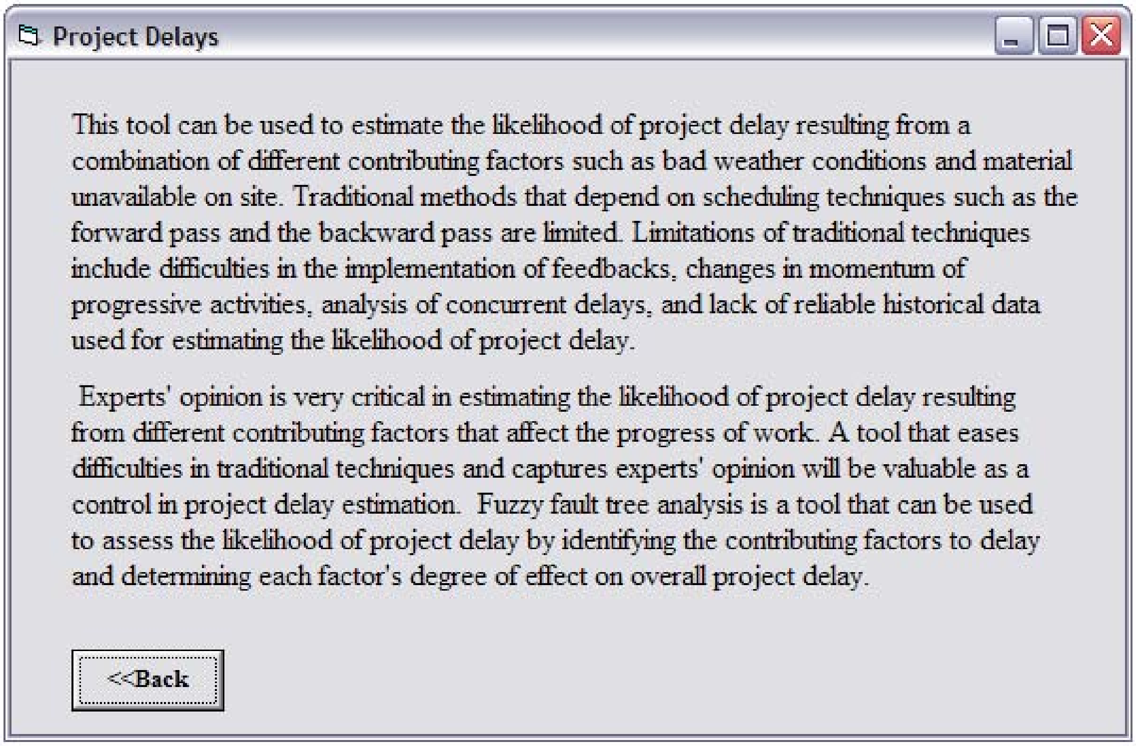


Figure 80. The Project Delays Information Screen.

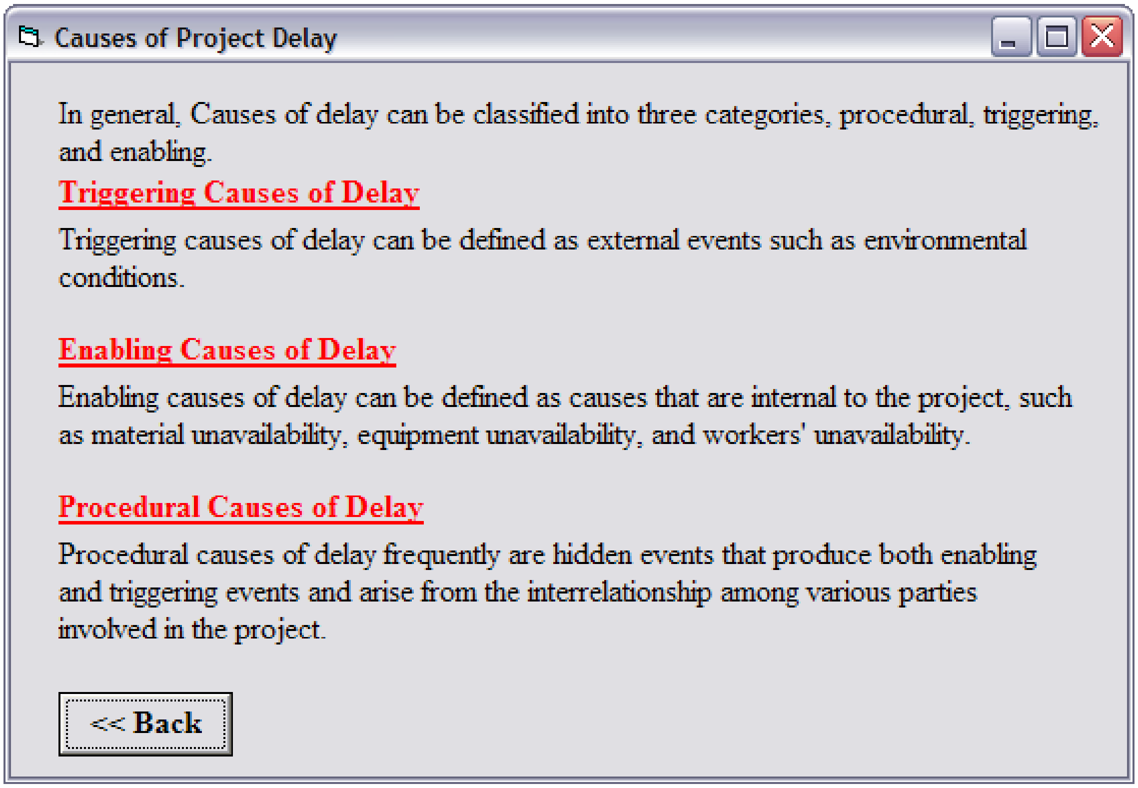


Figure 81. The Causes of Project Delay Information Screen.

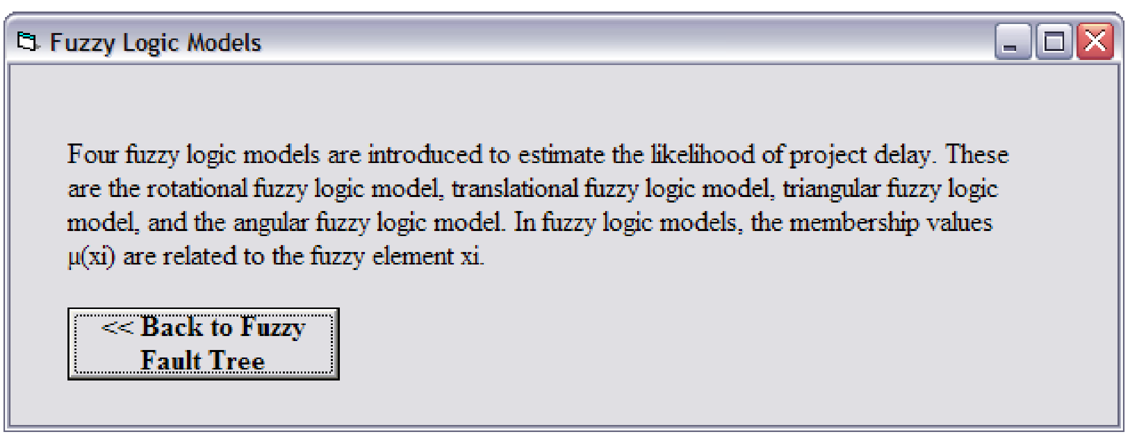


Figure 82. The Fuzzy Logic Models Information Screen.

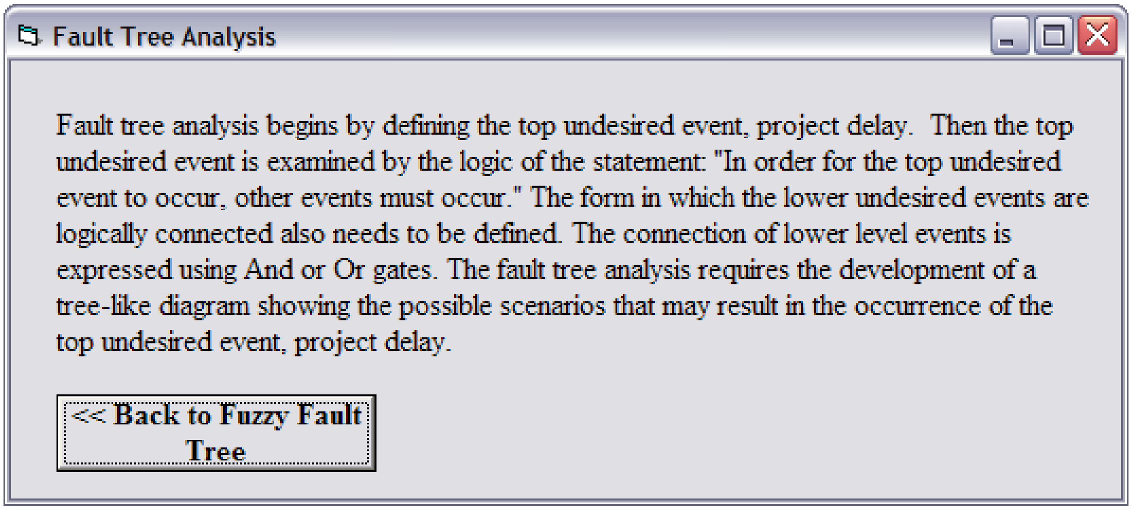


Figure 83. The Fault Tree Analysis Information Screen.

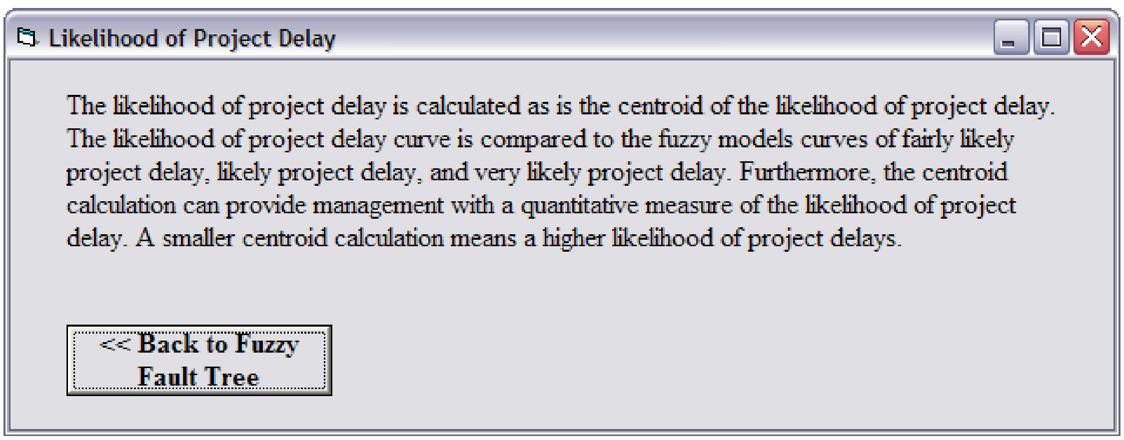


Figure 84. The Likelihood of Project Delay Information Screen.

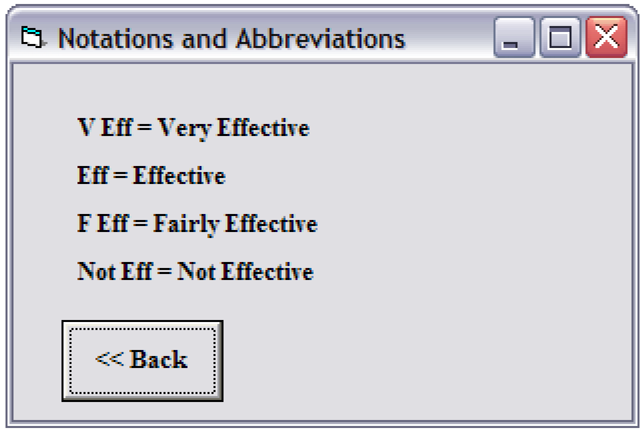


Figure 85. The Notations and Abbreviations Screen.

6.3 Illustration of the Software Program

Given a scenario where expert opinion regarding the amount of delay is drawn based on fuzzy conditions of causes of delay. Table 5 and 6 show a hypothetical scenario of an expert opinion, which is modeled using the fuzzy fault tree analysis computer software.

Causes \ Condition		Very Negative	Negative	Fairly Negative	Undecided	Positive
Triggering Delay Causes	Weather Condition	X				
	Unforseen Conditions		X			
	Natural Disaster				X	
Enabling Delay Causes	Material Related Causes		X			
	Workers Related Causes			X		
	Equipment Related Causes		X			
Procedural Daley Causes	Managerial Causes	X				
	Legal Causes					X
	Financial Causes			X		
	Operational Causes				X	

Table 5. Hypothetical Experts Opinion on the State of Causes of Project Delay.

Cause \ Effectiveness		Very Effective	Effective	Fairly Effective	Not Effective
Triggering Delay Causes	Weather Condition	X			
	Unforseen Conditions		X		
	Natural Disaster				
Enabling Delay Causes	Material Related Causes	X			
	Workers Related Causes		X		
	Equipment Related Causes		X		
Procedural Daley Causes	Managerial Causes	X			
	Legal Causes				
	Financial Causes	X			
	Operational Causes				

Table 6. Hypothetical Experts Opinion on the Degree of Effectiveness of Different Causes of Project Delay.

The computer software user can make a selection among the four fuzzy logic models to assess the likelihood of project delay. The four fuzzy logic models are: the rotational model, the translational model, the triangular model and the angular model. Figure 86 the model selection menu. The results of this hypothetical example are shown for the four fuzzy logic models listed above using three fuzzy logic operations. These three fuzzy logic operations are the fuzzy AND gate, the fuzzy OR gate and the fuzzy

MEAN gate. Figures 87, 88, 89 and 90 show the likelihood of project delay using the AND fuzzy logic operation using the four fuzzy logic models listed above. Figures 91, 92, 93 and 94 show the likelihood of project delay using the OR fuzzy logic operation using the four fuzzy logic models listed above. Figures 95, 96, 97and 98 show the likelihood of project delay using the Fuzzy Mean logic operation using the four fuzzy logic models listed above.

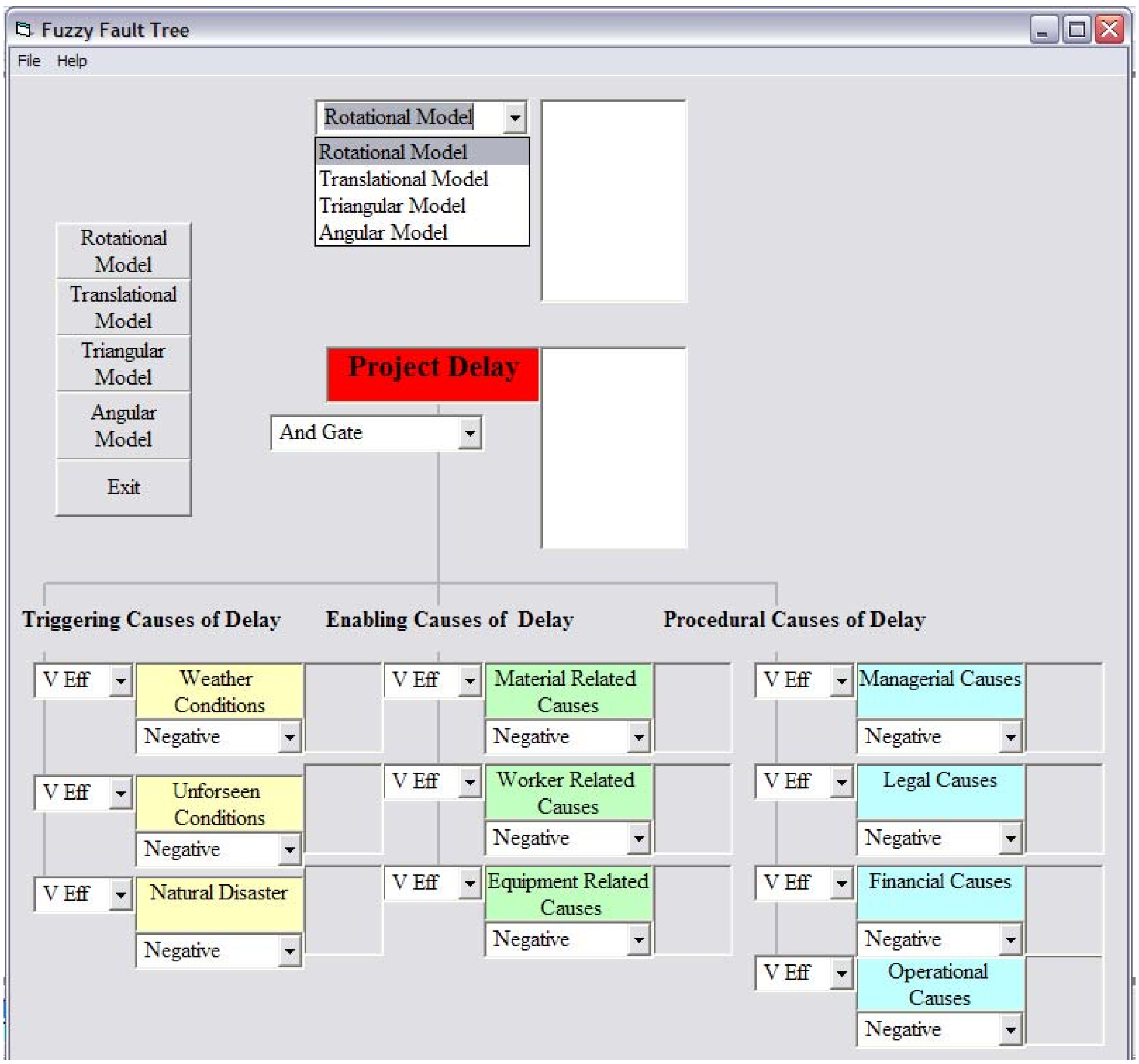


Figure 86. The Fuzzy Logic Model Selection Menu.

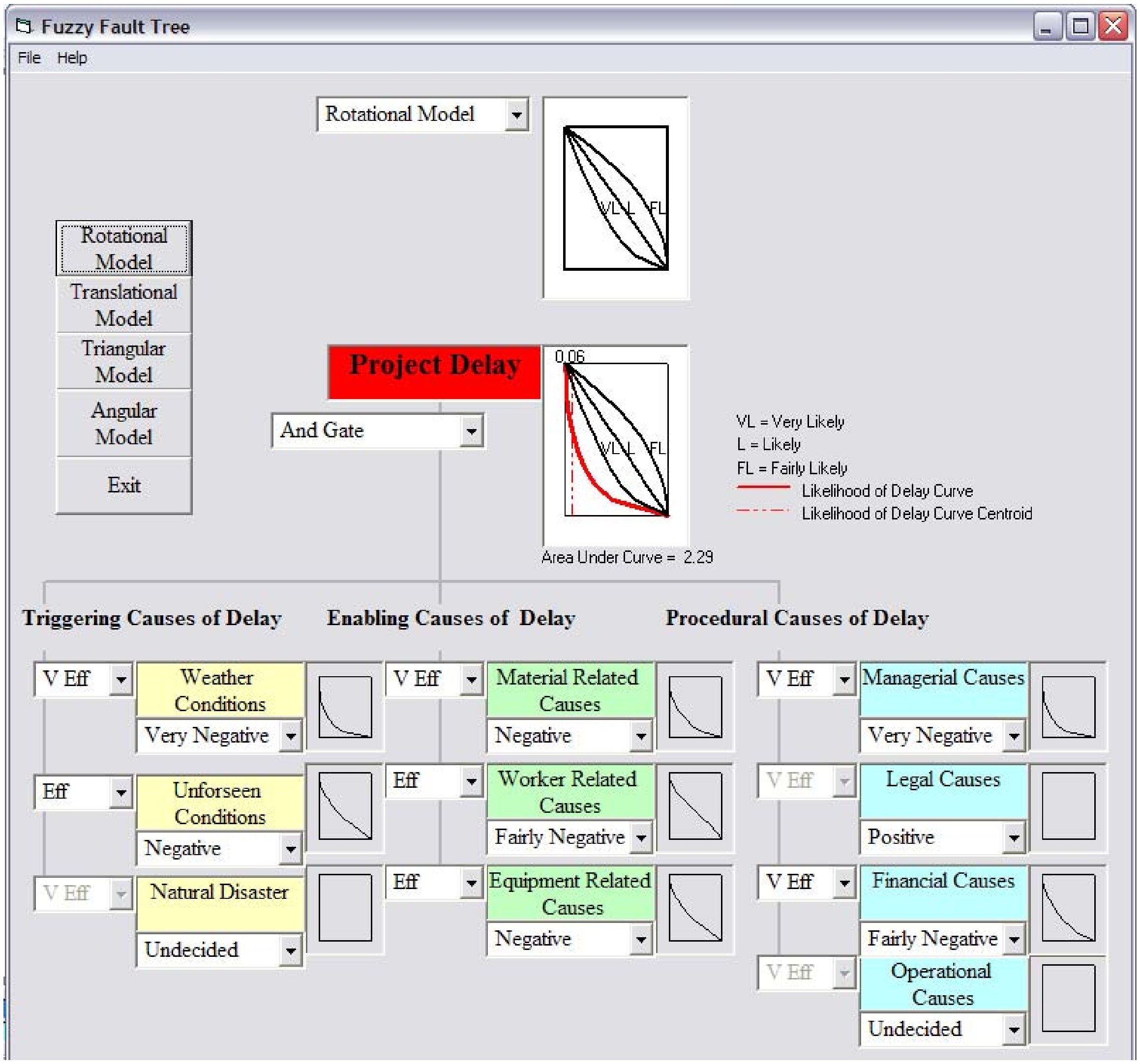


Figure 87. Likelihood of Project Delay with AND Operation using the Fuzzy Rotational Model.

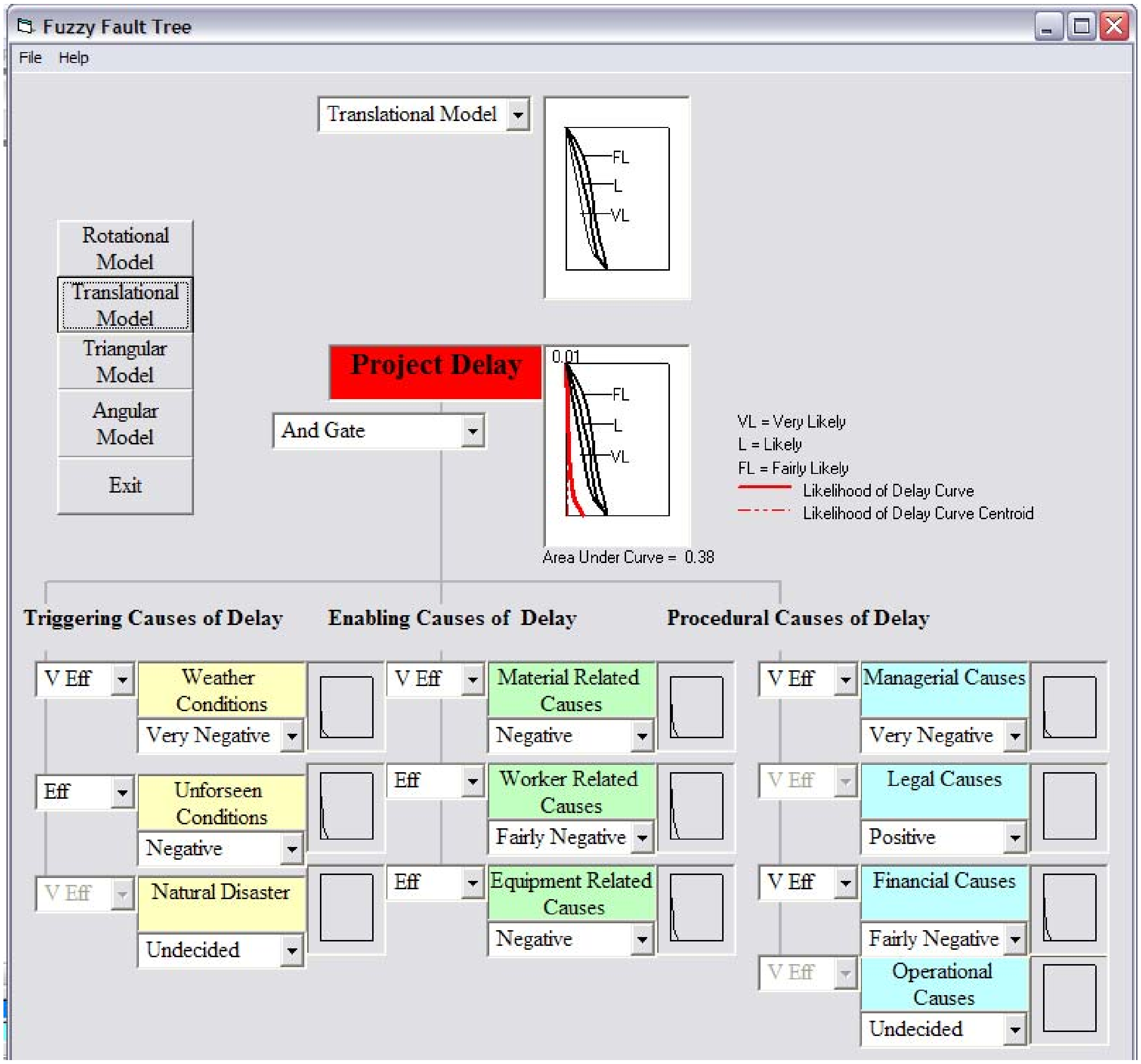


Figure 88. Likelihood of Project Delay with AND Operation using the Fuzzy Translational Model.

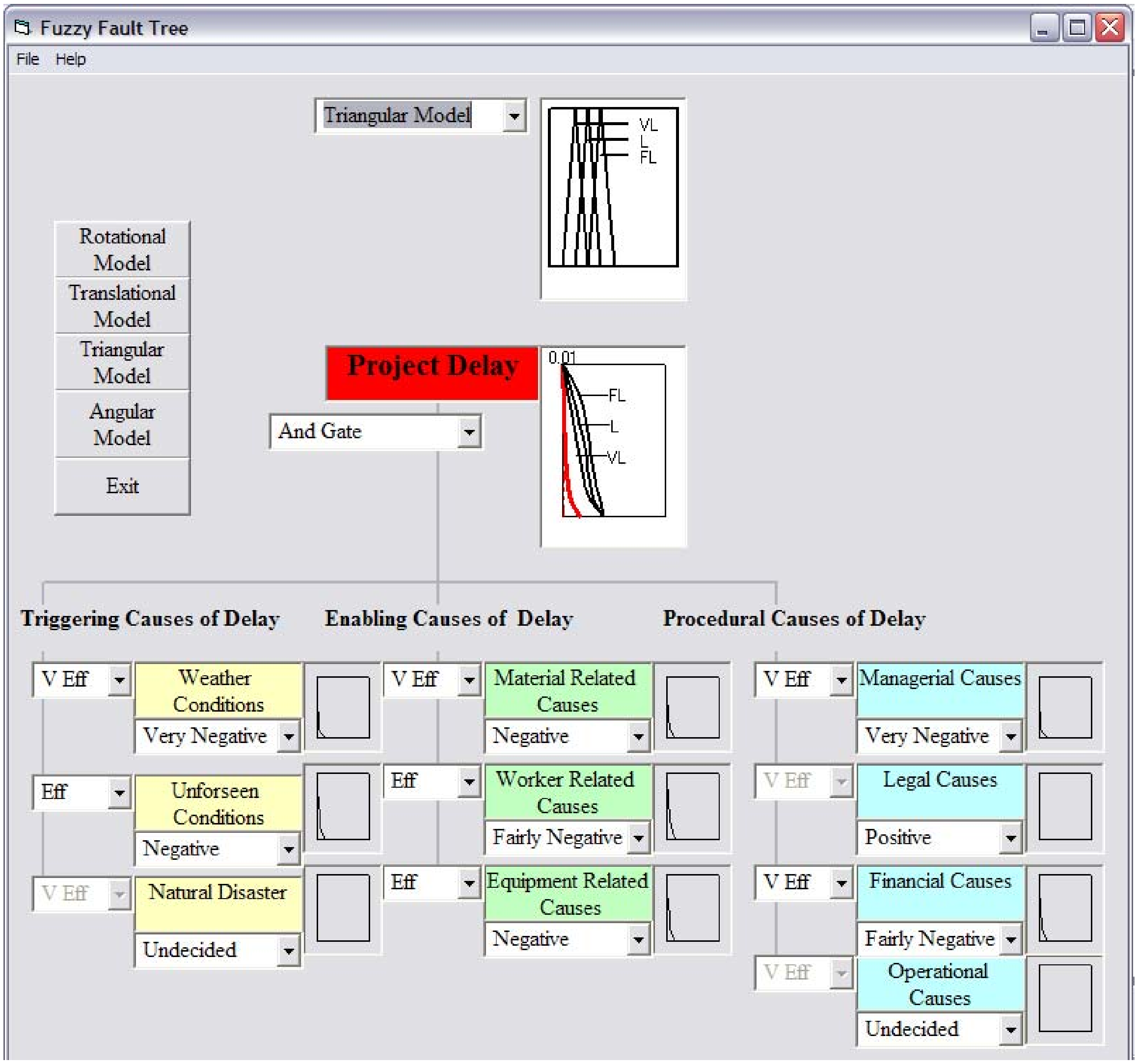


Figure 89. Likelihood of Project Delay with AND Operation using the Fuzzy Triangular Model.

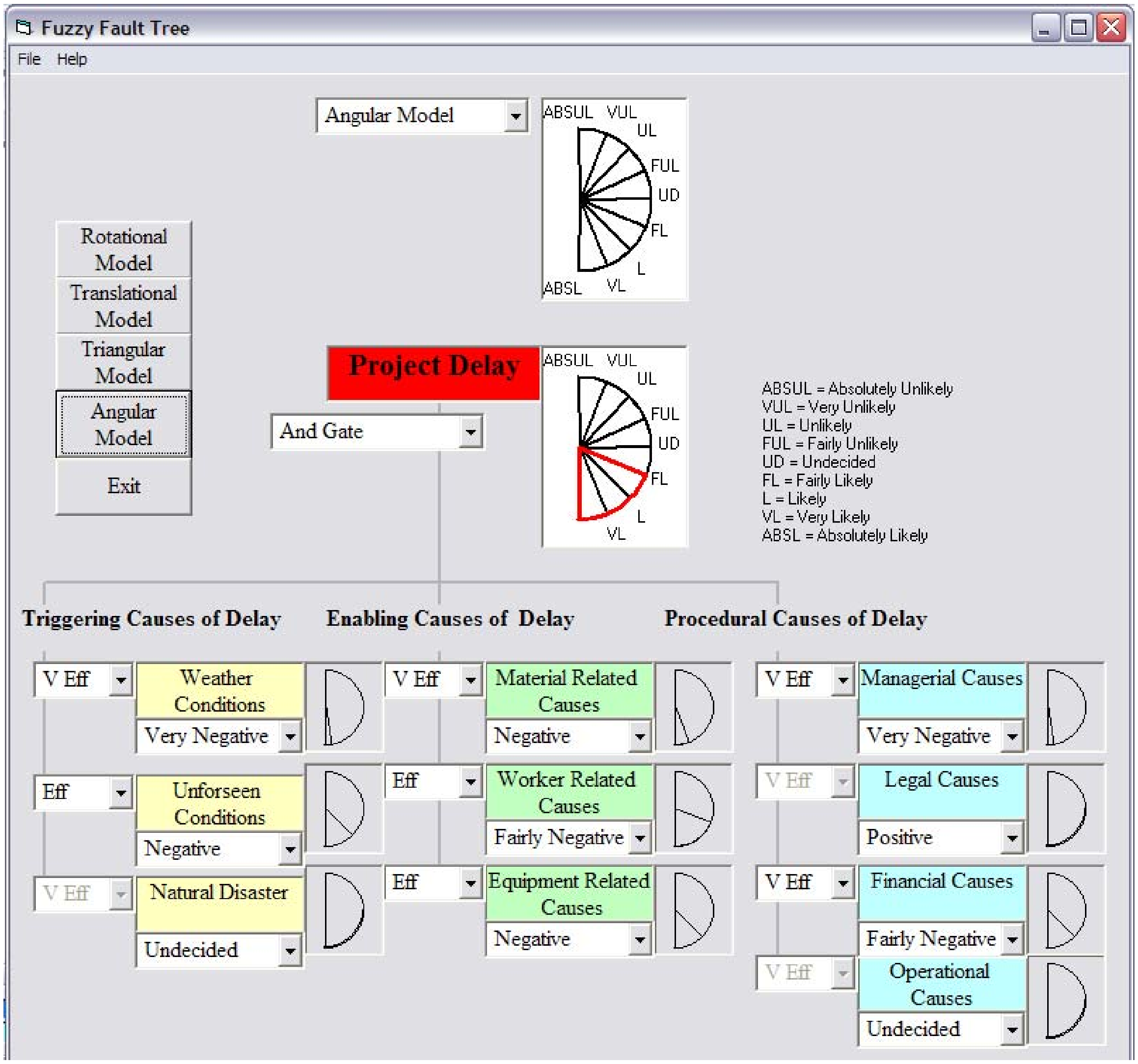


Figure 90. Likelihood of Project Delay with AND Operation using the Fuzzy Angular Model.

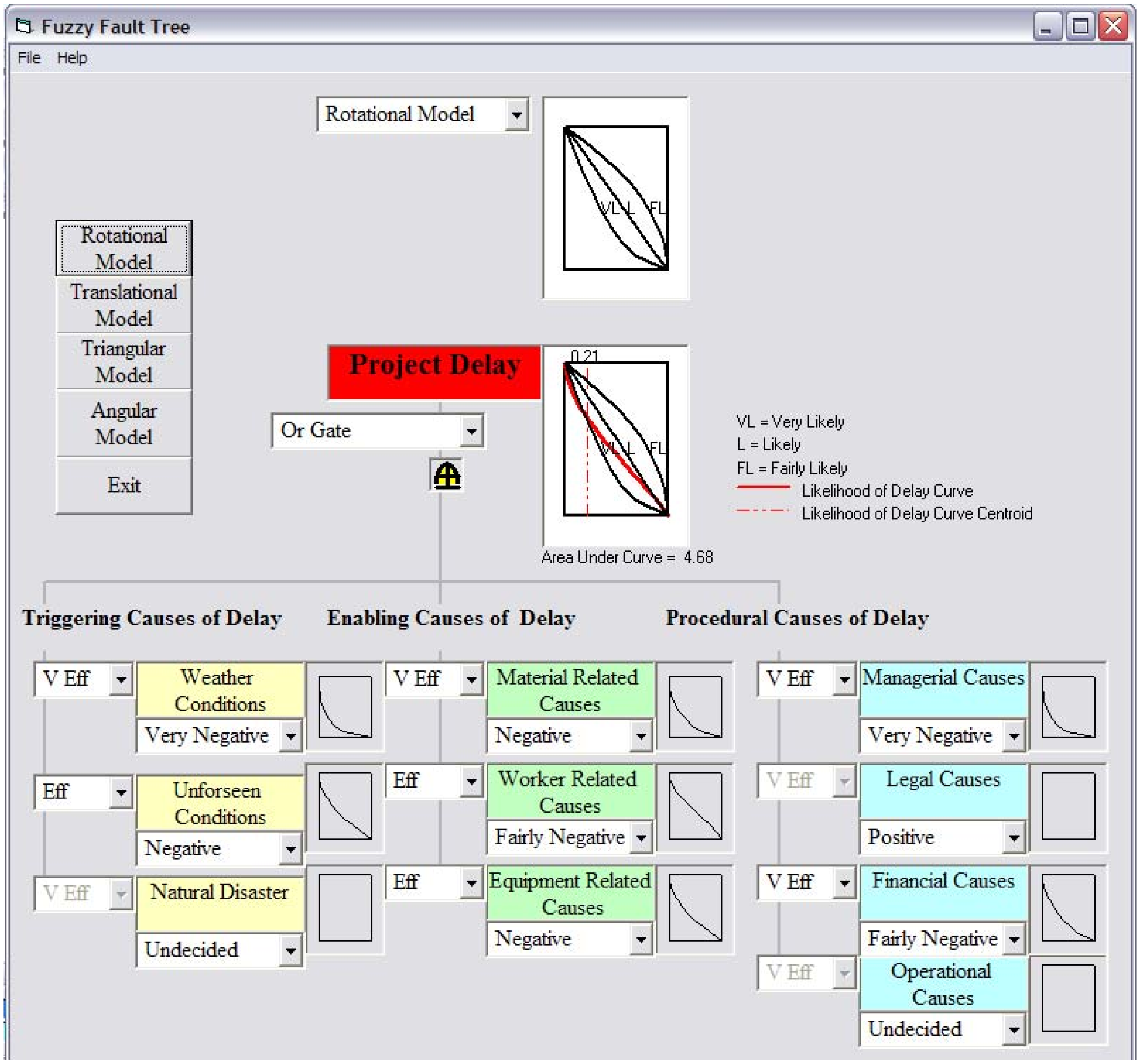


Figure 91. Likelihood of Project Delay with OR Operation using the Fuzzy Rotational Model.

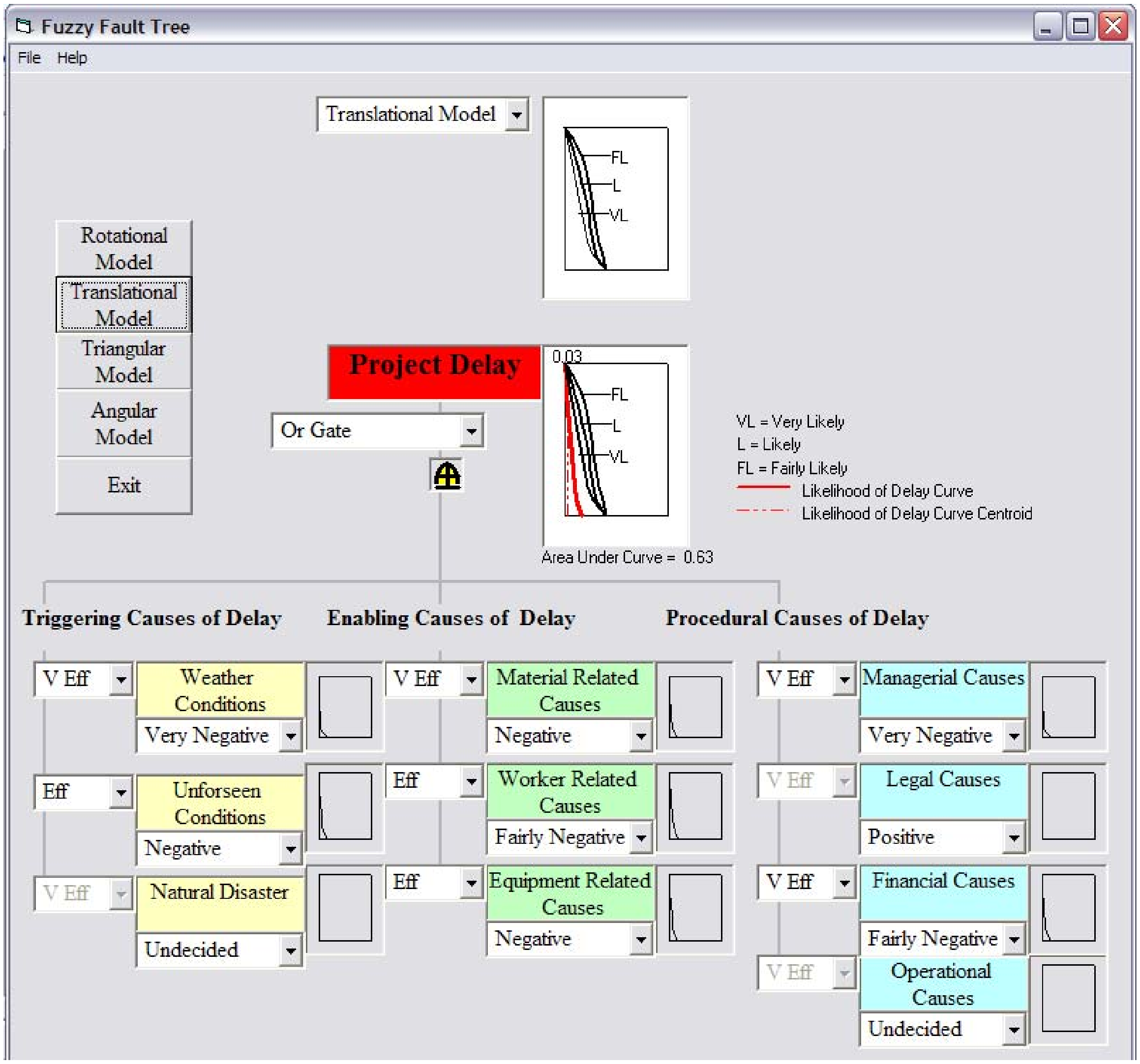


Figure 92. Likelihood of Project Delay with OR Operation using the Fuzzy Translational Model.

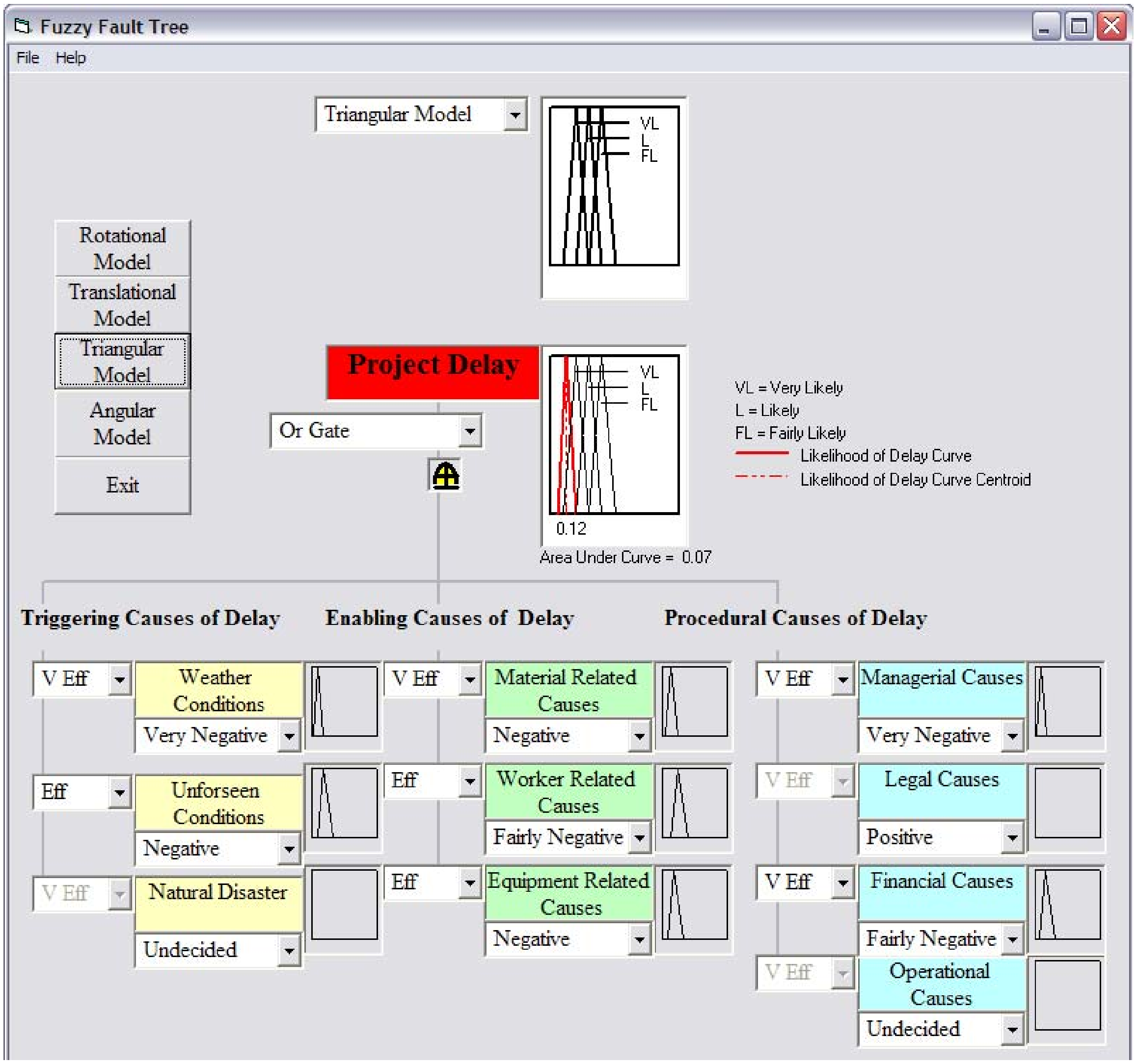


Figure 93. Likelihood of Project Delay with OR Operation using the Fuzzy Triangular Model.

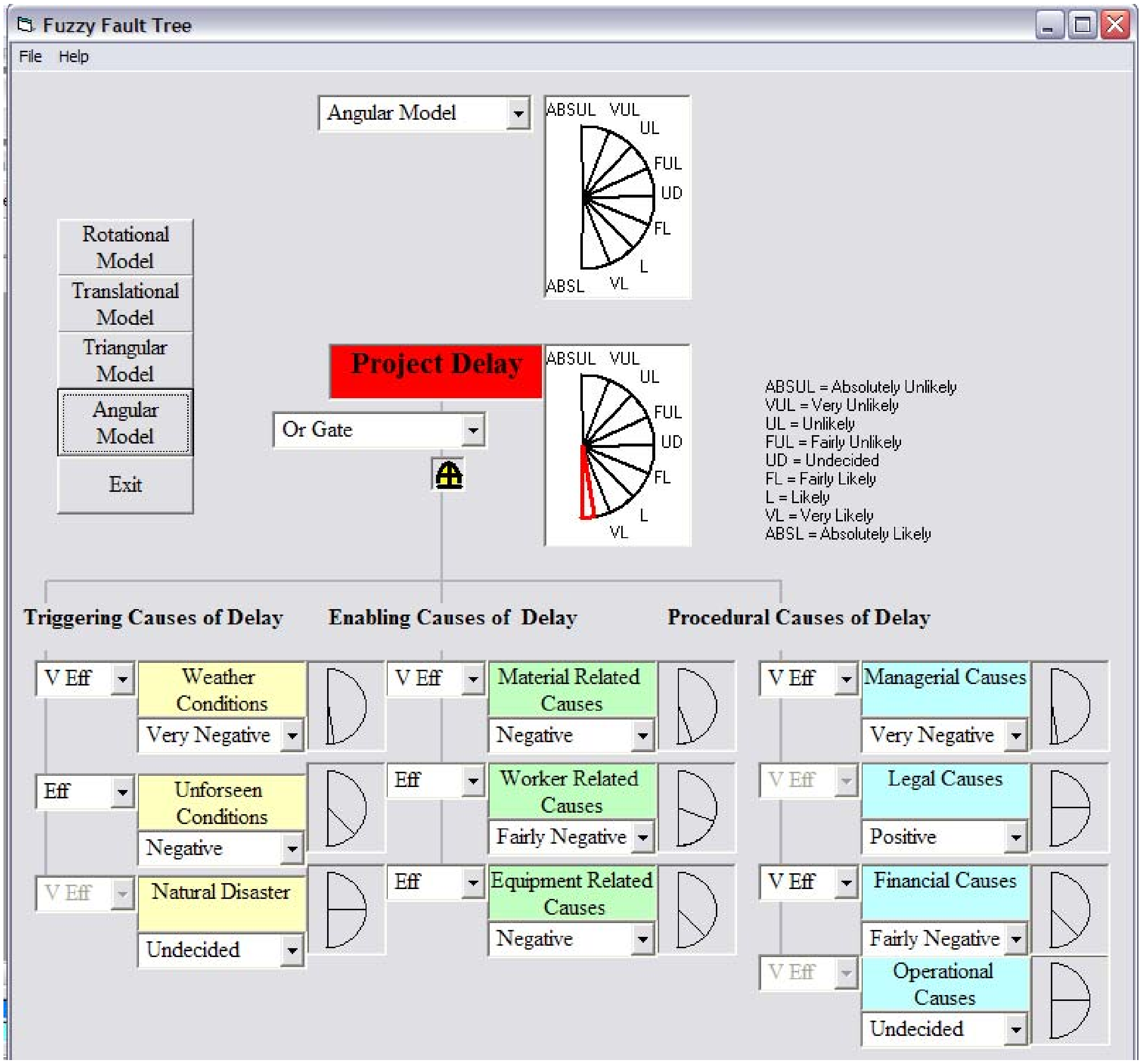


Figure 94. Likelihood of Project Delay with OR Operation using the Fuzzy Angular Model.

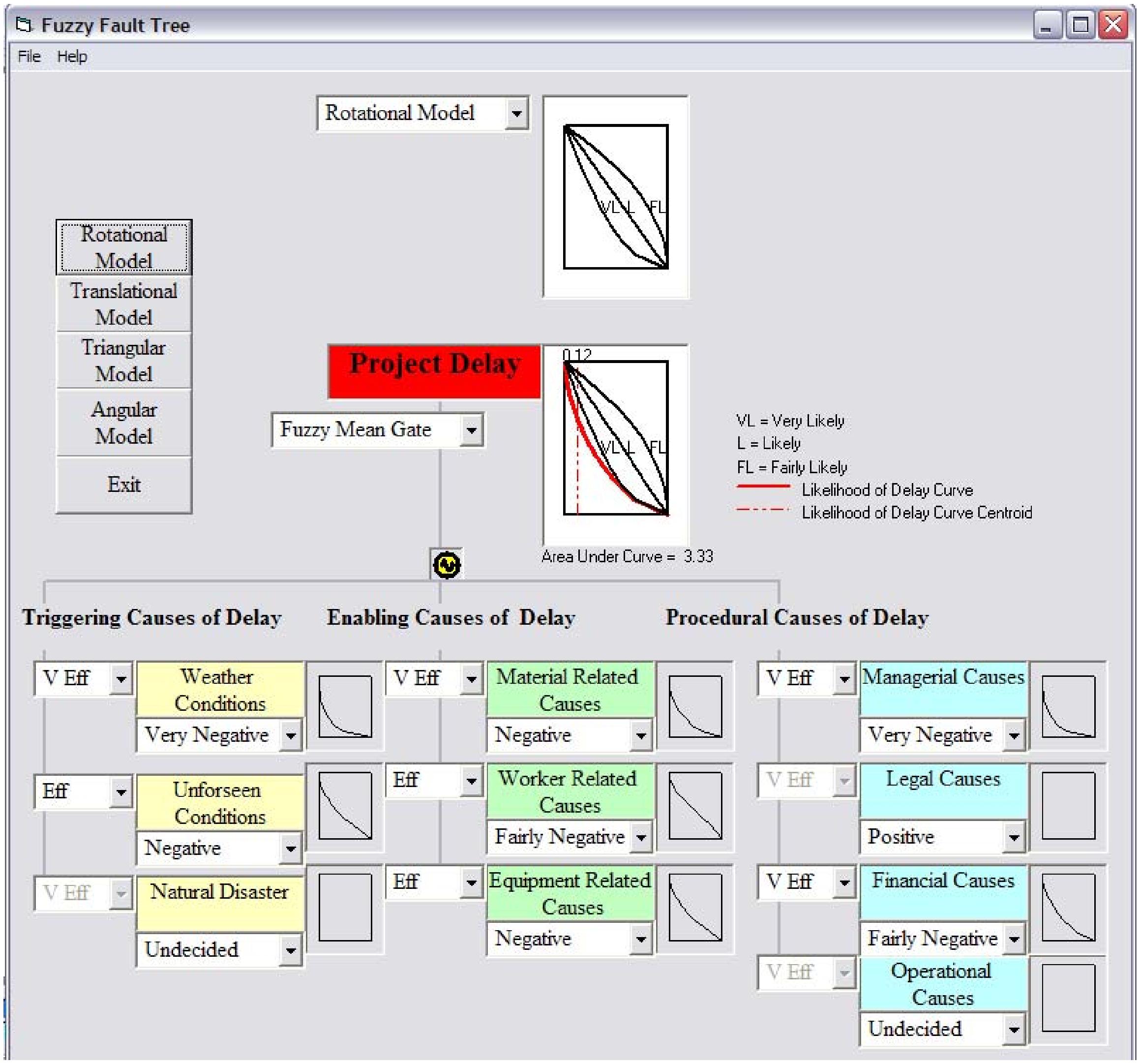


Figure 95. Likelihood of Project Delay with Fuzzy Mean Operation using the Fuzzy Rotational Model.

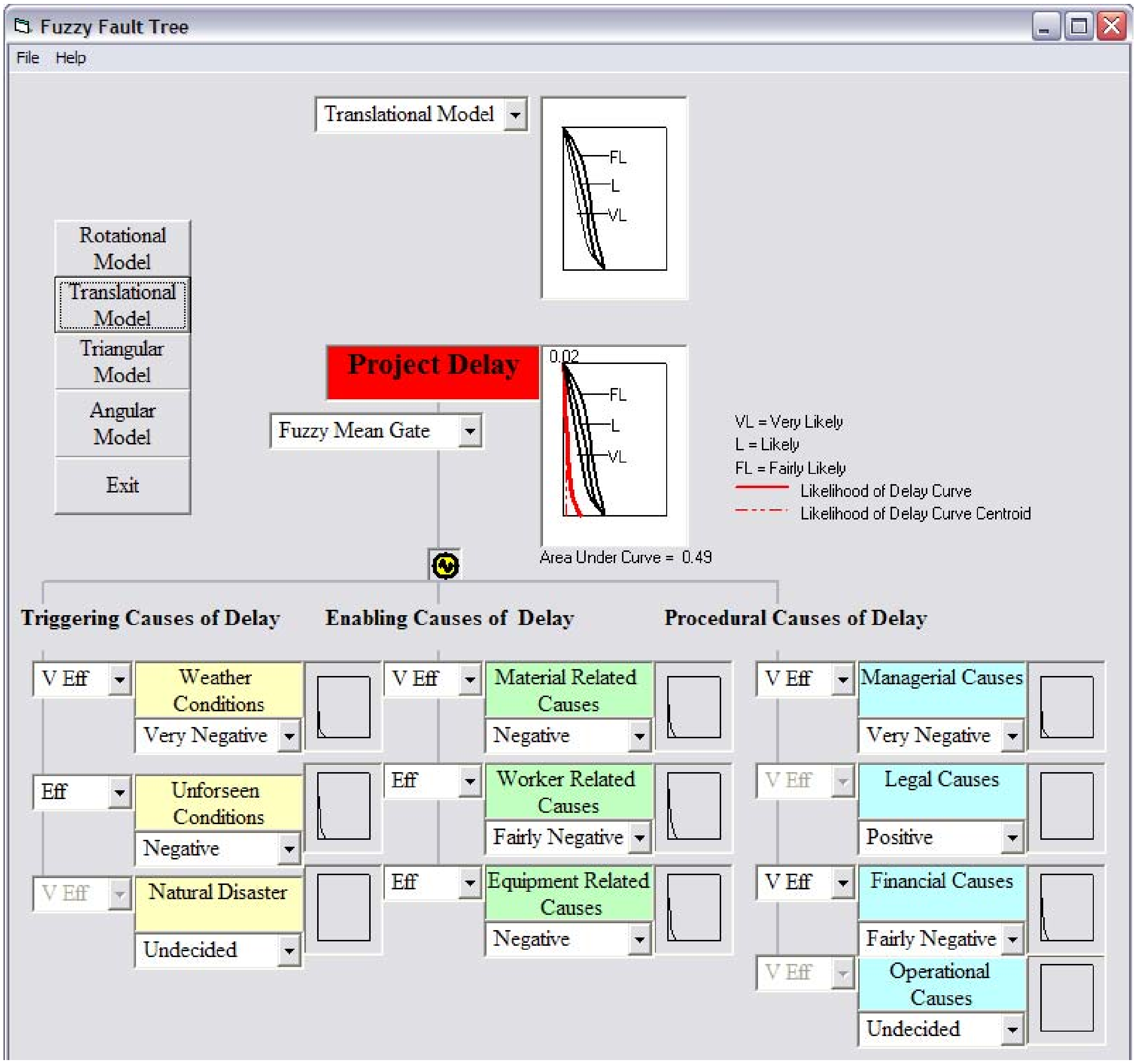


Figure 96. Likelihood of Project Delay with Fuzzy Mean Operation using the Fuzzy Translational Model.

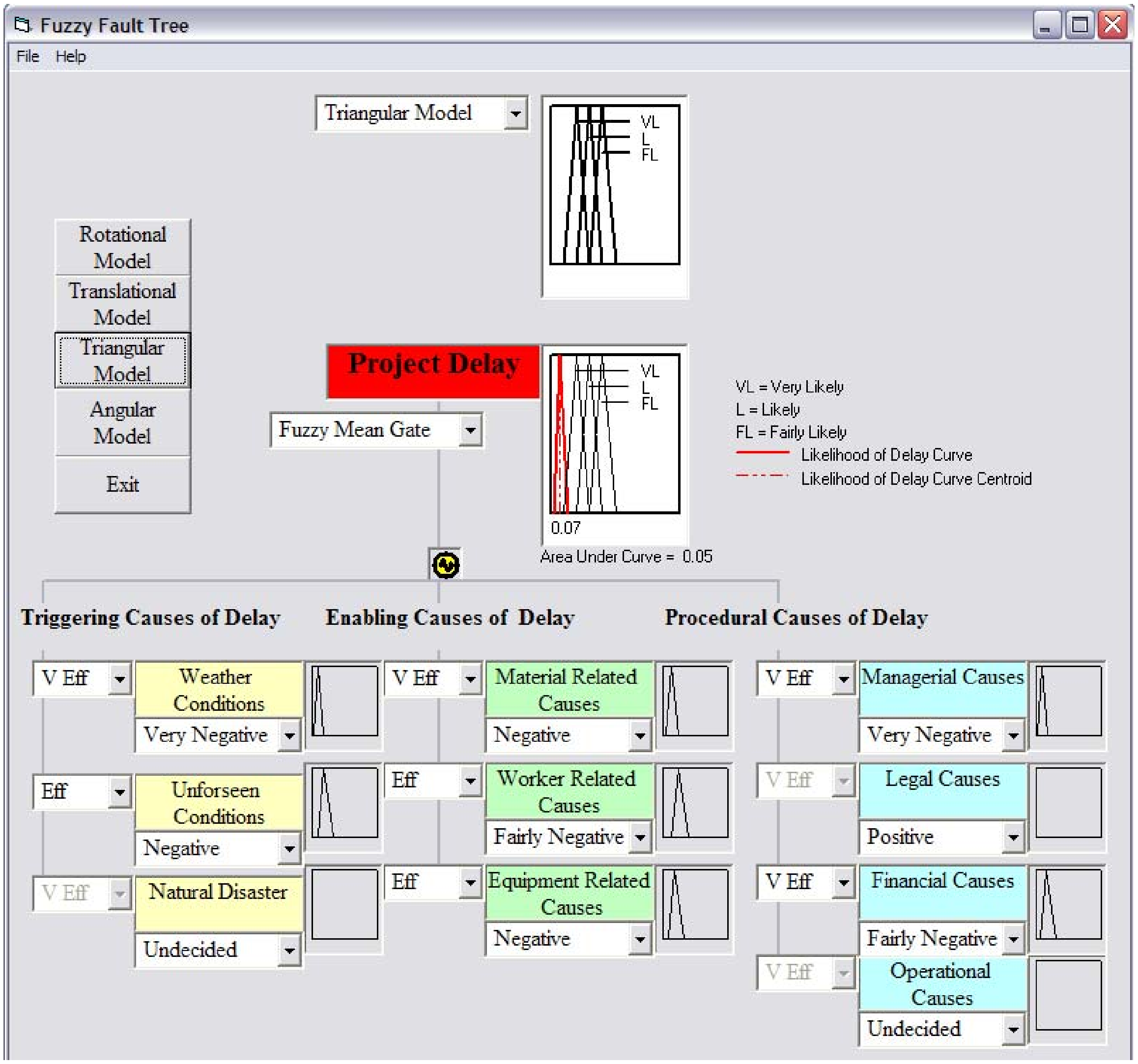


Figure 97. Likelihood of Project Delay with Fuzzy Mean Operation using the Fuzzy Triangular Model.

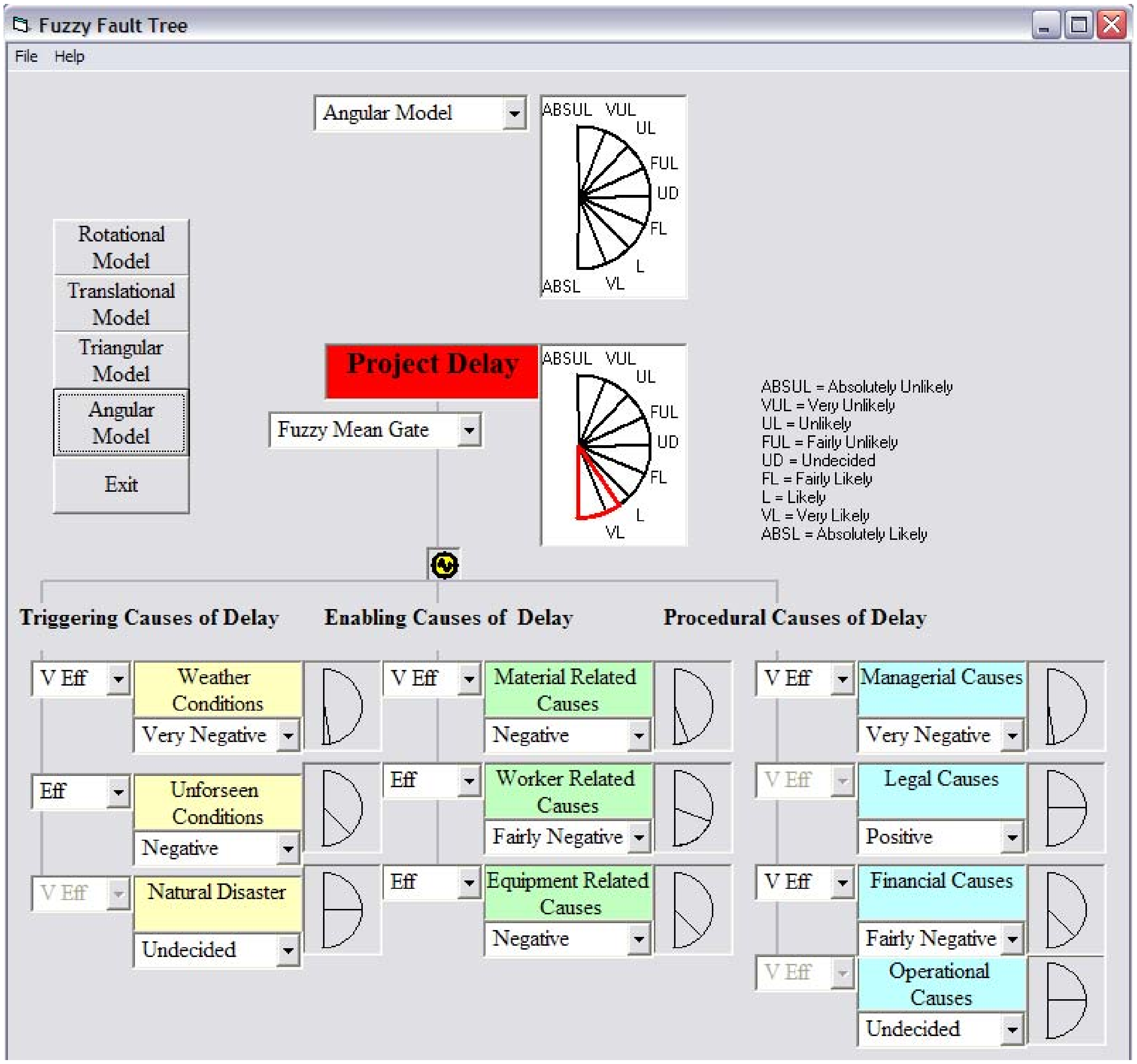


Figure 98. Likelihood of Project Delay with Fuzzy Mean Operation using the Fuzzy Angular Model.

In case the user makes a mistake by selecting a certain model and then the user clicks on a different model for analysis, the computer software prompts the user with a pop-up message as shown in Figure 99 provides the pop-up screen.

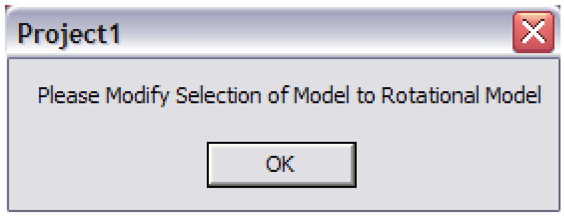


Figure 99. Prompt Screen to Warn Computer Software Users In Case of Wrong Selections.

Chapter 7

VALIDATION OF STUDY

7.1 Introduction

Validation of the computer model has been conducted using a survey that was distributed to independent expert who are experts in the construction industry and fuzzy logic experts. The survey was focused on potential users opinion in terms of the appearance of the computer model screens, the user interface of the computer model, and the importance and applicability of the computer model. The survey included ten questions where answers to these questions would range from absolutely positive to absolutely negative. Table 7 provides a list of the questions distributed to independent experts and fuzzy logic experts.

1. Appearance 1. Layout of screens (layout in terms of the proportions of the screen). 2. Information in each screen (is the information adequate and complete). 3. Clarity of screens (the clarity in terms of font size, font used, etc.) 4. Overall appearance of the screen.
2. User Interface 1. Overall navigation though out the program and the navigation between the screens. 2. Easiness of making selections in the computer program. 3. Overall user interface of the computer program.
3. The Computer Program 1. Importance of this topic (delays in construction projects) to the construction industry. 2. Application of the computer model to the construction industry. 3. Result of this computer program.

Table 7. Questions in Survey Distributed to Independent and Fuzzy logic Experts.

The survey has been given to two groups of experts, the independent experts and the fuzzy logic experts. The survey is not meant to be used for statistical analysis since it is completed by experts using subjective judgment. Results of each group are discussed below.

7.2 Independent Experts Results

The results of appearance validation questions provided by independent experts are shown below.

1. How do you rate the layout of screens (layout in terms of the proportions of the screen)?

Absolutely poor	
Very poor	
Poor	
Fairly poor	
Neutral	28.57%
Fairly good	21.43%
Good	35.71%
Very good	14.29%
Absolutely good	

2. How do you rate the information in each screen (is the information adequate and complete)?

Absolutely inadequate and incomplete	
Very inadequate and incomplete	
Inadequate and incomplete	
Fairly inadequate and incomplete	8.57%
Neutral	21.43%
Fairly adequate and complete	28.57%
Adequate and complete	14.29%
Very adequate and complete	7.14%
Absolutely adequate and complete	

3. How do you rate the clarity of screens (the clarity in terms of font size, font used, etc.)

Absolutely unclear	
Very unclear	
Unclear	
Fairly unclear	
Neutral	
Fairly clear	14.29%
Clear	28.57%
Very clear	35.71%
Absolutely clear	21.43%

4. How do you rate the overall appearance of the screen?

Absolutely poor	
Very poor	
Poor	
Fairly poor	
Neutral	21.43%
Fairly good	7.14
Good	42.86%
Very good	28.57%
Absolutely good	

The results of the user interface validation questions provided by independent experts are shown below.

1. How do you rate the overall navigation though out the program and the navigation between the screens?

Absolutely poor	
Very poor	
Poor	7.14%
Fairly poor	7.14%
Neutral	35.71%
Fairly good	14.29%
Good	21.43%
Very good	14.29%
Absolutely good	

2. How do you rate the easiness of making selections in the computer program?

Absolutely difficult	
Very difficult	
Difficult	
Fairly difficult	7.14%
Neutral	7.14%
Fairly easy	50.00%
Easy	21.43%
Very easy	14.29%
Absolutely easy	

3. How do you rate the overall user interface of the computer program?

Absolutely poor	
Very poor	
Poor	7.14%
Fairly poor	14.29%
Neutral	14.29%
Fairly good	35.71%
Good	14.29%
Very good	14.29%
Absolutely good	

The results of the computer program validation questions provided by independent experts are shown below.

1. How do you rate the importance of this topic (delays in construction projects) to the construction industry?

Absolutely unimportant	
Very unimportant	
Unimportant	
Fairly unimportant	
Neutral	
Fairly important	7.14%
Important	14.29%
Very important	35.71%
Absolutely important	42.86%

2. How do you rate the application of the computer model to the construction industry (do you think that this computer program can be implemented in real projects?

Absolutely inapplicable	
Very inapplicable	7.14%
Inapplicable	21.43%
Fairly inapplicable	
Neutral	35.71%
Fairly applicable	14.29%
Applicable	21.43%
Very applicable	
Absolutely applicable	

3. How do you rate the result of this computer program (is this result reasonable?)

Absolutely unreasonable	
Very unreasonable	
Unreasonable	
Fairly unreasonable	7.14%
Neutral	35.71%
Fairly reasonable	28.57%
Reasonable	21.43%
Very reasonable	7.14%
Absolutely reasonable	

Figure 100 provides a graph that illustrates appearance validation questions results provided by independent experts. Figure 101 provides a graph that illustrates user interface validation questions results provided by independent experts. Figure 102 provides a graph that illustrates the computer program validation questions provided by independent experts.

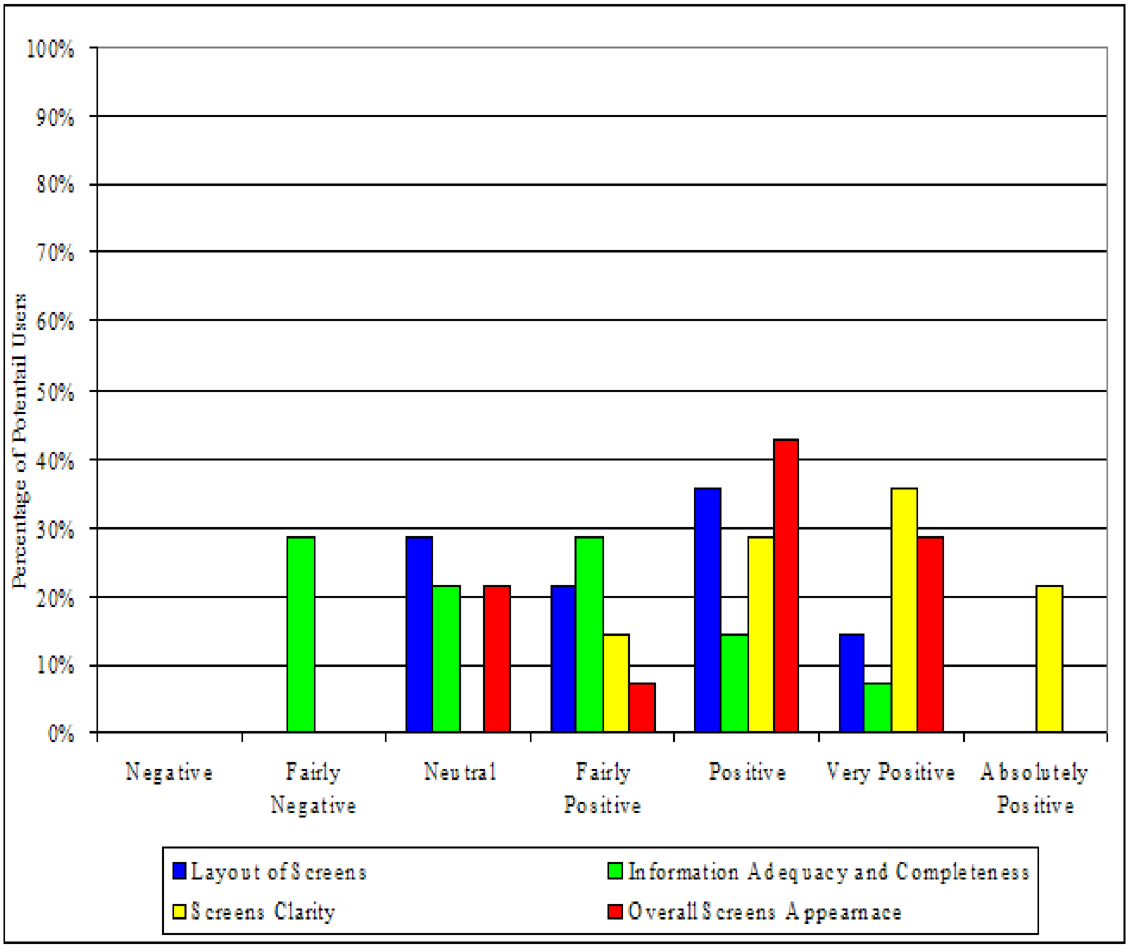


Figure 100. Appearance Validation Questions Results Provided by Independent Experts.

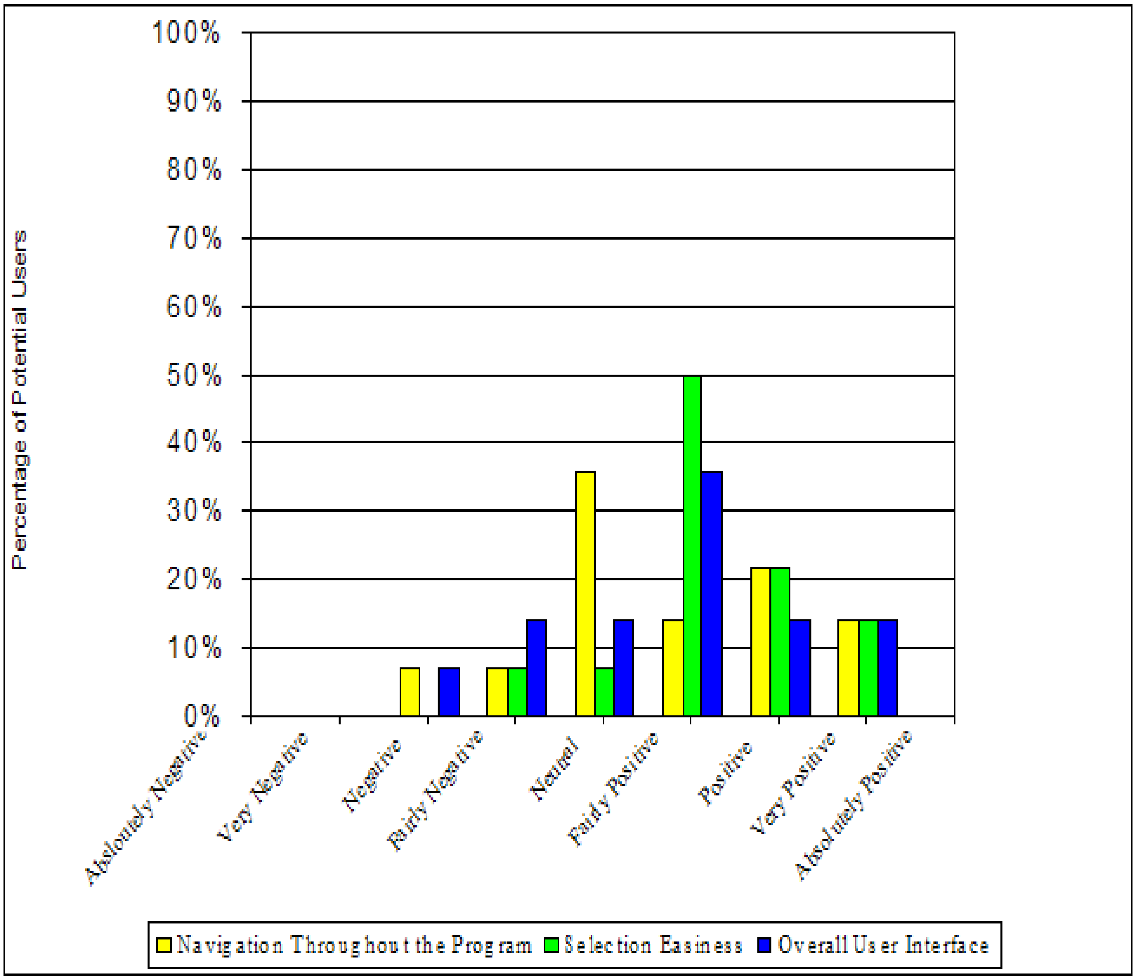


Figure 101. User Interface Validation Questions Results Provided by Independent Experts.

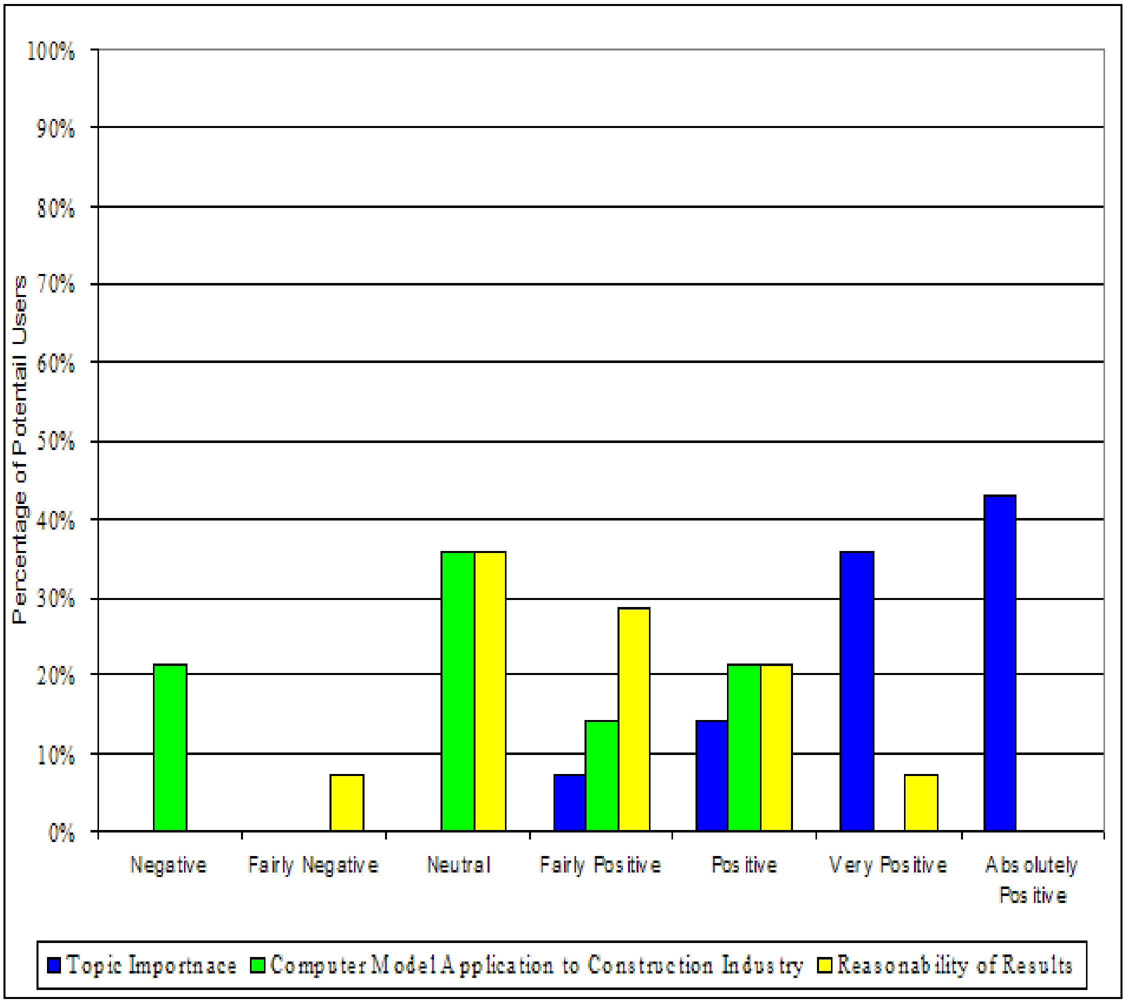


Figure 102. Computer Program Validation Questions Provided by Independent Experts.

7.3 Fuzzy Logic Experts

Validation of fuzzy logic experts has been performed in two rounds. First the questions were given to fuzzy logic experts and once the feedback is received, the corrections were implemented to the computer program and the same questions were given again to the same group of fuzzy logic experts. The comments received after the first validation are summarized as follows:

1. Some fuzzy logic experts suggested that implementation of the model by users from the construction industry might be hard since these users do not have any fuzzy logic knowledge.
2. Many experts that validated the fuzzy fault tree model indicated that there is a need to include a set of guidelines and examples on the use of the computer program. Some experts suggested a demo for illustrative purposes, which could be introduced in the computer program to ease the use of the computer program.
3. Some fuzzy logic experts indicated some formatting issues such as layout the screens, and font size.

After conducting the second validation, considerable improvement has been encountered in information provided on all screens and in screens clarity. The overall screens appearance remained the same after conducting the second validation. Fuzzy logic experts' opinion about the layout of the screens declined after the second validation, but no reasons for such decline was provided.

The results of appearance validation questions provided by fuzzy logic experts are shown below in Tables 8, 9, 10, and 11.

Results	**First Validation**	**Second Validation**
Absolutely poor		
Very poor		
Poor		
Fairly poor		
Neutral		
Fairly good	20%	40%
Good	40%	40%
Very good	40%	20%
Absolutely good		

Table 8. Layout of Screens Validations Results.

Results	First Validation	Second Validation
Absolutely inadequate and incomplete		
Very inadequate and incomplete		
Inadequate and incomplete		
Fairly inadequate and incomplete	20%	
Neutral	60%	
Fairly adequate and complete	20%	
Adequate and complete		80%
Very adequate and complete		20%
Absolutely adequate and complete		

Table 9. Information Screen Validation Results.

Results	**First Validation**	**Second Validation**
Absolutely unclear		
Very unclear		
Unclear		
Fairly unclear	40%	
Neutral	40%	
Fairly clear	20%	20%
Clear		60%
Very clear		20%
Absolutely clear		

Table 10. Screens Clarity Validation Results.

Results	**First Validation**	**Second Validation**
Absolutely poor		
Very poor		
Poor		
Fairly poor		
Neutral		
Fairly good	20%	20%
Good	60%	60%
Very good	20%	20%
Absolutely good		

Table 11. Appearance of Screens Validation Results.

The results encountered after the second validation in terms of questions related to the user interface indicated a considerable improvement in terms of both the navigation throughout the program and between screens and the level of easiness of making selections in the computer program. The fuzzy logic experts indicated a decline in the overall user interface but no particular reason has been provided for such decline.

The results of the user interface validation questions provided by fuzzy logic experts are shown below in Tables 12, 13, and 14.

Results	**First Validation**	**Second Validation**
Absolutely poor		
Very poor		
Poor		
Fairly poor		
Neutral	20%	
Fairly good		20%
Good	20%	40%
Very good	60%	20%
Absolutely good		20%

Table 12. Navigation Through out the Program and Between Screens Validation Results.

Results	First Validation	Second Validation
Absolutely difficult		
Very difficult		
Difficult		
Fairly difficult		
Neutral		
Fairly easy		
Easy	60%	60%
Very easy	40%	20%
Absolutely easy		20%

Table 13. Easiness of Making Selections in the Computer Program Validation Results.

Results	**First Validation**	**Second Validation**
Absolutely poor		
Very poor		
Poor		
Fairly poor		
Neutral		
Fairly good	20%	40%
Good	40%	20%
Very good	40%	40%
Absolutely good		

Table 14. Overall User Interface Validation Results.

Fuzzy logic experts' opinion in terms of the topic importance has improved after the second validation. Also, the fuzzy logic experts' indicated that they think that the computer model is more applicable to the industry after the second round of validation. The overall computer program results have improved according to the fuzzy logic experts after the second validation.

The results of the computer program validation questions provided by fuzzy logic experts are shown below in Tables 15, 16, and 17.

Results	**First Validation**	**Second Validation**
Absolutely unimportant		
Very unimportant		
Unimportant		
Fairly unimportant		
Neutral	20%	
Fairly important		
Important	20%	20%
Very important	20%	40%
Absolutely important	40%	40%

Table 15. Topic Importance Validation Results.

Results	**First Validation**	**Second Validation**
Absolutely inapplicable		
Very inapplicable		
Inapplicable		
Fairly inapplicable		
Neutral	40%	
Fairly applicable		20%
Applicable	60%	60%
Very applicable		20%
Absolutely applicable		

Table 16. Computer Model Application to Construction Industry Validation Results.

Results	First Validation	Second Validation
Absolutely unreasonable		
Very unreasonable		
Unreasonable		
Fairly unreasonable		
Neutral		
Fairly reasonable	20%	
Reasonable	40%	60%
Very reasonable	40%	40%
Absolutely reasonable		

Table 17. Results of Computer Program Validation.

Figures 103, and 104 provide graphs that illustrate appearance validation questions results provided by fuzzy logic experts for first and second validations. Figures 105, and 106 provide graphs that illustrate user interface validation questions results provided by fuzzy logic experts for first and second validations. Figures 107, and 108 provide graphs that illustrate the computer program validation questions provided by fuzzy logic experts for first and second validations.

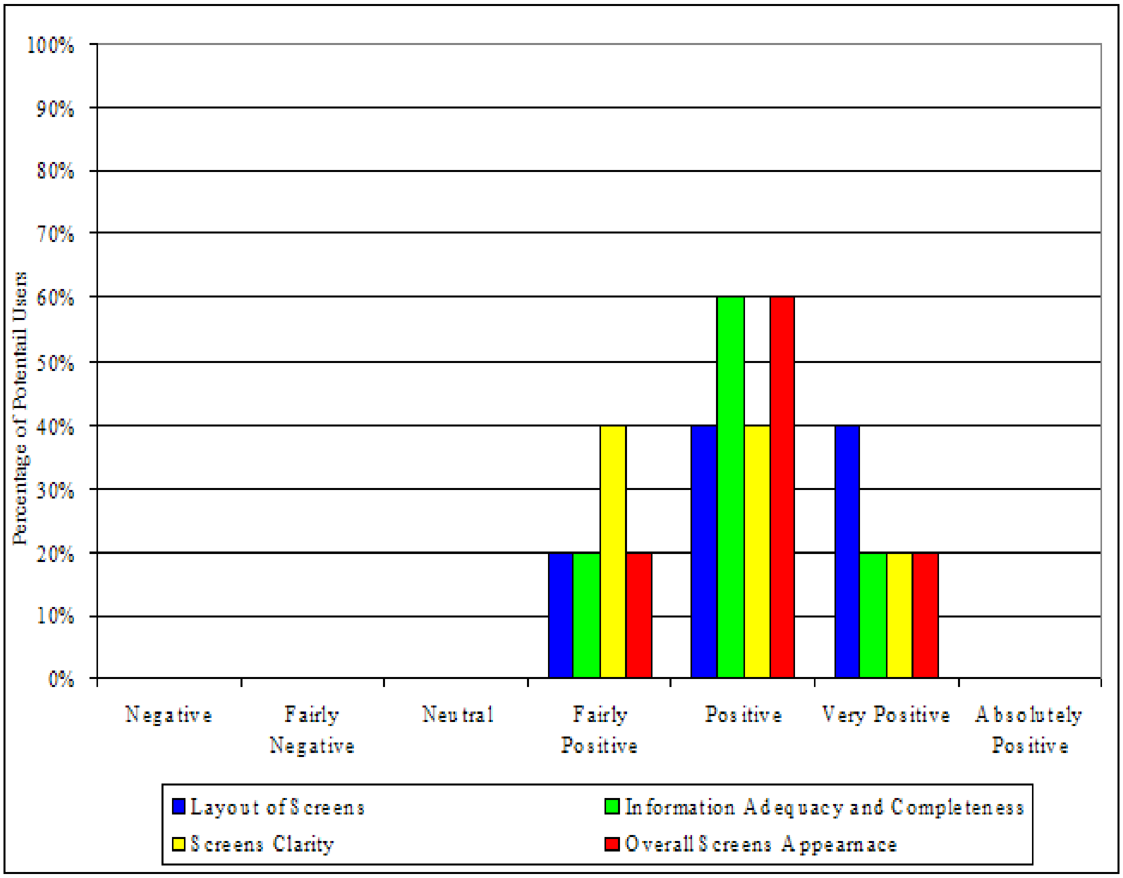


Figure 103. Appearance Validation Questions Results Provided by Fuzzy Logic Experts for First Validation.

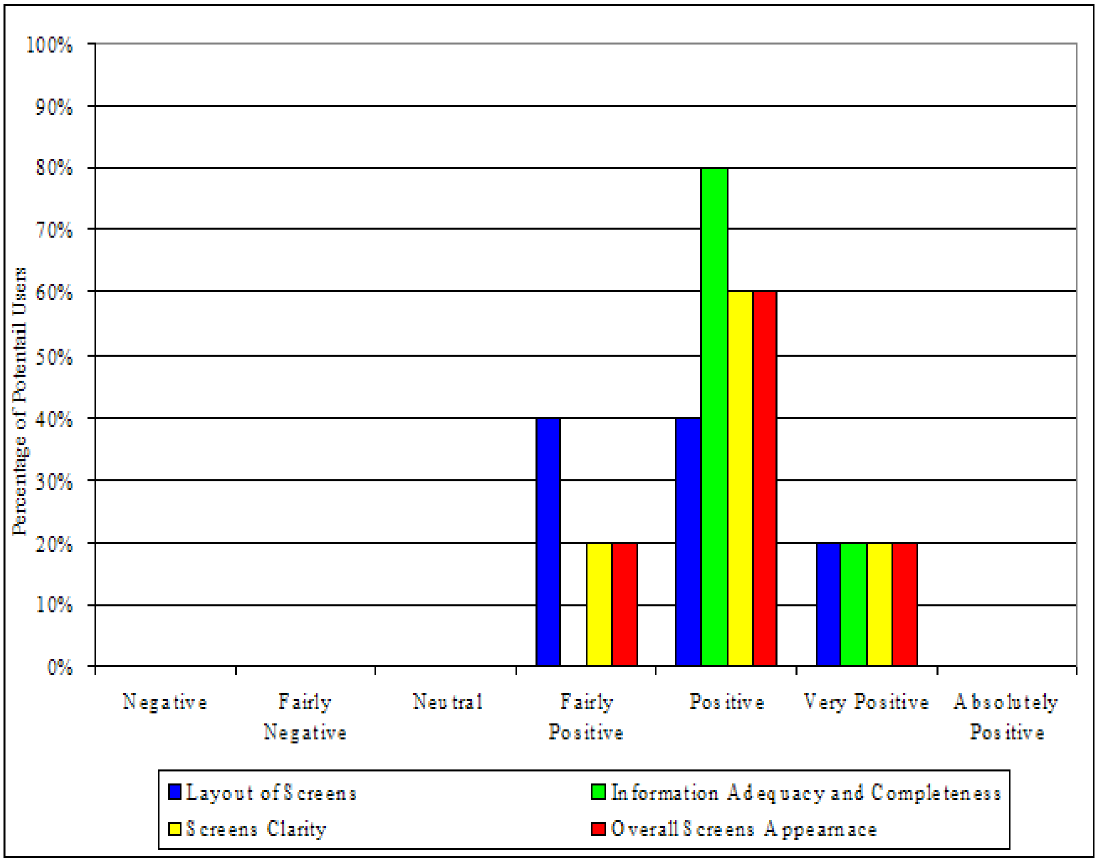


Figure 104. Appearance Validation Questions Results Provided by Fuzzy Logic Experts for Second Validation.

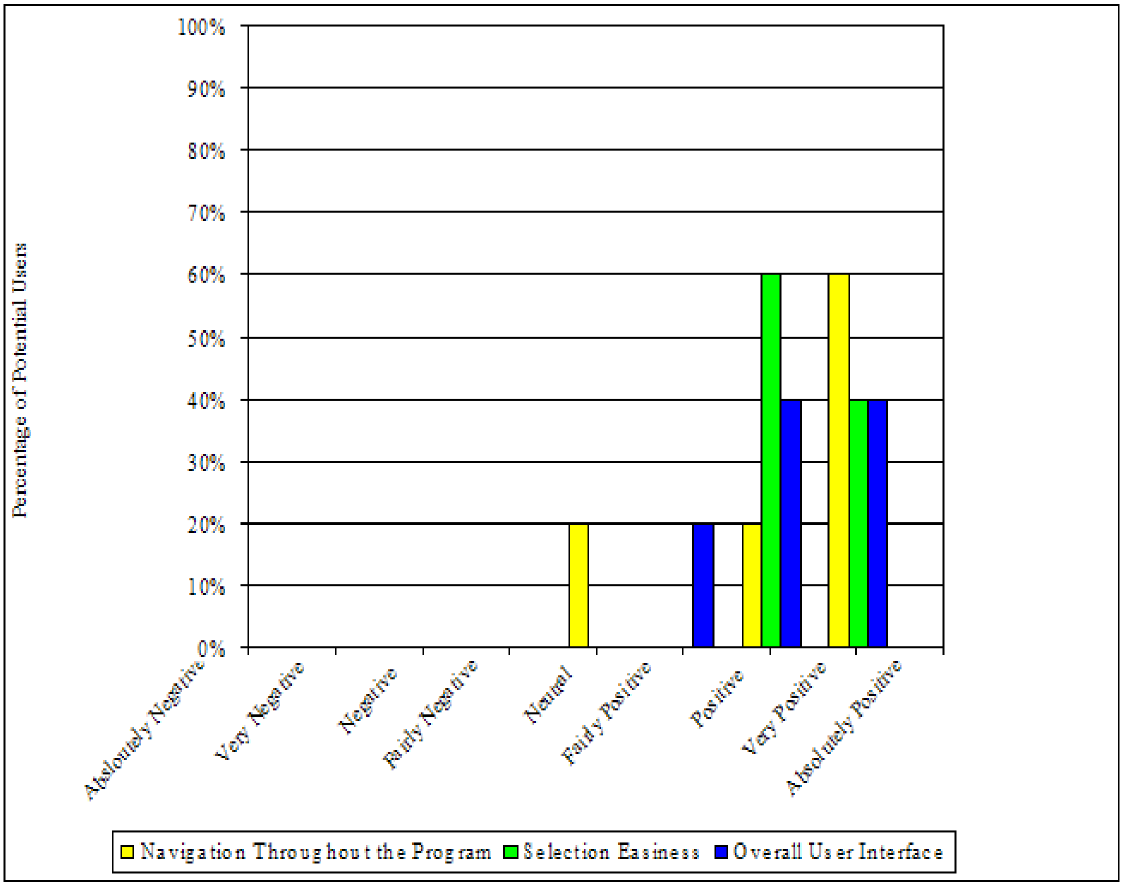


Figure 105. User Interface Validation Questions Results Provided by Fuzzy Logic Experts for First Validation.

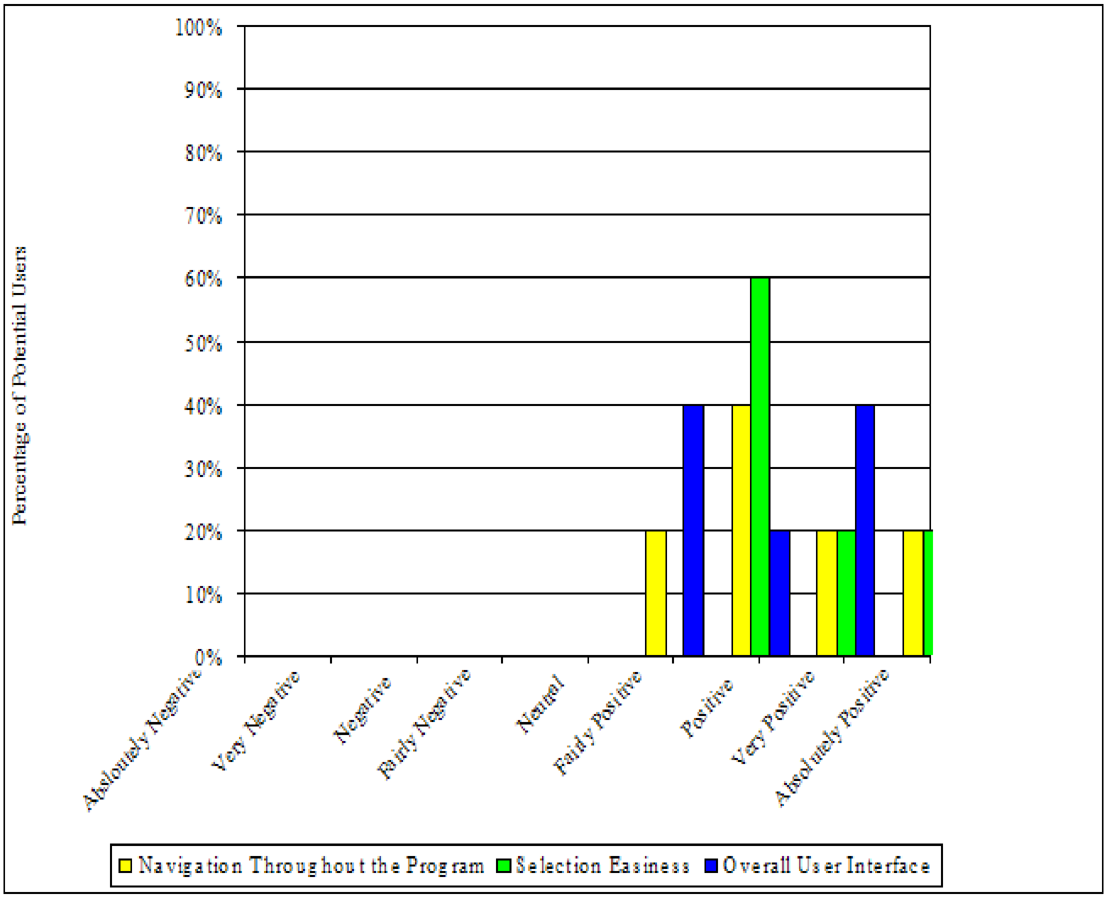


Figure 106. User Interface Validation Questions Results Provided by Fuzzy Logic Experts for Second Validation.

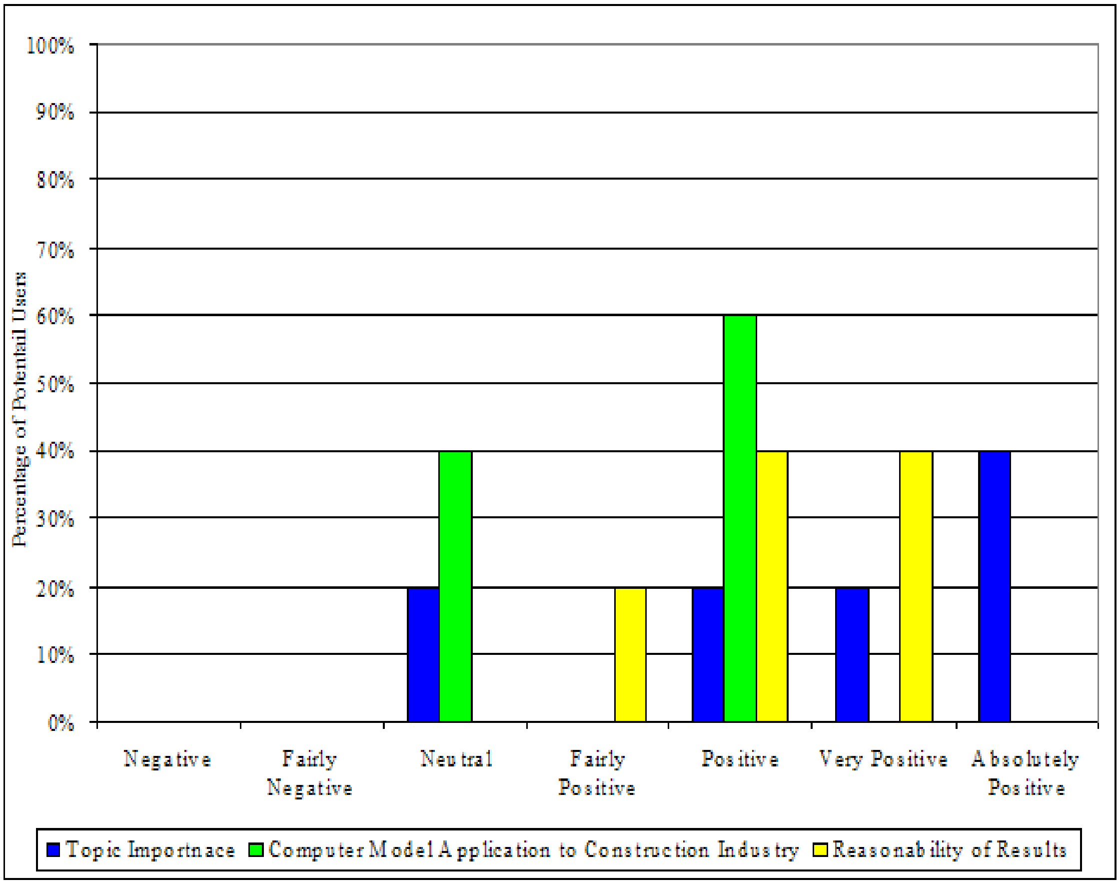


Figure 107. Computer Program Validation Questions Provided by Fuzzy Logic Experts for First Validation.

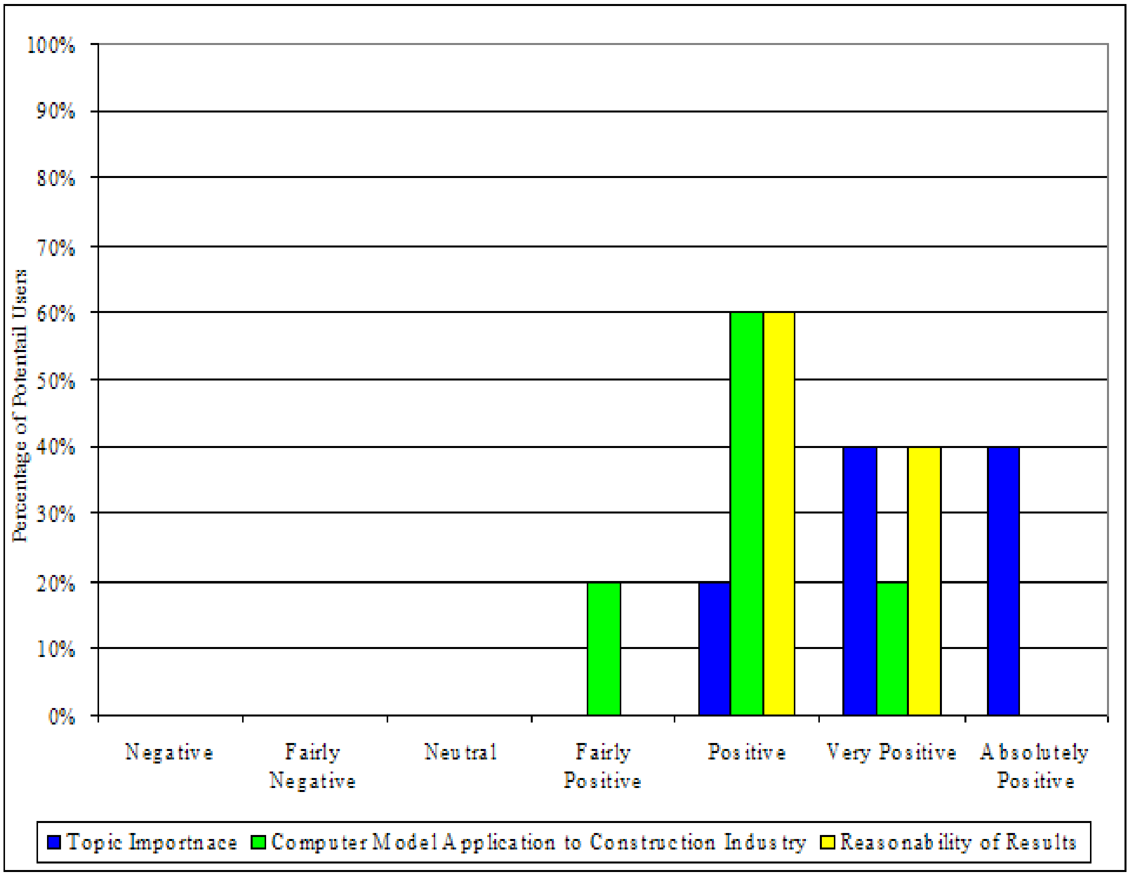


Figure 108. Computer Program Validation Questions Provided by Fuzzy Logic Experts for Second Validation.

7.4 Independent Experts Comments

Comments provided by independent experts are as follows:

1. Implementation of the program in the current form might be difficult especially to schedule engineers. Some experts suggested including a broader help menu and some examples on the use of the program.
2. Results might not be clear to typical users.
3. Some experts indicated that some terms like V.Eff, Eff, F.Eff are not clear. The suggestion has been taken into consideration and an abbreviation screen has been added to the program.
4. Some experts indicated that the models do not include the positive values (for example, good weather condition.) The program is intended to model only negative aspects of the project and is limited to negative conditions, which might result in project delay.
5. Some of the comments indicated that the program is very general. Future studies that would study each factor in further details is suggested for future research.
6. Most of experts indicated that the topic is very important in the construction industry and suggested further detailed studies of different factors that contribute to project delay.
7. Some experts indicated that traditional methods of scheduling are sufficient to quantify delays and that new methods are not needed as management needs to deal with unpredictable delays.

Chapter 8

CONCLUSION AND RECOMMENDATIONS OF STUDY

8.1 Summary of Study

Delays in construction projects are problematic to all parties involved in a project. If potential delays are not studied and analyzed prior to their occurrence, management might be faced with a problem that needs a reactive approach and this situation might result in litigations and disputes. In the planning phase, management must adopt a proactive approach to mitigate and eliminate future challenges. Among the different challenges that face management is time. In case the actual time needed to complete tasks differs from the planned time, the project might end up consuming more time than planned. In early planning phases management needs to implement proactive methods to minimize and if possible eliminate delays. In case sources of delay are hard to manage, management needs to increase the planned time required to complete task(s).

Delay is considered as an unfavourable event that managers plan for prior to project execution phase. Managers draw hypothetical scenarios of what could go wrong in the execution phase to avoid any source of uncertainty. What-if kind of planning is essential to determine hypothetical scenarios of future events and to manage all sources of uncertainties. Management depends on the experience of the managers involved in the what-if hypothetical scenario concerning what could cause project delay. Success of such analysis depends on the experience of experts involved in the analysis and their possibility of predicting what could take place in the future.

In order to analyze project delay, the causes that contribute to delay are dealt with more easily than other factors suggested by different methods of delay classification. In general, the causes of delay can be classified into three categories: procedural, triggering, and enabling. Procedural causes are hidden events that produce both enabling and triggering events and arise from the interrelationship among various parties involved in the project. Triggering delay causes can be defined as external delay causes while enabling delay causes can be defined as internal delay causes. Different causes of delay affect the top undesired event (project delay) in different degrees. There is a need to implement a method of analysis that captures different degrees of effectiveness for different causes of project delay.

Different methods of analysing delay can be adopted to mitigate the likelihood of project delay. Deterministic scheduling methods that depend on increasing the planned time of activities or adding time buffers to the activity duration can be erroneous since these methods are intended to manage high probability of occurrence, low impact uncertainties. Such contingency planning methods fail in case low probability of occurrence and high impact events take place. For example, in case a natural disaster takes place such as a flood or an earthquake, such an event might halt the project. In such a case, implementation of deterministic scheduling methods such as the critical path method is questionable.

Fault tree analysis is a deductive approach that is designed to identify different contributing factors to project delay. In traditional fault tree analysis historical data is widely used to determine the probability of an event to take place. In probabilistic fault tree analysis, no partial states are considered. If an event occurs in the fault tree analysis, this means that the event triggers the top undesired event. Minimal cut sets or the combination of basic events that guarantee the occurrence of the top undesired event (project delay), are ranked based on the probabilistic value of their occurrence and the logical relationship between the minimal cut sets. Hence, management can focus on critical branches with highest probability of occurrences. The main goal behind this approach is to eliminate or minimize the likelihood of occurrence of basic events that trigger the top undesired event (project delay).

Implementation of probabilistic fault tree analysis to manage construction project delays is questionable for many reasons. First, the probabilistic fault tree analysis is based on historical probabilistic data. Projects are unprecedented and are usually performed in an open system where uncontrollable factors govern the likelihood of events to take place. Therefore, implementation of historical data becomes questionable. Second, the assumption in fault tree analysis is that all basic events are independent. Different factors that contribute to project delay are in fact statistically dependent. Furthermore, in the construction sites, probabilistic values are often expressed subjectively in linguistic terms. Transferring linguistic terms into quantitative probability values is difficult and implementation of probabilistic fault tree analysis in such case is questionable. Also, since the traditional fault tree analysis is based on Boolean algebra, no partial states are considered. In probabilistic fault tree analysis, once an event takes place, it triggers the occurrence of the upper level event. Partial contribution of basic events to upper level events is not considered in the probabilistic fault tree analysis. In actual projects, analysis of events requires a model that mimics the real project. The type of gate along with the effectiveness of every event relative to the upper level event is needed to perform the analysis. For example, if weather is bad and work is undertaken in a closed environment where the building ceiling is completed, the weather conditions in such cases affect the progress of work differently than in cases where work is undertaken in an open environment.

Zadeh introduced linguistic expressions mathematically using a fuzzy set concept. Several models that represent the Boolean linguistic values mathematically can be used. This study follows the non-deterministic fuzzy set approach that uses subjective appraisal using qualitative data. Fuzzy set models are created to transform linguistic terms into mathematical representations. Four fuzzy logic models are introduced in this study; these four fuzzy logic models are computerized using Visual Basic. The four models introduced and discussed in this study are: the translational model, Baldwin's rotational model, the angular model, and the triangular model. These models are created to help the project managers assess the likelihood of project delay prior to the occurrence of delay. The four models are different from each other and the user may select one of the four models to subjectively assess the likelihood of project delay.

8.2 Conclusion of Study

A new classification of causes of project delay is introduced in this study. Causes of project delay are classified into procedural delay causes, triggering delay causes and enabling delay causes. Procedural delay causes are related to management actions and strategies that impact other causes of delay such as triggering delay causes and enabling delay causes. Triggering delay causes such as weather conditions, natural disasters, unforeseen conditions and environmental conditions are external to the project. Enabling delay causes are internal to the project such as material related causes, workers related causes and equipment related causes.

Probabilistic fault tree analysis is based on implementation of historical data. Implementation of probabilistic fault tree analysis into construction project is not practical due to many reasons. One of the reasons is that projects are unique in their nature and each project represents a new challenge to management, thus implementation of historical data into unprecedented projects is questionable. Another reason is that management use linguistic terms to express their opinion in terms of causes of project delay and their effectiveness on the project delay. Quantification of such linguistic terms using probabilistic fault tree analysis is difficult.

The fuzzy fault tree analysis is introduced in this study as a method to analyze project delay using four different fuzzy logic models. The four fuzzy logic models are Baldwin's fuzzy logic model, the angular fuzzy logic model, the triangular fuzzy logic model and the translational fuzzy logic model. The alpha cut method (α-cut method) is implemented to capture the cause of delay and the effectives of the cause on the project delay. The alpha cut method (α-cut method) is used in Baldwin's, the triangular and the translational fuzzy logic models. In the angular fuzzy logic model, trigonometric properties are used to capture the different causes of project delay and their effectiveness on project delay.

Baldwin's rotational fuzzy logic model is implemented into the fuzzy fault tree analysis. Baldwin's rotational fuzzy logic model uses ramp functions where linguistic terms are represented using fuzzy membership values set by Baldwin's model. All linguistic hedges are represented by the powers of the above membership functions. The strength of Baldwin's rotational model is that all membership functions overlap, which makes fuzzy operations of the AND and the OR gates easy. Furthermore, the likelihood of delay membership function can be easily compared to Baldwin's predefined membership functions to assess the severity of the likelihood of project delay. The weakness of Baldwin's rotational model lies in the fact that the membership functions of the terms *very negative*, *negative* and *fairly negative* are fixed and the end user cannot change these membership functions.

Another fuzzy logic model that has been implemented by the fuzzy fault tree analysis and programmed using Visual Basic is the angular model. The angular model prepared by Hadipriono and Sun represents fuzzy linguistic values using angles that range from 0 to 90^o for positive linguistic terms and from 0 to -90^o for negative linguistic terms. The angular model is easy to interpret since the linguistic terms are represented by angles that can be easily compared to the predefined angular model angles introduced by Hadipriono and Sun. In the angular model, relations between extreme values (for example *positive* and *negative*) in fuzzy operations of the AND and the OR operation can be difficult.

The triangular model is implemented to assess the likelihood of project delay. The triangular model is implemented into the fuzzy fault tree analysis using a computer program to model the scenario of different causes that contribute to project delay and the likelihood of delay is assessed using a membership function. The membership function is quantified using the weighted average method. The strength of the triangular model lies in the fact that this model is very easy to interpret. Furthermore, assessment of the degree of likelihood of delay to occur is determined according to the horizontal shift of the likelihood of delay membership value. If the likelihood of delay membership function shifts to the left, this is an indication that the set of input values (causes of project delay and their effectiveness) are in critical condition and management need to take actions to prevent the project delay. If the likelihood of delay membership function shifts to the right, this is an indication that the set of input values (causes of project delay and their effectiveness) are in better condition than before and that management actions are minimizing the likelihood of project delay. Furthermore, the triangular model is very clear and easy to interpret by users of the model. Also, the triangular model can provide flexibility in the membership function of linguistic terms. This is due to the fact that the triangular model requires a range of input values by experts to determine the membership function. Other fuzzy logic models such as Baldwin's, the translational and the angular model use fixed and predefined membership functions or angles to illustrate linguistic terms. The flexibility of the triangular model is not implemented into the fuzzy fault tree computer program developed for this study since the *very negative*, *negative* and *fairly negative* membership functions are fixed in the model and flexibility can be added in future research. The weakness of the triangular model lies in the fact that overlap of triangles can be limited. This weakness can cause a problem in determining the fuzzy set operations results such as the fuzzy AND and the fuzzy OR.

The fuzzy translational model is implemented into the fuzzy fault tree model to assess the likelihood of project delay. The fuzzy logic operations that combine different causes of project delay and effectiveness of these different causes of project delay to the likelihood of project delay are simplified by employing a computerized fuzzy fault tree analysis using Visual Basic. Furthermore, the likelihood of project delay is determined given a scenario of causes of delay that might take place and the effectiveness of these causes on the project delay. The likelihood of project delay is determined using a membership function that is transferred into a quantitative measure using the weighted average defuzzification method. The strength of the transltional method is that this method is clear from the experts' side since the translation of the likelihood of delay membership function can assess the severity of delay. If the likelihood of delay shifts to the left, then management needs to be alerted that given the set of contributing factors to delay, the likelihood of delay is getting higher and a set of actions need to be taken. The drawback of the translational model is that intersection of different membership functions can be limited, which result in difficulties in getting the likelihood of project delay.

Validation of the computer program has been designed toward the evaluation of the construction of the four fuzzy logic models in terms of the appearance of the screens, the user interface and the computer program in general. Many comments by experts that validated this fuzzy fault tree indicated that there is a need to further discuss which model is to be used. Determining the model that is best suited for a given project is beyond the scope of this study. In order to further study and compare the different fuzzy logic models, a sensitivity analysis study needs to be conducted. Future research should focus on these illustrative examples that can be suggested based on the sensitivity analysis studies. Experts indicated that the topic is very important in real construction projects and that there is a need to further analyze causes of delay.

The fuzzy fault tree analysis is a tool that provides users with a proactive tool of assessing the likelihood of project delay. Managers and construction planners can implement the fuzzy fault tree computer program to assess the likelihood of project delay at early stages and can take preventive actions to mitigate and sometimes eliminate project delays. The fuzzy fault tree program introduced in this study is a very simple and easy to use tool that does not require prior knowledge of fuzzy logic. Planners and managers can simply select the contributing sources and causes of delay that might occur in a given project and they can assess the effectiveness degree of these different contributing delay causes using linguistic terms and they can determine the relationship among these different contributing factors using fuzzy AND, fuzzy OR or fuzzy mean gates depending on their opinion. In case the management is optimistic, and believe that only one cause would take place at a time, the OR gate can be selected. In case the management is on the pessimistic side and they think that all contributing causes of delay would take place simultaneously, the AND gate can be selected. If management would take the average of different contributing factors the fuzzy mean gate can be selected. Flexibility in setting the scenario of what could take place can provide management with a computer model that mimics reality. Such modeling can be helpful in assessing the likelihood of project delay and in taking proactive procedures to minimize or completely eliminate the likelihood of project delays.

8.3 Recommendations of Study

Based on the research conducted and the validation of the fuzzy fault tree analysis by experts, there are many areas for further development and improvement. Areas of further refinement of the fuzzy fault tree include the following:

1. Further expansion of causes of delay. Causes of delay are expressed in general terms. Future studies could include further detailed studies of different causes of project delay. For example, weather condition is a triggering delay cause that could be further classified into different types of bad weather conditions such as rain, wind, cold weather and hot weather conditions.

2. The gates included in the fuzzy fault tree analysis are limited to the AND gate, the OR gate and the fuzzy mean. Future studies could implement fuzzy logic operations that represent a conditional (implication) relation using ITFM, TFM, rule-based approaches.

3. Future studies can be designed in order to compare between the probabilistic fault tree analysis and the fuzzy fault tree analysis. Furthermore, a sensitivity analysis study can be performed to determine which model can be used for a given set of conditions in a construction project. Further studies and analysis is needed to recommend a certain fuzzy logic model.

4. The implementation of the fuzzy models can represent input flexibility. Current model included in the fuzzy fault tree analysis is designed with a fixed set of membership

values. Future research can provide the user with the flexibility of selecting the fuzzy membership values of the different fuzzy logic models.

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APPENDIX

Likelihood of Project Delay Estimator

Introduction

This is a tool that can be used to estimate the likelihood of project delay as a result of a combination of different contributing factors (ex. bad weather condition, and material unavailable on site). Traditional methods depend on scheduling techniques, such as the forward pass and the backward pass are limited. Limitations of traditional techniques include difficulties in implementation of feedbacks and changes in momentum of progressive activities, difficulties in analysis of concurrent delays, and lack of historical data that can be reliable in estimating the likelihood of project delay. Experts' opinion is very critical in estimating the likelihood of project delay as a result of different contributing factors that do affect the progress of work. A tool that eases difficulties in traditional techniques and captures experts' opinion in terms of causes of project delay and the contributing degree of each factor to the overall project delays is needed since a control tool to estimate the likelihood of project delay. Schedule Fault Tree is a tool that can be used to assess the likelihood of project delay as a result of identifying the contributing factors that cause delay and determining the degree each factor can affect the overall project delay.

After running the computer software, please make a selection among the following different choices:

1. Appearance

1. How do you rate the layout of screens (layout in terms of the proportions of the screen)?

Absolutely poor	
Very poor	
Poor	
Fairly poor	
Neutral	
Fairly good	
Good	
Very good	
Absolutely good	

2. How do you rate the information in each screen (is the information adequate and complete)?

Absolutely inadequate and incomplete	
Very inadequate and incomplete	
Inadequate and incomplete	
Fairly inadequate and incomplete	
Neutral	
Fairly adequate and complete	
Adequate and complete	
Very adequate and complete	
Absolutely adequate and complete	

3. How do you rate the clarity of screens (the clarity in terms of font size, font used, etc.)

Absolutely unclear	
Very unclear	
Unclear	
Fairly unclear	
Neutral	
Fairly clear	
Clear	
Very clear	
Absolutely clear	

4. How do you rate the overall appearance of the screen?

Absolutely poor	
Very poor	
Poor	
Fairly poor	
Neutral	
Fairly good	
Good	
Very good	
Absolutely good	

Comments:

2. User interface

1. How do you rate the overall navigation though out the program and the navigation between the screens?

Absolutely poor	
Very poor	
Poor	
Fairly poor	
Neutral	
Fairly good	
Good	
Very good	
Absolutely good	

2. How do you rate the easiness of making selections in the computer program?

Absolutely difficult	
Very difficult	
Difficult	
Fairly difficult	
Neutral	
Fairly easy	
Easy	
Very easy	
Absolutely easy	

3. How do you rate the overall user interface of the computer program?

Absolutely poor	
Very poor	
Poor	
Fairly poor	
Neutral	
Fairly good	
Good	
Very good	
Absolutely good	

Comments:

3. The computer program

1. How do you rate the importance of this topic (delays in construction projects) to the construction industry?

Absolutely unimportant	
Very unimportant	
Unimportant	
Fairly unimportant	
Neutral	
Fairly important	
Important	
Very important	
Absolutely important	

2. How do you rate the application of the computer model to the construction industry (do you think that this computer program can be implemented in real projects?

Absolutely inapplicable	
Very inapplicable	
Inapplicable	
Fairly inapplicable	
Neutral	
Fairly applicable	
Applicable	
Very applicable	
Absolutely applicable	

3. How do you rate the result of this computer program (is this result reasonable?)

Absolutely unreasonable	
Very unreasonable	
Unreasonable	
Fairly unreasonable	
Neutral	
Fairly reasonable	
Reasonable	
Very reasonable	
Absolutely reasonable	

Comments: