5-1-2017

Dynamic Risk Analysis of Construction Delays Using Fuzzy-Failure Mode Effects Analysis

Mohammadsoroush Tafazzoli
University of Nevada, Las Vegas

DYNAMIC RISK ANALYSIS OF CONSTRUCTION DELAYS USING FUZZY-FAILURE MODE EFFECTS ANALYSIS

By

Mohammadsoroush Tafazzoli

Bachelor of Civil Engineering
Azad University
2009

Master of Transportation Engineering
Tehran Azad University
2012

A dissertation submitted in partial fulfillment
of the requirements for the

Doctor of Philosophy – Civil and Environmental Engineering

Department of Civil and Environmental Engineering and Construction
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
May 2017

UNLV | GRADUATE COLLEGE

Dissertation Approval

The Graduate College
The University of Nevada, Las Vegas

March 17, 2017

This dissertation prepared by

Mohammadsoroush Taffazoli

entitled

Dynamic Risk Analysis of Construction Delays Using Fuzzy-Failure Mode Effects Analysis

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy – Civil and Environmental Engineering
Department of Civil and Environmental Engineering and Construction

Pramen P. Shrestha, Ph.D.
Examination Committee Chair

Donald F. Hayes, Ph.D.
Examination Committee Member

Moses Karakouzian, Ph.D.
Examination Committee Member

Hualiang Teng, Ph.D.
Examination Committee Member

E. Lee Bernick, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

ABSTRACT

Dynamic Risk Analysis of Construction Delays Using Fuzzy-Failure Mode Effects Analysis

By: Mohammadsoroush Tafazzoli, B.C.E, M.T.E

Pramen P. Shrestha, Ph.D., Committee Chair

Considering the tremendous losses in the worldwide economy caused by construction delays, it is essential to invest in minimizing the risks of delays. In order to make this happen, two measures should be taken:

1) The roots and fundamental causes of delay should be identified and strategies to mitigate their risks be developed (General remedy).

2) The most significant potential causes of delay in each project should be identified and these causes should be given priority to control (Project-Specific Remedy).

The current research invests in both of the measures. To provide the general remedy, causes of delay in the construction industry of the United States is investigated through a national survey responded by the 224 construction experts with an average experience of over 27 years. The results

of this study rank the criticality of the thirty main causes of construction delay in the U.S construction industry.

The focus of the research is on the project-specific remedy. The research aims at designing a tool, which can prioritize different causes based on their criticality. This is crucial as there is often a large number of potential causes and investing in prevention of all of them is not practical. The designed tool is capable of identifying the most critical causes by assessing its status of the potential causes of delay in three elements of criticality which are: 1) The likelihood of occurrence of the cause, 2) the severity of the cause in creating delays (in case it happens), and 3) the resolvability or likelihood of handling the potential cause before it creates a delay, in case it happens. The three elements of assessment are inserted in a designed tool in Matlab®, which uses a fuzzy logic system to generate a "risk priority number'. This number is a representative of the riskiness of each potential cause.

The next contribution of the research is a model that is capable of predicting the percentage of delay based on the "fuzzy risk priority number". This model uses the output of the aforementioned fuzzy inference system to make a prediction about the percentage of delay. The model was tested by comparing its predictions with actual data (the delay that has actually happened) and has been able to predict the amount of delay with an error of less than 20%.

To my supportive father, kind mother, and lovely wife who stood by me patiently.

Mohammadsoroush Tafazzoli

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1. Problem statement

Delays during construction process are imposing huge losses on economies all over the world (Abdulla et al. 2002). The statistics indicate that, at a global level, considerable percentages of all construction projects are not completed on time. (Sambasivan et al. 2007) Although science and engineering have been applied in the construction industry to make it more standardized, repeatable, and predictable, the complexity of construction projects still seem to make delays unavoidable. Advanced software tools, which identify the duration and relationships of all activities still fail to provide a precise prediction of the real substantial completion time.

When compared to other industries, construction is showing much higher rates of delay and lower rates of productivity. Although many manufacturing industry methods have been attempted to be applied in construction, there are reasons why they cannot be as successful. Some of these reasons are shown in Table 1 (Forbes et al. 2010).

The complexities of construction projects and their inherent uncertainty make delay predication almost impossible because there is no way that all the involving factors in the progress of projects and their interactions, can be accurately predicted.

In delay analysis, the main parameter to categorize the delays is their avoidability. Based on this concept, delays can be either avoidable or unavoidable. On the other hand, there is disagreement about some delay-causes to be categorized. For example, lack of resources might be considered as an unavoidable delay-cause while by taking some specific measures, this issue can be anticipated and scheduled accordingly to mitigate its probable occurrence impacts. Blaming other involved parties is the common issue while tracking the causes of delay. Additionally, there is no commonly approved approach that can predict and prevent the occurrence of delays.

In the real world, due to the aforementioned complexities in the construction industry, quantifying the risk of delay with numbers is complicated. However, experts can have judgments about the status of the project in different aspects like the quality of communication between team members, the overall quality of design, the reliability of suppliers, and so on. Most of these judgments are made using linguistic terms. The challenge here is how to translate these linguistic terms to numeric values and develop a model that can combine all linguistic terms to effectively evaluate the risk of delays and show the criticality of each potential delay-cause.

Table 1.1. Manufacturing vs. Construction industry complexities in controlling delays (contents taken from Forbes et al. 2010)

Manufacturing Industry	Construction Industry
Location is permanent	Location changes in each project
System is closed.	System is open.
Personnel are unchanged	Personnel may change in each projects
Work is (usually) done indoors and weather condition cannot affect it.	Adverse weather may decelerate the speed or pause the project.
Most process can be automatized	Human error and weaknesses is involved in most of the processes
Project is repeated in huge numbers and corrective measures can be taken.	It is a one-time project and most of time lesson learnt cannot be applied later.

1.2. Research objectives

This research aims at two main goals: 1) identifying the most critical causes for the occurrence of delay in construction projects of the USA. 2) Developing a tool that can predict a range of possible delay (in percentage), by evaluating the riskiness of causes of delay, in a dynamic way, using

Fuzzy failure mode Effect Analysis. The ultimate general goal of the project will be therefore, decreasing the risk of delay by detecting the most critical causes during construction and preventing their (severity of) occurrence.

1.3. Research method

The research is based on a combination of data obtained from experts (by running two nationwide surveys) and statistical fuzzy-analysis, which generates a fuzzy inference system (provided in a tool) that can predict the percentage of the possible delay.

The first survey aims at collecting data to investigate the most critical causes of delay in the United States and their relative importance. The top causes are then selected for the prediction tool, which is designed in Matlab. This tool evaluates the riskiness of the most critical causes of delay, in terms of severity (S), chance or the frequency of occurrence (O), and the probability of not being detected or controlled (D). Using these three inputs, the tool generates a Fuzzy Risk Priority Number (FRPN), which represents the overall riskiness of project in the occurrence of delay.

The second survey is conducted to test the quality of prediction in the tool. If the actual data of the completed delayed projects correlates with the percentages of delay that the tool provides, the tool can be used to predict delays in construction.

1.4. Scope and limitation

Although a comprehensive list of delay-causes is provided for evaluation, delay-causes are numerous and some of them might not be included. This study only focuses on the causes that are suggested by similar construction delay studies (explained in detail in chapter 2) as “the most important”. In addition, general terms have been used to mention to a potential cause. For instance, when “poor design” is the cause, the delay-risk-assessment does not go deeper to study different types of design issues.

1.5. Research novelty

Most delay studies that have been conducted before, investigate the causes of delay for a specific area, i.e. they have attempted to determine what factors are responsible for the occurrence of delay in a certain country or region. (Abu-Dayyeh, 1997; Alkas et al., 1996; Al-Momani, 2000; Assaf et al., 1995; Bubshait et al., 1998; Chan et al., 1997; El Razek et al., 2008; Faridi et al., 2006; Frimpong et al., 2003; Hamzah et al., 2011; Kartam, 1999; Kazaz et al., 2012; and more).

Many other researches are based on conducting surveys and running simple statistical analysis that identify critical causes of delays (Chan et al., 1997; El Razek et al., 2008; Frimpong et al., 2003; Koushki et al., 2005; Odeh et al., 2002; and more). The results of such studies cannot necessarily be applied to other construction projects because although projects' duration is affected by the overall status of delay-causes in their area, projects may have very different characteristics, which put generalizing same delay-causes for all of them under question.

This research tries to fill the gap of relying exclusively on historical data to predict the chance of delay. The approach presented in this research utilizes the data that represent the actual condition of the project and evaluates the risk of delay based on the *actual* and *current* status of different potential causes. Figure 1.1 shows the framework of the research, which has the four main parts of literature review, data collection, developing the model and testing the model.

The tool, which is developed in this research, enables the construction manager to predict the most critical causes at any stage of the project. This dynamic (changing based on the status of the project) system makes it possible to do corrective actions to prevent delays in iterative cycles i.e. it enables the construction manager to make corrective actions for most critical causes, and run the tool to come up with updated causes, which are less critical. Based on budget limitations, the construction team can decide to continue making improvements to reach higher levels of certainty.

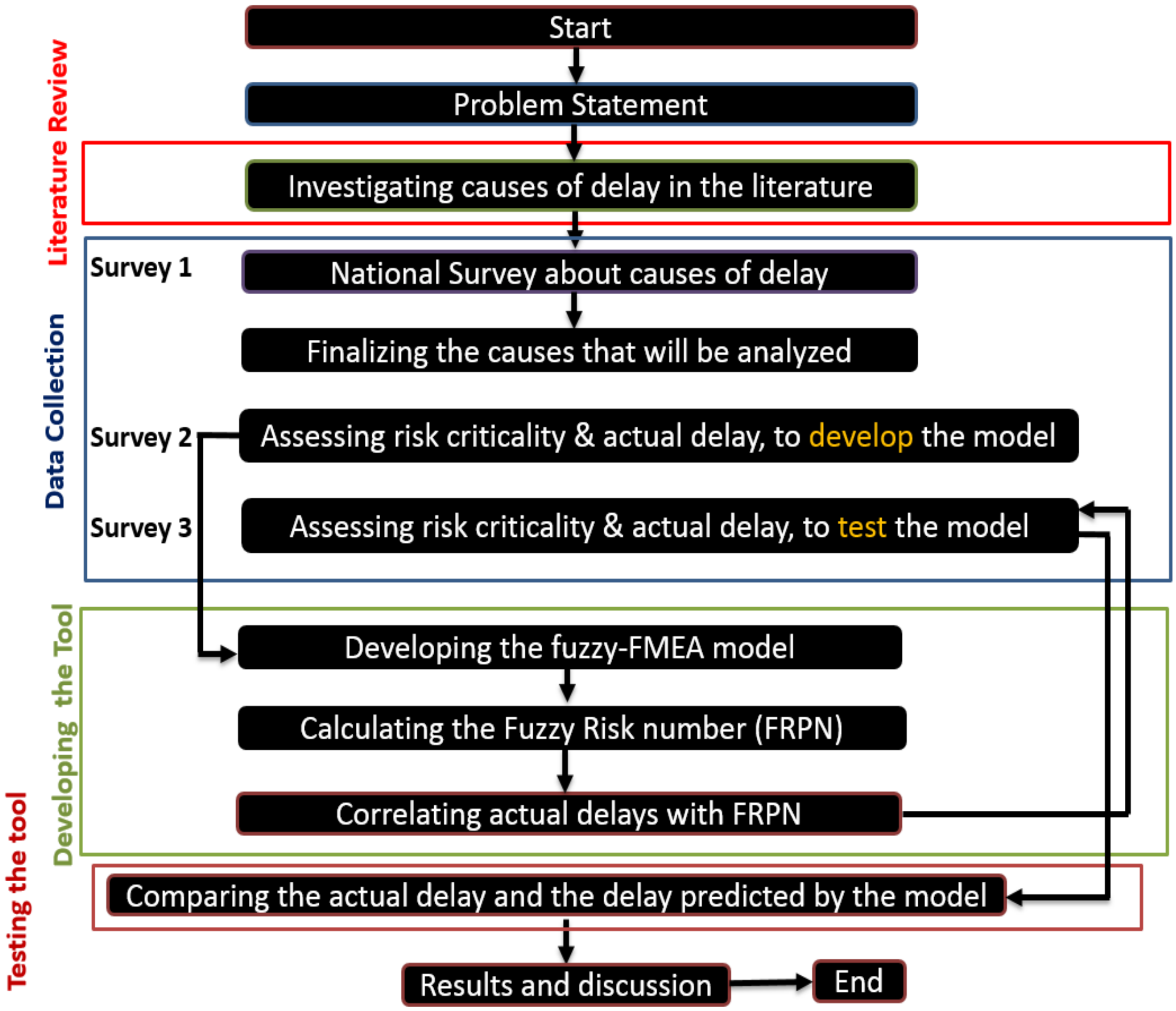


Figure 1.1. The Path of the research

Additionally, the mathematical method, that combines Failure Mode Effects Analysis (FMEA) with fuzzy logic both of which have proven to be very strong tools in assessing risks. The shortcoming of FMEA has been minimized using fuzzy logic, which is widely used as a strong tool in aerospace, army, and industry to name a few. Fuzzy logic, which simulates the human thinking in decision-making, supplements FMEA to cover its shortcomings. More details about both methods are provided in chapter two.

The current chapter provides an explanation about the problem statement. In chapter two, the background studies about construction-delay will be reviewed. Chapter 2 also provides some information about the application of the methods of this research in previous research. Chapter 3 will explain the methodology in a systematic format. Chapter four represents the results of the study and finally chapter 5, will be dedicated to the conclusions and discussion.

CHAPTER 2: LITERATURE REVIEW

In this chapter, previous delay-studies are reviewed to identify the main gaps in the body of knowledge about the analysis of construction-delays. This chapter also reviews the application of the methods that are applied in this research in other studies. Based on this, FMEA and Fuzzy logic will be explained. The contents of this chapter can be divided into the three following parts:

2.1. Construction-delay studies in the literature

2.2. Introducing Failure Mode Effect Analysis (FMEA) method and its applications in construction-related studies

2.3. Introducing Fuzzy-Inference System (which is used in this study) and its applications in construction-related studies

2.1. Construction-delay studies in the literature

Frimpong et al. (2003); Majid (2006), and Olawale et al. (2013) named three main criteria for the success of a construction project:

i. Being completed on time,

ii. Being completed within budget, and

iii. Compliance with the specifications.

In the highly competitive construction market, focusing on delivering the project based on these three criteria is essential. The occurrence of delay may have many consequences for the project and bad reputation for the contractors. Majid (2006), and Mahamid et al. (2012) noted that the adverse results of delay can vary from increased costs and productivity reduction to terminating the contract.

2.1.1. Challenges in delay prevention

One challenge in introducing a universal prescription to prevent or handle delays in construction projects is their uniqueness in the volume of work, the time needed, the project objectives, the environment in which the project is being constructed, difficulty level, deadlines, budgets, personnel, delivery method and payment method. This volume of variation does not provide constant variables based on which the process can be fully formulated and controlled. Between time and budget, time has been proved harder to get controlled (Mahamid et al. 2012). In fact, construction industry projects are commonly know as projects with high chance of delays (Duran 2006). Luu et al. (2009), and Al-Humaidi and Tan (2010), emphasized the importance of predicting the probability of delays.

2.1.2. Delay-causes identification studies

There is an abundant of research studying the causes of construction-delays. The majority of research has focused on identifying the causes and introducing preventive solutions. More in-depth studies have focused on identifying which causes of delay are more important. The common method of doing this has been conducting surveys taken by experts of the construction industry in certain regions. Table 2 shows a summary of some of these studies.

Table 2.1. Existing literature regarding construction delay analysis

Author	Year	Content	Studied area
Assaf et al.	1995	Listed major delay causes in large residential projects using relative importance index method. Identified Fifty-six causes delay causes and categorized them in nine groups	Saudi Arabia
Ogunlana et al.	1996	Studied the causes of construction delays in building projects.	Thailand
Chan et al.	1997	Used relative importance method to evaluated 83 potential delay factors, in eight major categories.	Hong Kong

Odeyinka et al.	1997	Investigated delay caused for residential projects in three categories of client, contractor, and extraneous-related factors.	Nigeria
Kartam	1999	Presented a written exposition of a generic methodology for analyzing delay claims in 14 steps.	NA
Noulmane et al.	1999	Conducted a research about delay causes in highway projects.	Thailand
Al-Momani	2000	Investigated eight delay causes for 130 projects in the public sector and developed a simple linear regression model for the planned and actual time of the project.	Jordan
Frimpong et al.	2003	Investigated 26 factors that can cause delays in projects related to groundwater construction.	Ghana
Koushki et al.	2005	Conducted a survey about the delays in the construction of private residential projects.	Kuwait
Wiguna et al.	2005	Studied the risks that result in construction delays in residential projects.	Indonesia
Faridi et al.	2006	Investigated major delay causes in the construction industry of UAE	UAE
El Razek et al.	2008	Investigated the major causes of delay in the viewpoints of contractors, consultants, and owners.	Egypt
Tumi et al.	2009	Investigated significant factors causing delay in the construction industry of Libya.	Libya
Hamzah et al.	2011	Introduces types of delays based on the literature.	Malesia
Kazaz et al.	2012	Examined 34 causes of time extensions in the construction under seven factor groups. The factors' levels of importance affecting the project duration were gathered.	Turkey
Mahamid et al.	2012	Investigated the time performance of road construction projects, identified 52 causes of delay and their severity.	Palestine

2.1.3.1 Excusable delay

These delays are those that cannot be anticipated nor controlled. Excusable delays can be also divided into two sub categories: non-compensable delays, and compensable delays.

I. Non-Compensable delay: These types of delay are related to causes, which are hard or impossible to be controlled. Adverse weather, acts of God, fires, and floods are examples of non-compensable delays. These types of delay are sometimes controversial due to the common understanding of them. For instance, when adverse weather is being considered, the adversity should be severe enough which cannot be anticipated at that time of the year in the working region. Therefore, not any improper weather can be classified as an excuse for a time extension. Determination of unusually severe weather is based on historical data for the area.

II. Compensable Delay: These types of delay are also unpredictable and beyond the contractor's control with the difference that for them the contractor is entitled to both a time extension and an additional compensation. In many cases, governmental issues are the main causes of compensable delays. Constructive changes and suspension of work are two examples for compensable delays.

2.1.3.2. Non-excusable delays

These delays are controllable by the contractor and can be foreseen. The root causes of non-excusable delays are commonly the following reasons:

- underestimation of production rates
- poor scheduling
- poor management
- construction errors

- equipment problems
- liquidated damages or termination of contract (Idaho Transportation Department Report)

Concurrent and non-current delays, as implied by the name, refer to the timing of the factors that are causing delay to the project. Based on this, a ‘non-current’ delay is a type of delay in which only one factor is delaying the project. These types of delays are commonly easier to calculate the time and money loss resulting from the issue. On the other hand, in a ‘concurrent delay, more than one factor is responsible for the occurrence of delay either at the same time or at the time interval that has overlaps. These types of delay are very typical in construction projects and are more complicated to determine what extent each of the factors has contributed to the delay. (Hamzah et al. 2011). This categorization can be also based on the time in which delay happens. Figure 2.1 shows how delays are categorized based on the region, compensability, and timing. Also, figures 2.2 and 2.3 show categories of delay based on the responsible party (Venkatesh et al., 2012; Sambasivan et al. 2007; and Odeh et al., 2002)

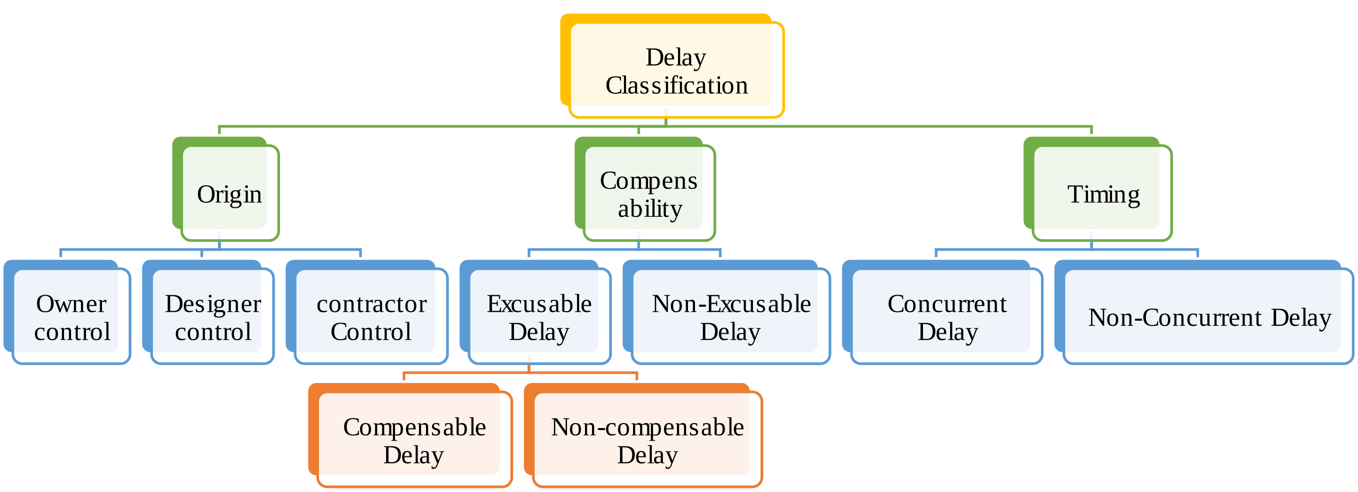


Figure 2.1. Classification of construction delays (Al-Humaidi, 2002)

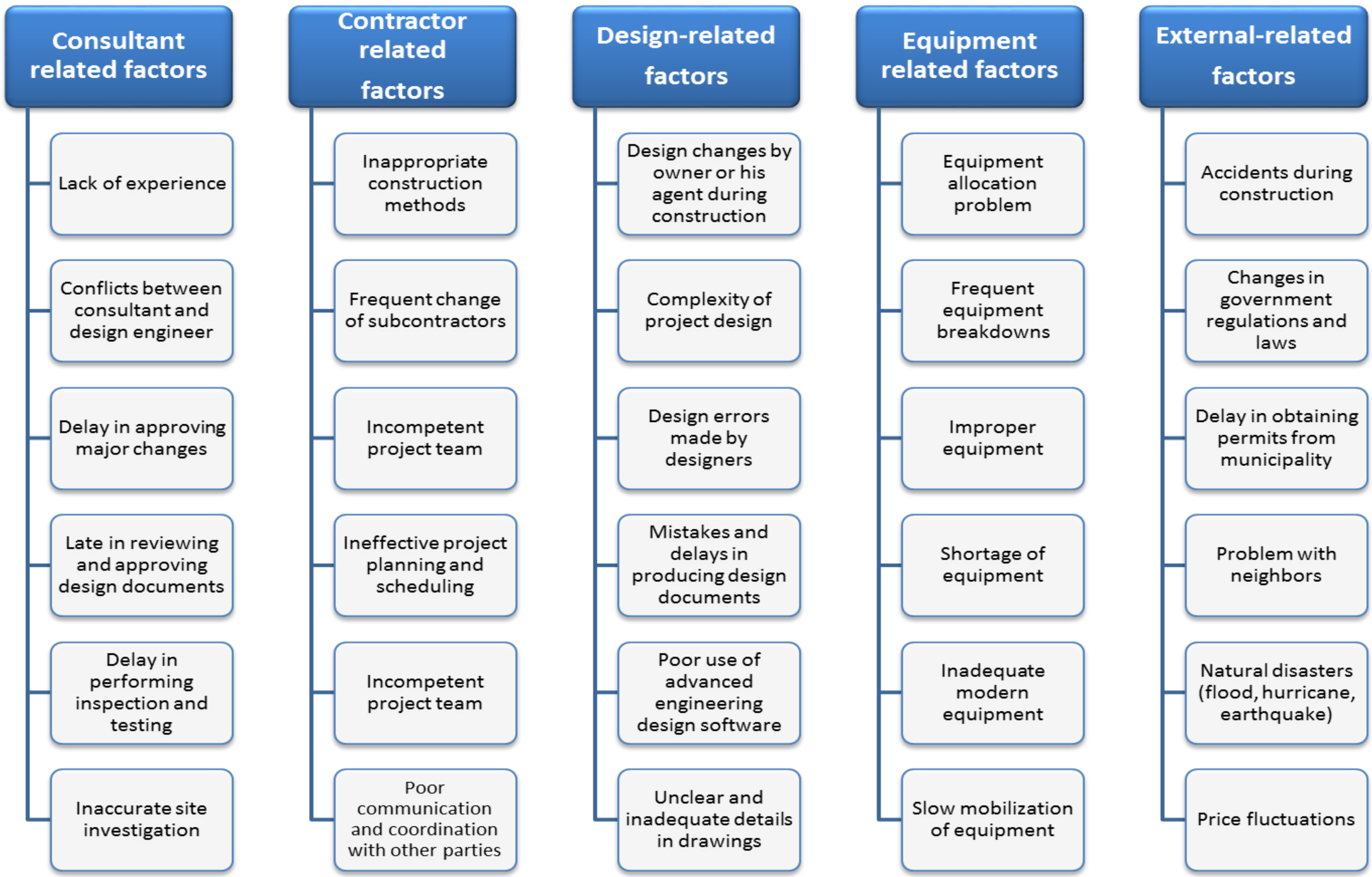


Figure 2.2. Categories of construction delays based on the responsible party

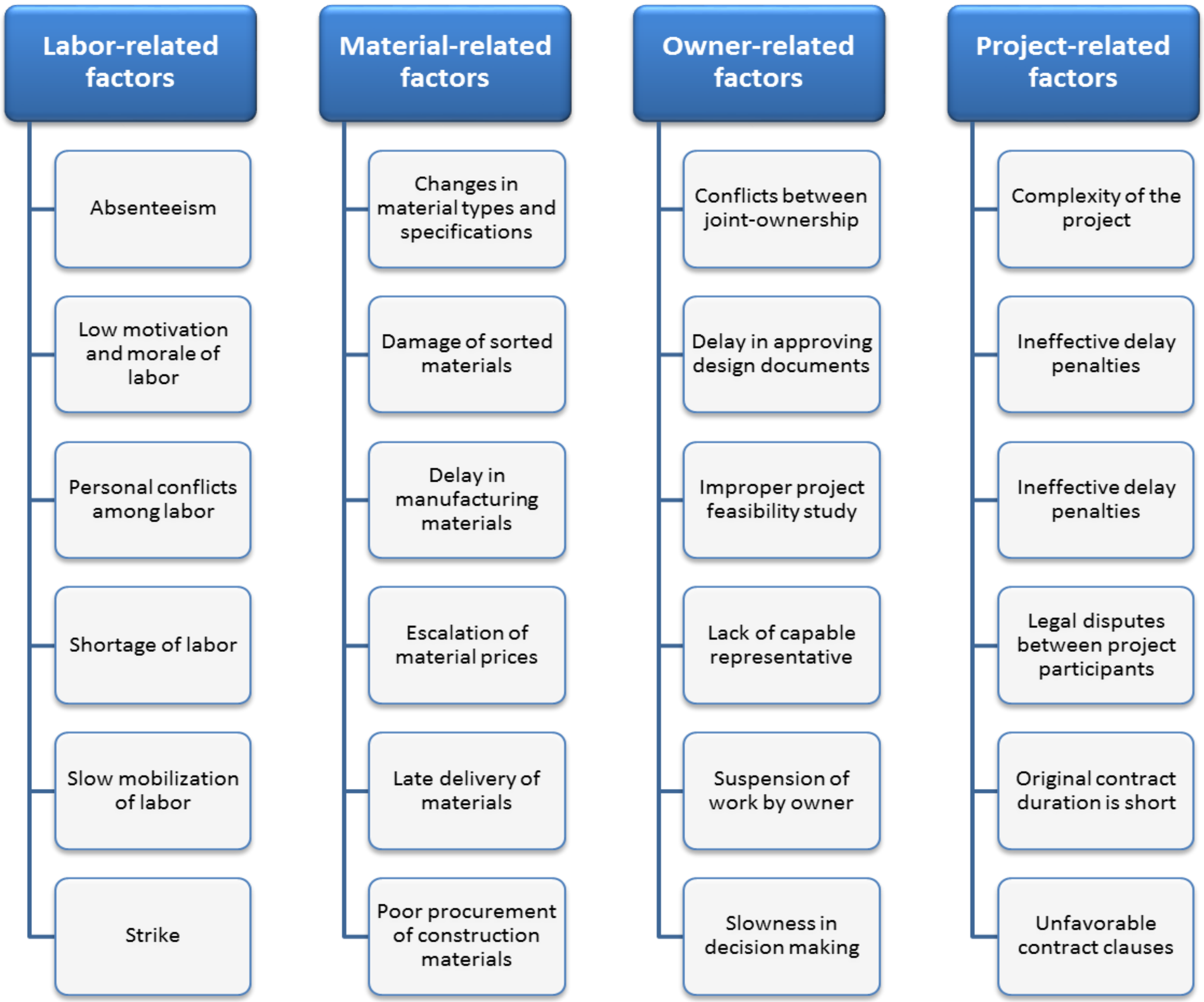


Figure 2.3. Categories of construction delays based on the responsible party

2.2. Introducing Failure Mode Effect Analysis Method & its applications in construction-related studies

The method used in this research for dynamic analysis of delay is Failure Modes and Effects Analysis (FMEA). FMEA is an approach to analyze qualitative data, which was first formalized in 1949 by the US Armed Forces. Another remarkable use of FMEA was in the Apollo Mission in a project for risk control. FMEA was also used in a big space project in the 1960s, to send a man to the moon. FMEA was first used in automobile industry by the Ford Motor® in the late 1970s to increase safety and regulations as well as improving production and design. "The FMEA method is broadly used in different industries (Fadlovich, 2007).

2.2.1. FMEA's elements

The first step of implementing FMEA is to understand its elements. An FMEA typically consists of ten elements. Figure 2.4 shows these elements and their order. What follows is a brief explanation of each element.

2.2.1.1. Item.

Item is the subsystem or component which is going to be analyzed. (Except for System FMEA for which, the item is the system itself.)

2.2.1.2. Function

Function explains the task, which is expected from the items in ideal conditions; i.e. if there is no interference or no flaw occurs for the item or other items that affect the under-analysis-item. Function sheds light on how the system may encounter a failure by clarifying the intended purposes of the item.

2.2.1.3. Potential failure mode

Potential failure mode explains any possible issue that can effect normal function of the item (anything that can disturb a task, interfere a normal process, pause, delay or stop the flow of production, etc.).

2.2.1.4. Potential Effects

The effect is the result of the failure. It explains what will go wrong in the system and what potential consequences it may have on the system/ subsystems or the end-user. Effects can have a broad range. For example in a factory, one big malfunction can affect a factory's interest; from there its workers' chance of wage-increase can be affected. This, in turn, may affect the economic conditions of the workers' families. Economic conditions can also have many other effects.

2.2.1.5. Severity

Severity is shown with a number typically ranking between 1 to 10 where 10 represents the most severe and 1 represents the least sever for a given failure mode. Severity is assessed disregarding the likelihood of occurring or being detected.

2.2.1.6. Cause

Cause explains why the failure happens. When using "Design FMEAs", cause clarifies the design deficiency. Whereas when using "Process FMEAs", the cause clarifies manufacturing or assembly deficiency (Carlson 2012).

2.2.1.7. Occurrence

The occurrence is the term used to show the likelihood that the expected failure mode happen. Note that occurrence is assessed based on the mere likelihood of occurrence. It means its severity

and chance of detection should not be taken into consideration when rating its occurrence. (Carlson 2012).

2.2.1.8. Controls

Controls are the measures that are planned with the goal of minimizing the risk for each failure mode in case they occur (Carlson 2012). They target at prevention or detection of failure modes before they can have a big impact on the process.

2.2.1.9. Detection

Detection means the chance that the failure mode can be detected. It is essential to keep in mind that while rating the detection, the severity or likelihood of occurrence should not be involved in choosing the score as these three criteria are assessed separately and independently.

2.2.1.10. Risk Priority Number (RPN)

RPN provides a numerical value for each of potential modes of failure. This value is the result of multiplying the values for severity, the likelihood of occurrence of the failure, and the chance of detection of the failure (Carlson, 2014)**.** As an example when the chance of occurrence is 5, the severity is 4, and the detection is 3, the resulting RPN value will be $5 \times 4 \times 3 = 60$. It is obvious that the higher is the RPN value, the riskier is that potential failure mode.

The ten elements of FMEA are shown via an example in Figure 2.4. It should be noted that not all these ten elements are included in the methodology of this research. The present research only focuses on core elements of FMEA, which are severity, occurrence, detection, and risk priority number. Focusing on the root causes of occurrence of delay and solutions to prevent them are out of the scope of this study.

2.2.2. How FMEA Works

FMEA relies on the knowledge and experience of experts on the job to figure out the potential failure modes, rank priority for attention according to the respective consequences of the failures, and eliminate the chance of potential failures occurring (McDermott, 1996). The RPN, which is the output of FMEA, is a multiplication of severity, detection, and occurrence. As it was mentioned above a higher RPN value is a representative of a riskier mode of failure. Figure 2.5 shows the iterative process of FMEA. The detailed process of applying FMEA will be explained in more details chapter 3.

Item	•contract
Function	•explains rights and responsibilities to perform tasks for the involving parties of a project.
Failure mode	•changing the contents of the contract (change-order)
Potential effect	•delay, additional costs
Severity	•depending on the magnitude can cause long or short delays (assessed by a number between 1 to 10)
Cause	•unforeseen conditions, substitutions, miscommunications before design, economical issues, etc.
Occurrence	•happens very frequently (assessed by a number between 1 to 10)
Controls	•Conducting a “Constructability Review”, listing options, risks, etc.
Detection	•may take different amounts of time to be detected based on the magnitude (assessed by a number between 1 to 10)
Risk Priority Number	•Multiplication of numbers assigned for severity, occurrence and detection (result is a number between 1 to 1000)

Figure 2.4: An example of 10 elements of FMEA in construction industry

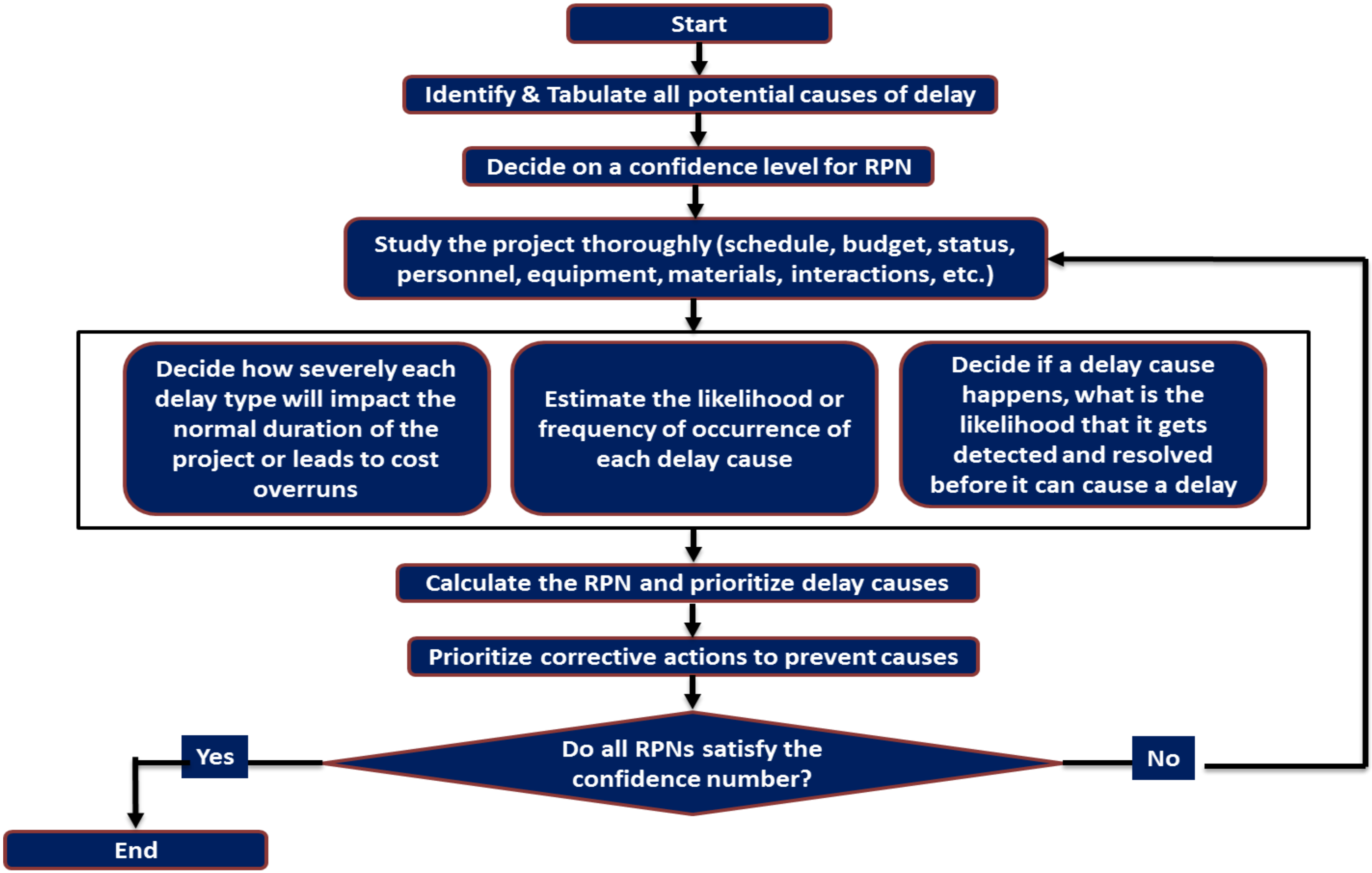


Figure 2.5. The iterative Process of FMEA

FMEA has been used as the analytical tool in many studies. Table 2.2 lists some of them:

Table 2.2. Examples of studies that have used FMEA for criticality ranking

Author	Year	Brief Discerption
Rhee et al.	2003	Presented Life Cost-Based FMEA, which provides a method to measure based on the cost. The presented approach aims at selecting the best design alternative with the purpose of reducing the life-cycle costs.
Sharma et al.	2007	Used FMEA to analyze system failure behavior and plan suitable maintenance system to act accordingly.
Cheng et al.	2008	Used FMEA as a decision-making tool in design and construction of drainage systems for high-rise buildings.
Chin et al	2008	Used FMEA evaluation approach for new product concepts, which performs FMEA to improve quality and reliability at the conceptual design stage.
Abdelgawad et al.	2010	Used FMEA and fuzzy AHP to address the shortcomings of the traditional FMEA method.
Murphy et al.	2011	Presented a method to extract constraints for innovation from building projects using stakeholder management competencies.
Filip	2011	Used FMEA to identify potential issues from a system, subsystem or component in industrial processes.

2.2.3. FMEA limitations

Although FMEA has been widely used in different risk analysis its applications have some limitations. What follows is a list of these limitations that must be considered:

i. The Risk Priority Number (RPN), calculated by O × S × D, overlooks the relative importance of these parameters, and its use can result in misunderstandings (Yeh and Hsieh, 2007). This issue causes different combinations of S, O, and R ratings to possibly produce the same RPN value while the hidden risk of them may differ. (Pillary et al, 2003). Figure 2.6 shows an example of two different combinations of S, O and R values resulting the same RPN value.

	S	O	D	RPN
Potential Delay cause 1	4	5	6	120
Potential Delay cause 2	2	6	10	120

Figure 2.6. Limitation of FMEA: Same RPN for different values of S, O, and D

ii. An expert's subjective judgment–which is used in FMEA–is described via simple words, which can sometimes be imprecise, or vague.

iii. Evaluating the reliability and safety of a product or a process with precision, is hard using FMEA, as the statement in FMEA is often subjective and described qualitatively using words (Pillay et al., 2003).

Figure 2.7 shows some other limitation of FMEA. To resolve these limitations, a great deal of research has been directed in the past decade toward enhancing the performance of FMEA (Xu et al., 2002). To deal with the shortcoming of FMEA, fuzzy logic will be used in the method of this research to process the inputs generated by FMEA.

Fuzzy-FMEA approach has been proven able to express the vague and uncertain situations of conflict risks; therefore, it is used in this research for modeling the quantitative degree of expected

delay risk to fill the gaps of FMEA method. Fuzzy-FMEA is useful in conducting the FMEA, using information and experts' expertise that is often uncertain or vague within the context of the situation (Bowles and Pelaez, 1995). In addition, Fuzzy-FMEA case study shows that the proposed model is more sensitive than the traditional FMEA method in terms of distinguishing risk priority (Yu et al., 2012).

FMEA	Fuzzy FMEA
Same product of S, O & D values lead to same risk level	Same product of S, O & D values (may) lead to different risk levels
S, O and D are given same weights	S, O and D are given different weights
Expert knowledge is not evolved in deciding the aggregate impact of S,O and D	Aggregate impact of S, O and D is decided by experts
Easy and quick in risk evaluation	Tedious and time consuming in risk evaluation
Less reliable results	More reliable results
Mathematically straight forward	Mathematically complex

Figure 2.7. Traditional FMEA vs. Fuzzy-FMEA

2.3. Introducing fuzzy-inference system and its applications in construction-related studies

Many events in the world have more than simple true and false values. Traditional mathematics had some challenges in making calculations about such events. While in "crisp sets", membership in the set has only two values (member or non-member), in such events there are *degrees* of truthfulness and falsehood (Zadeh 1965; Lin et al., 1994; and Lah et al., 2005). A famous example for understanding the difference between them is made about weather: "Today is sunny", might be 100% true if no clouds can be seen in the sky; 70% true if there are some clouds, 50% true if

it's hazy or 0% true if it rains all day long. Figure 2.8 shows another example for comparing crisp and fuzzy sets:

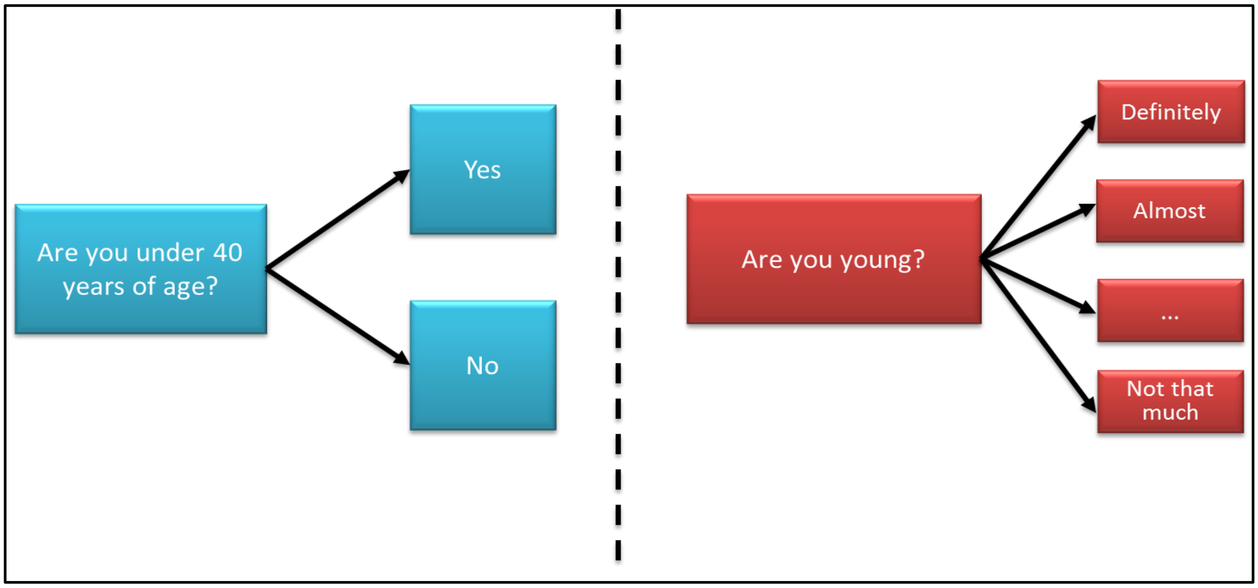


Figure 2.8. Membership in crisp sets (left) vs. fuzzy sets (right)

There was a need to introduce a set, which can simulate this degree of membership. Lotfizadeh realized this need and introduced fuzzy set theory in 1965. He defined a fuzzy set as “a class of objects with a continuum of grades of membership” (Zadeh, 1965). The membership value is a number between zero and one, which shows to what degree an abject, belongs to a fuzzy set. Despite the simple definition, fuzzy logic has been used in many industries to simulate the decision making process of the human brain in complicated systems and machines. Despite the short history Fuzzy is broadly used and has been replaced with traditional mathematics for many applications (Zimmermann 2001).

Zimmermann (2001) noted that fuzzy logic is particularly helpful for approximate reasoning in which values are affected by the intuitive thinking of humans. Fuzzy logic is particularly useful when it is difficult to assume an absolute true or false value (Zadeh 1965; Lin et al. 1994; Lah et al. 2005). Fuzzy logic is a data analysis methodology to transform “crisp” theory to “continuous.”

Fuzzy modeling facilitates translating linguistic terms, which are commonly used in human judgments to formulate the observed problem into a fuzzy system based on mathematical tools.

2.3.1. Fuzzy set

Since fuzzy logic was introduced in 1965, it has been extensively used to solve problems in which partial truth was a better representative of the reality and the type of data based on which the analysis is conducted is not precise and human judgments or descriptive language have been involved in it (Baloi et al., 2003). Zadeh (1965) noted that as systems get more complex, human brain decreases in making accurate statements and judgments about their behavior. Probability theories are used as a common tool to tackle uncertainties. While FST is not a replacement for the probability theory, it tries to handle problems in which the probability theory cannot vigorously provide solutions. (Baloi et al., 2003).

Fuzzy logic is a superset of Boolean logic that is used to mathematically model partial truth, which varies between “absolutely true" to "absolutely false". As implied by the name, fuzzy logic can be used for phenomena that are approximate and not exact (Like the level of riskiness). Fuzzy logic has been widely used since its introduction in 1965 because it has the capability to simulate human reasoning and common sense, which is extensively used in many decision-makings that we do every day. In other words, fuzzy logic, that is deriven from fuzzy set theory, is a multi-valued logic that fits evaluating values that are approximate rather than precise reasoning. In doing so, non-numeric (words) are often used to facilitate the description of rules and facts that are otherwise difficult to express in terms of binary logic (Zadeh, 1999).

Fuzzy systems are preferable to classical methods in some applications for the two following reasons:

I. Where approximate reasoning is applied and in systems where a classical mathematical model does not work well.

II. Where input values are based on estimations rather that precise measurements or where values are estimated under incomplete or uncertain information.

2.3.2. Membership in a fuzzy set

The main difference between memberships of an element in a fuzzy set compared with a classical set is that in a fuzzy set, membership does not have a crisp zero or one value. In a binary classical set, the membership is defined by a binary term according to bivalent condition, it means an element can either belong to a set or not belong to it. Here membership has a degree. This facilitates mathematically model many phenomena in which information is not complete or precise and therefore the membership cannot have an absolute zero or one value.

Figure 2.9 shows the concept of degree of membership in a graphical way. The famous example, which is commonly used to define this concept, is the way temperature of a room is defined. The top half of the figure is based on crisp values for membership. In this bivalent set, certain crisp values are defined to identify the boundaries between different temperatures. For instance, the weather is assumed as “cool” if the temperature varies between 0 to 10 degrees Celsius. All sets (which are defined by a color) are mutually exclusive. Any given temperature can only be a member of a unique set. Assume the weather is 10 degrees Celsius; it is hard to decide if the weather crisply belongs to the set “cool” or “warm”. There should be a way to eliminate the crisp boundaries between every two consecutive sets to be able to explain the membership because it is not right to claim that once the weather changes from 10 to 11 degree, it will change from cool to warm. The fuzzy set theory is to model this gradual transition between sets. Based on this concept,

the bottom half of the figure translates the classical sets into fuzzy sets. As it can be seen, in these sets, the transition is gradual.

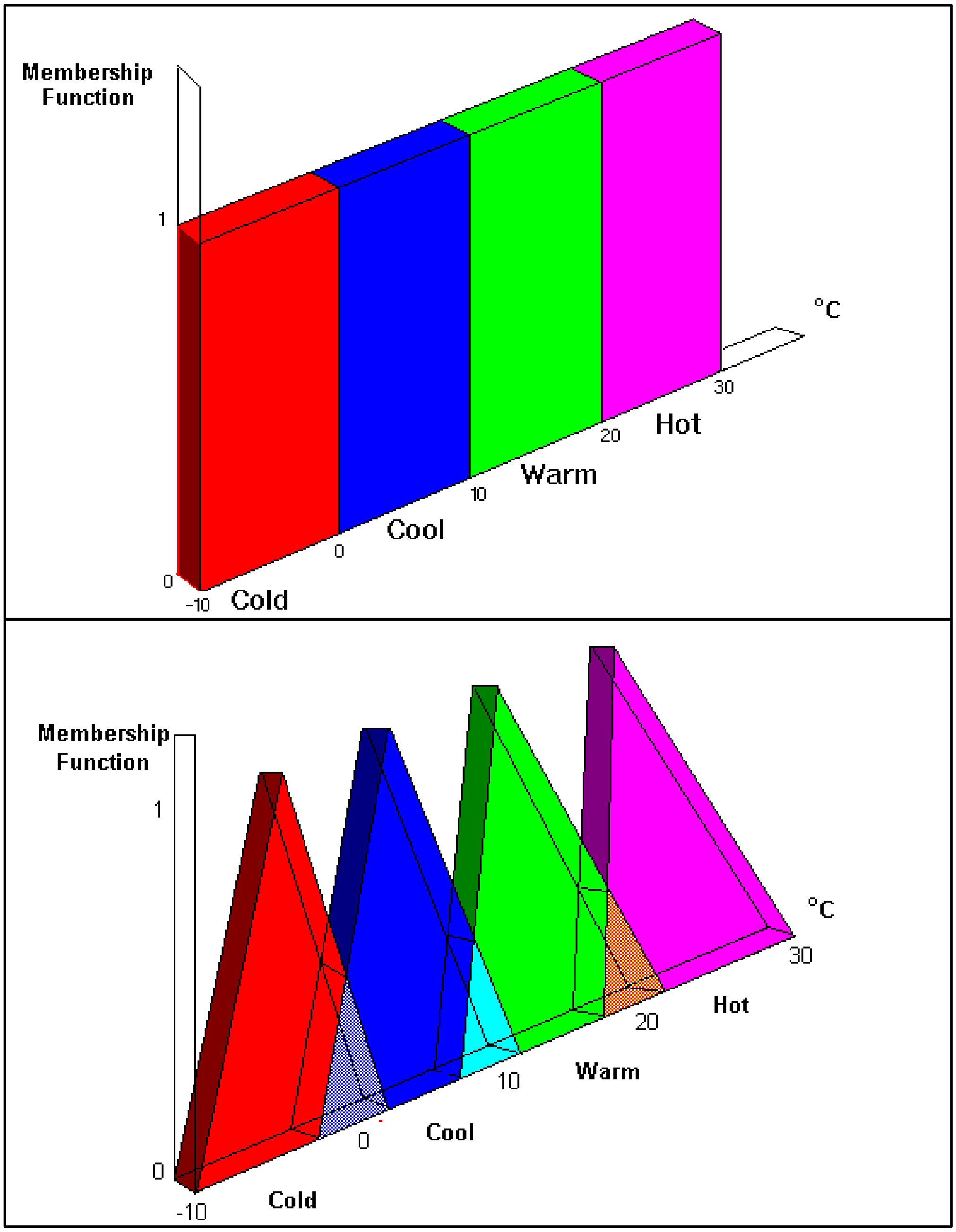


Figure 2.9. Comparing the boundaries between sets in classical sets (top half) vs. fuzzy sets (bottom half) to characterize the temperature of a room (Figure retrieved from: http://www.doc.ic.ac.uk/~nd/surprise_96/journal/vol4/sbaa/report.fuzzysets.html).

2.3.3. Fuzzy numbers

Unlike "ordinary numbers" (single-value-numbers) which have an exact value, by "fuzzy number" we mention to quantities whose value is not precise. Fuzzy numbers are members of a fuzzy set ranging (usually) between 0 and 1 based on their degree (grade) of membership where 0 represents the smallest possible membership and 1 represents the greatest degree of membership. A fuzzy number is a special case of a convex, normalized fuzzy set of the real line. (Dubois et al., 2007). It is said that for their characteristics (which were explained in this chapter), fuzzy numbers can reflect the physical world more realistically than ordinary numbers. Calculations with fuzzy numbers makes it possible to model uncertainty on parameters, properties, geometry, etc. There is a variation of fuzzy numbers of which the Triangulate Fuzzy Number is explained because it is used in thus study.

2.3.4. Triangular fuzzy number

Triangular fuzzy number (TFN) is one of the most common types of fuzzy numbers which is widely used in fuzzy computations. A TFN is a fuzzy number represented with the three following points:

$A = (a_1, a_2, a_3)$

$$\mu_{(A)}(x) = \begin{cases} 0, & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{cases}$$

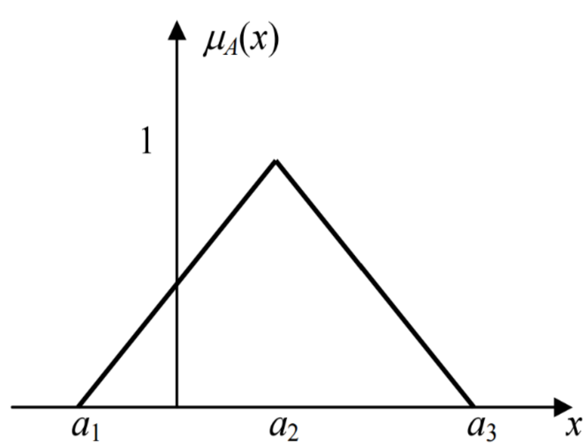


Figure 2.10. Triangular fuzzy number

2.3.5. Mamdani-fuzzy inference system (used in this research)

Among different fuzzy methods, Mamdani is the most common method; this method is considered in among the first control systems, which are based on fuzzy set theory. Mamdani method was first introduced in 1975 by Ebrahim Mamdani (Mamdani et al, 1975). This method is based on the famous Lotfizadeh's paper (1973) and used his theory to control a steam engine and boiler combination using a set of linguistic control rules, which were developed from experienced human operators.

An example of a Mamdani inference system is shown in figure 2.11.

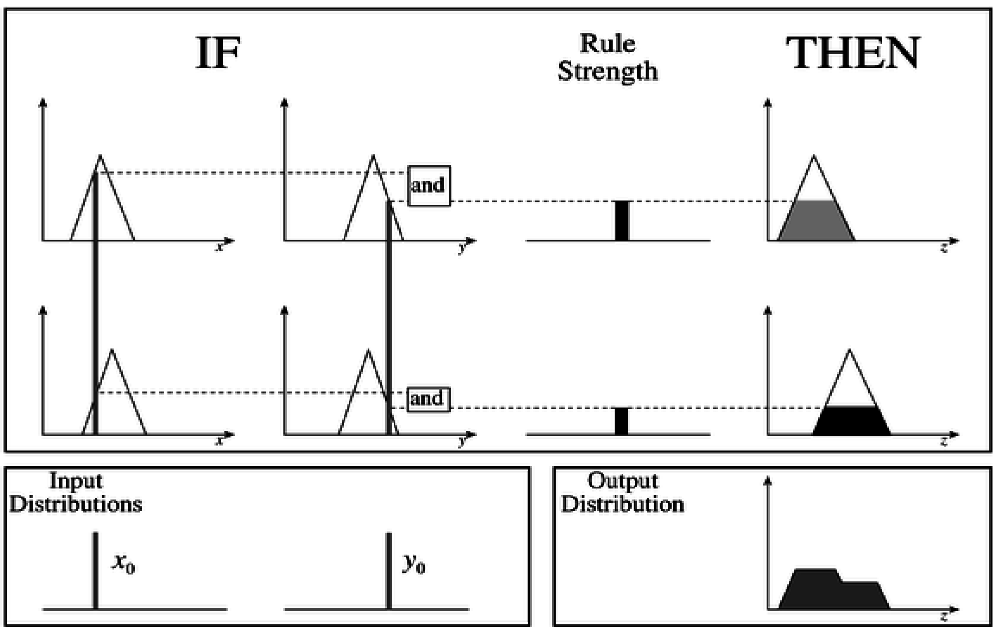


Figure 2.11. A two input, two rule Mamdani FIS with crisp inputs (Courtesy of Princeton University)

There are six steps in applying Mamdani's FIS:

1. Fuzzy rules are determined

2. The inputs are fuzzified via input membership functions,

3. Fuzzified inputs are combined based on fuzzy rules

4. The consequence for each is found through combining rule strength and output membership function

5. The consequences are combined to get an output distribution, and

6. The output are difuzzified and converted back to crisp and numerical values

These steps are explained in more details below:

2.3.5.1. Determining a set of fuzzy rules

The first step of using Mamdani's FIS is to determine a set of fuzzy rules. Fuzzy rules are a set of conditional statements that define the way fuzzy inference system should combine the fuzzy inputs to make a decision. Fuzzy rules are defined in if-then statements like this:

if (input1 is membership function1)

and/or (input2 is membership unction2)

and/or ...

then (output n is output membership function n).

An Example of these rules can be used to determine the amount of tip for a waiter at a restaurant:

if *the service is good, the atmosphere is pleasant,* ***and*** *the food quality is average* ***then*** *the amount of tip should be fairly high.*

It should be noted that each membership functions also needs to be defined; for instance in the aforementioned example, we need to define what we mean by "good quality service" (input1), "pleasant atmosphere" (input2), "average food quality" (input3), and "fairly high tip" (output1).

The process of defining inputs and processing them through a membership function is called fuzzification. The definition of the combinations of "and" / "or" in the fuzzy rule is also called fuzzy combination.

2.3.5.2. Fuzzification

The second step of using Mamdani's FIS is called fuzzification. There are different definitions for fuzzification:

- Silva et al (2009): A process in which crisp values are transformed into degrees of membership for linguistic terms of fuzzy sets.
- Castro et al (2009): A process in which system input and/or output are decomposed into fuzzy sets.
- Ibanez et al (2009): A process in which a mapping is established from crisp input values to fuzzy sets.

2.3.5.3.Fuzzy combinations (T-norms)

Fuzzy combination is the linguistic term we use to generate a combination of the status of the input variables. These terms are commonly "and", and "or" and less commonly "not". Another term, which is used to represent fuzzy combinations, is "T-norms". "and" ,and "or" T-norms are explained below:

Fuzzy "and"

The mathematical illustration for T-norm "and" is:

$$\mu_{A \cap B} = T\ (\mu_A(x), \mu_B(x))$$

μ_A: the membership in class A

μ_B: the membership in class B

There are two main methods to compute "and", which are explained below:

- Computing "and" using Zadeh method:

$$\mu_{A \cap B = \min(\mu A(x), \mu B(x))}$$

- Computing "and" by multiplication of membership values:

$$\mu_{A \cap B = (\mu a(x) \times \mu b(x))}$$

Both techniques have the two properties below: (Note that membership function value varies between 0 and 1):

- T(0,0) = T(a,0) = T(0,a) = 0
- T(a,1) = T(1,a) = a

One of the strengths of FIS is that the computed “and” with both mentioned methods is useful to calculate the Boolean "and". Table 2.3 illustrates how the Boolean "and" operates. In this logic, the fuzzy "and" is an extension of the Boolean "and" to all numbers ranging between 0or1.

Table 2.3. Boolean “and” in different combinations of two inputs

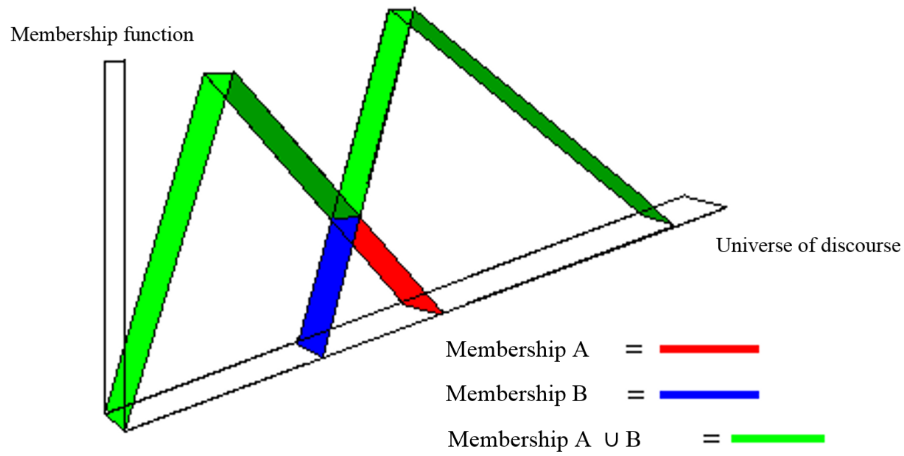
Input 1 (A)	Input 2 (B)	Output (A “and” B)
0	**0**	**0**
0	**1**	**0**
1	**0**	**0**
1	**1**	**1**

2.3.5.4. Consequence

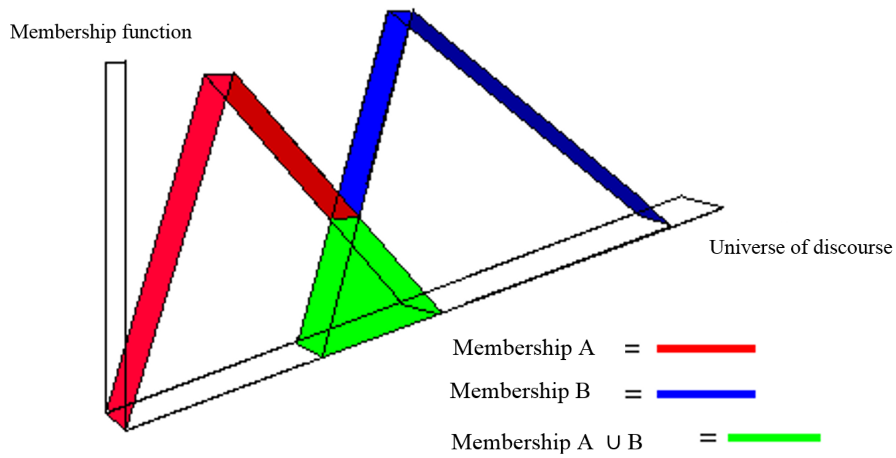
The consequence of a fuzzy rule is the part containing “then” in the fuzzy rule statement. The consequence is derived from inputs by calculating the rule strength by aggregating the fuzzified inputs using the fuzzy combination process. (fuzzy "and", “or”, “not”).

Figure 2.12 shows a graphical view of some of the operations on fuzzy sets:

$$\mu_{A\cup B} = \max(\mu_A , \mu_B)$$



$$\mu_{A\cap B} = min(\mu_A , \mu_B)$$



$$\mu_{\bar{A}} = 1 - \mu_A$$

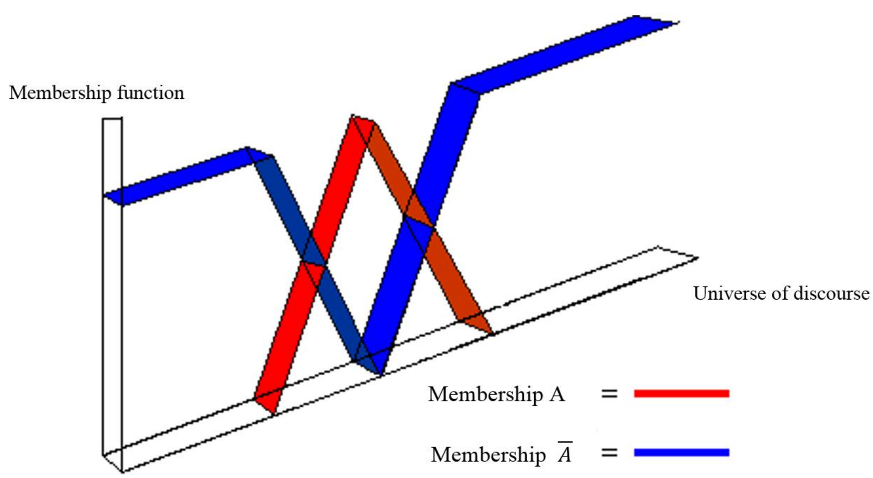


Figure 2.12. Graphical view of three operations on membership function
*(*Figures retrieved from:
http://www.doc.ic.ac.uk/~nd/surprise_96/journal/vol4/sbaa/report.fuzzysets.html*)*

2.3.5.5. Combining outputs to obtain an output distribution

Once the consequence of each fuzzy rule is determined, all outputs can be combined to get one fuzzy output distribution. The fuzzy term "or" is generally used to combine all consequences. As it is seen in figure 2.13. The first three rows of the figure show three fuzzy rules; in each of these rows, the left half is the "if" part of the fuzzy rule statement and the right half is the consequence (output membership function). The output distribution, which comes in the fourth row, is the combination of all three output membership functions. Defuzzification process converts these membership functions to crisp values.

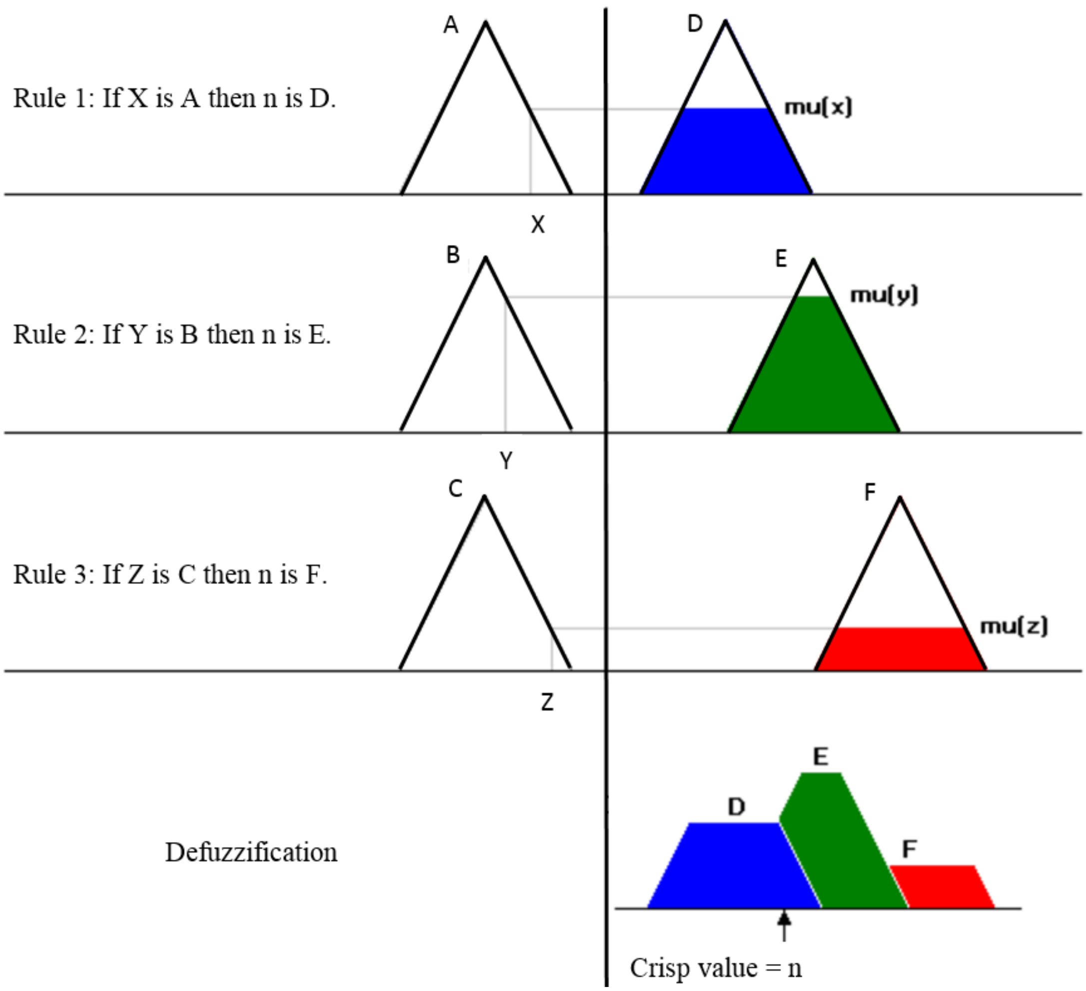


Figure 2.13. Combining the consequences to obtain an output distribution and defuzzification (Figure retrieved from Wikipedia)

2.3.5.6. Defuzzification of output distribution using centroid of area:

The final step of using an FIS is to convert the outputs into crisp values. This facilitates decision-making based on the outputs of the model because there is a certain answer (zero or one) for each scenario, rather than fuzzy answers, which work, based on shades of gray. This process is called defuzzification.

Centroid of area: This method is the most common way of difuzzification, which is widely used.

$$Z_{COA} = \frac{\int_Z \mu_A(z)\, z\, dz}{\int_Z \mu_A(z)\, dz}$$

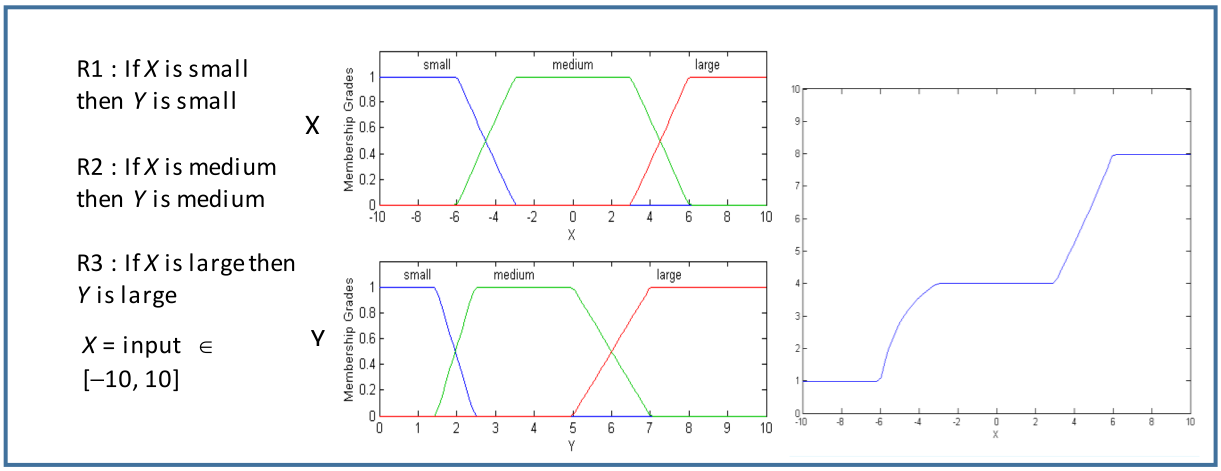


Figure 2.14. A simple example of fuzzy rules (left), fuzzification (middle) and defuzzification using COA (right)

2.3.6. Tsukamoto - Fuzzy Inference System

The second fuzzy inference system, which is used in this research, is Tsukamoto. In this technique, all consequences of fuzzy rules are combined to make a monotonical fuzzy set membership function. The outputs of each rule are converted into a crisp value. Finally, to combine the overall outputs, the weighted average of the output of each rule is commutated. Tsukamoto fuzzy inference system is not as commonly used as Mamdani's technique. The reason is less transparency compared with Mamdani's technique (Chaudhari et al., 2014). On the other hand, the benefit of

Tsukamoto is eliminating the time-consuming defuzzification process (George et al., 2008). Therefore, it is more computationally efficient.

The rules in this inference system are stated as: “If x is small then y is c1. If x is medium then y is c2.” Here the consequent of the rules are fuzzy sets. The output of Tsukamoto fuzzy inference system is crisp even if the input is fuzzy (Jang et al, 1977). Figure 2.15 shows the process of Tsukamoto’s technique.

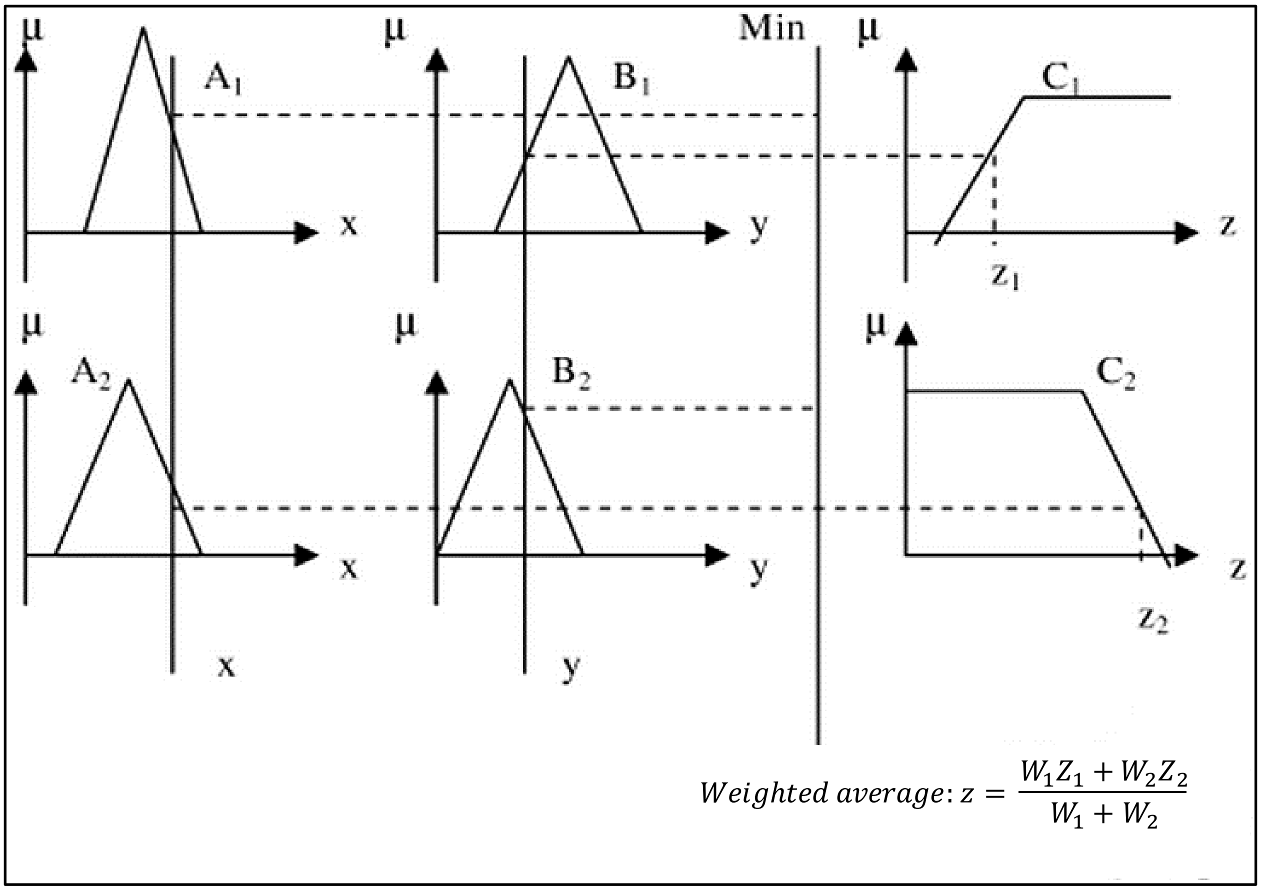


Figure 2.15. Tsukamoto Fuzzy Model (George et al., 2008)

2.3.7. Applications of Fuzzy Logic in Construction Management

The application of fuzzy logic has been gaining popularity in the research area of construction management over the past decade (Chan et al., 2009).

- Ebrahimnejad et al. (2008) used fuzzy logic as a multi-attribute decision making tool for risk evaluation in construction projects. They compared two methods of fuzzy TOPSIS and fuzzy LINMAP methods in construction risk evaluation.
- Chen et al, (2009) combined fuzzy logic with analytic hierarchy process (AHP) for risk assessment of international construction projects. They proposed a risk index model, which evaluates sources of risk and accordingly prioritize the projects to be used as a decision making tool.
- Chan et al. (2009) comprehensively studied the applications of fuzzy logic in construction management studies discipline. They noted that these studies in the past decade could be divided into two broad fields: One) fuzzy set/fuzzy logic and two) hybrid fuzzy techniques. However, hybrid fuzzy technique means the combination of the fuzzy method with other mathematical techniques. (This will be discussed in more details in chapter four). In this study, it was also noted that there is an increasing trend of applying fuzzy logic in construction management research.

Table 2.4. Applications of Fuzzy logic in construction management research (Chan et' al 2009)

Journal name	Year Published	Author(s)	Theory/ Concept	Field / Application	Relevance/ Classification
JCEM	1996	Lorterapong , P et al.	Fuzzy sets theory	Project network analysis	Time performance
JCEM	1998	Fayek et al.	Fuzzy set theory	Competitive bidding strategy	Decision making; assessment
JCEM	1998	Chao et al.	Fuzzy logic	Construction technology	Evaluation
CME	1999	Okoroh et al.	Fuzzy sets theory & Fuzzy logic	Subcontractor selection	Modeling
ECAM	2000	Kumar et al.	Fuzzy sets theory	Assessment of working capital requirement	Assessment
CME	2000	Tah et al.	Fuzzy logic	Construction project risk assessment	Assessment
IJPM	2001	Leu et al.	Fuzzy sets theory	Construction time-cost trade-off	Modeling
JCEM	2002	Tam et al.	Fuzzy sets	Site preparation	Decision making
CME	2002	Li et al.	Fuzzy sets theory	Sustainable housing	Decision making
JCEM	2002	Knight, K., et al.	Fuzzy logic	Cost control; project management	Cost performance; decision making
CME	2003	Zhang at al.	Fuzzy sets	Dynamic resource allocation	Decision making
CME	2003	Kishk, M. et al.	Fuzzy sets theory	Whole-life costing	Cost performance

IJPM	2003	Baloi, D., et al.	Fuzzy sets theory	Risk management	Performance
JCEM	2004	Seo et al.	Fuzzy set theory	Environmental sustainable buildings	Decision making; assessment
CME	2004	Wang at al.	Fuzzy sets theory	Project management decisions	Decision making
JCEM	2004	Bonnal et al.	Fuzzy sets	Project scheduling	Time performance
IJPM	2004	Wei et al.	Fuzzy sets theory	Selection of ERP system	Modeling
IJPM	2004	Tseng et al.	Fuzzy sets theory	Multi-functional project team formation	Modeling
JCEM	2004	Choi et al.	Fuzzy sets	Risk assessment	Assessment
BIJ	2004	BIJ et al.	Fuzzy logic	Distributor benchmarking	Benchmarkin g/Assessment
JCEM	2004	Zayed et al.	Fuzzy logic	Productivity Quantitative	Assessment
JCEM	2005	Zheng et al.	Fuzzy sets theory	Project management; risk management; productivity	Time and cost performance
JME	2005	Sánchez et al.	Fuzzy sets	Value management Evaluation;	Decision making
JCEM	2005	Oliveros, A.V.O., et al.	Fuzzy logic	Project management; activity delay analysis	Time performance
ECAM	2005	Shang et al.	Fuzzy logic	Intelligent risk assessment system	Assessment

JCEM: Journal of Construction Engineering and Management, ASCE;
CME: Construction Management and Economics;
IJPM: International Journal of Project Management;
JME: Journal of Management in Engineering, ASCE;
ECAM: Engineering, Construction and Architectural Management; and
BIJ: Benchmarking: An International Journal.

2.3.7.1. Applications of Fuzzy logic in Construction Decision-Making

The existing uncertainties of construction makes application of fuzzy logic suitable in dealing with these uncertainties, particularly in decision-making. Singh et al. (2005) attempted to mitigate subjectivity while considering multi-criteria for selecting contractor using fuzzy set theory. Another example of this is the research done by Tam et al. (2002) when they attempted to improve site layout to increase productivity despite the heterogeneity nature of construction projects. The third example of this can be found in Wang et al. (2004) research when they tried to find a decision-making tool to consider the conflicting goals that govern using resources. Additionally, Fayek et al. (1998) used fuzzy set theory to develop a competitive bidding strategy model that can help a company achieve its objectives in bidding. In addition, Lin et al. (2004) used fuzzy logic to come up with decisions of whether to bid or not based on multi-criteria that need to be considered without subjectivity.

2.3.7.2.Applications of Fuzzy logic in Construction Performance

For an optimal balance of time and cost, uncertainties about productivity, resource availability, and weather need to be considered. Zheng et al. (2005) used fuzzy set theory to provide the optimal balance of time and cost. In addition, Bonnal et al. (2004) analyzed fuzzy project-scheduling approach, used fuzzy set theory, and proposed a framework to address the resource constrained-scheduling problem. Oliveros et al. (2005) used fuzzy logic model to integrate daily site reporting of activity progress and delays; their developed model could schedule updating and forecasting system for construction projects. Knight et al. (2002) utilized it to assess the potential for cost overruns. Their method was able to assess the amount of possible risk on a project and the likelihood of profit making.

2.3.7.3.Applications of Fuzzy logic in Construction Evaluation/Assessment

Choi et al. (2004) used fuzzy set theory in risk assessment of underground construction projects. Kumar et al. (2000) applied fuzzy in the assessment of working capital requirement in construction projects to overcome the difficulty of considering qualitative factors for the evaluation of working capital requirement by incorporating linguistic variables into workable mathematical propositions. Zayed et al. (2004) applied fuzzy logic to develop a productivity index model that can reduce the subjective effect in refining productivity assessment. Tah et al. (2000) combined fuzzy logic with a hierarchical risk breakdown structure to build up a model for qualitative risk assessment.

2.3.7.4. Applications of Fuzzy logic in Construction Modeling

Okoroh et al. (1999) used fuzzy set theory to select subcontractor and developed a model for analyzing the subcontractor's risk elements in construction refurbishment projects. Wei et al. (2004) used fuzzy to developed a comprehensive framework for an appropriate enterprise resource planning. Tseng et al. (2004) used fuzzy set theory and grey decision theory to develop a method for the multifunctional team formation. They utilized gray decision theory to select desired team members through abstract information. Leu et al. (2001) developed a model for optimal construction time-cost trade-off using the fuzzy logic that could consider the effects of both uncertain activity duration and time-cost trade-off.

2.4. Hybrid Fuzzy Techniques

Hybrid fuzzy techniques are the methods that combine fuzzy set/fuzzy logic with other techniques. In fact, one of the advantages of fuzzy logic is its flexibility to be combined with other mathematical methods to enhance the methodology and precision of results. There are numerous studies using hybrid fuzzy technics. Hsieh et al. (2004) combined fuzzy with analytical hierarchy process to develop a method for selecting planning and design alternatives. Bouchereau et al.

(2000) used a hybrid fuzzy model to translate the customers' needs into technical requirements for a product or process life cycle. Some of the methods found in the literature that has combined fuzzy logic with other mathematical method are:

- fuzzy neural network
- neuro-fuzzy
- fuzzy reasoning
- fuzzy expert system
- fuzzy analysis
- fuzzy clustering
- fuzzy-FMEA
- fuzzy AHP
- Fuzzy fault tree

2.4.1. Fuzzy-FMEA

Failure mode and effect analysis has been widely used as a risk analysis technique, which has been recommended by international standards such as US Department of Defense. Despite its widespread use, there are some limitations in this method. These limitations are explained in more details in chapter three. To enhance the quality of risk analysis of FMEA, fuzzy logic has been proved to be one of the most effective supplements for FMEA. Fuzzy logic, as opposed to probabilistic techniques, is suitable for handling situations in which data are not available or are difficult to obtain, or in which assessments are made in linguistic and subjective terms. The characteristics of fuzzy logic make it proper for risk analysis in which uncertainties are high. Combining fuzzy with FMEA, make them a suitable decision support tool to aid in risk management in the construction industry (Abdelgawad et al., 2010).

The combination of FMEA and fuzzy logic is commonly addressed as "fuzzy- FMEA" in the literature. The main feature of fuzzy-FMEA is that instead of multiplication of values for severity,

detection, and occurrence, fuzzy calculations come to play to combine the effects of these three elements and come up with the criticality level of each potential risk. To do so, S, O and R must be first converted (translated) into fuzzy representations. This process is called fuzzification. Experts' assessments about S, O, and R are used as the inputs of the model. In the next step, the system identifies membership function (degree of membership) for each of the linguistic terms by establishing an "if-then" rule for all fuzzified events. The if-then rules are used to make fuzzy inference from the inputs. They define the relationship between input variables ("if" part) and the conclusion ("then" part). One major task of fuzzy calculations is to check the degree of matching for any combination of the three input values. Once this step is done, the outputs are once again translated to crisp values, which is in fact the "fuzzy risk priority number (FRPN)". This process is called "defuzzification". Fuzzy-FMEA process is explained in more details in chapter four.

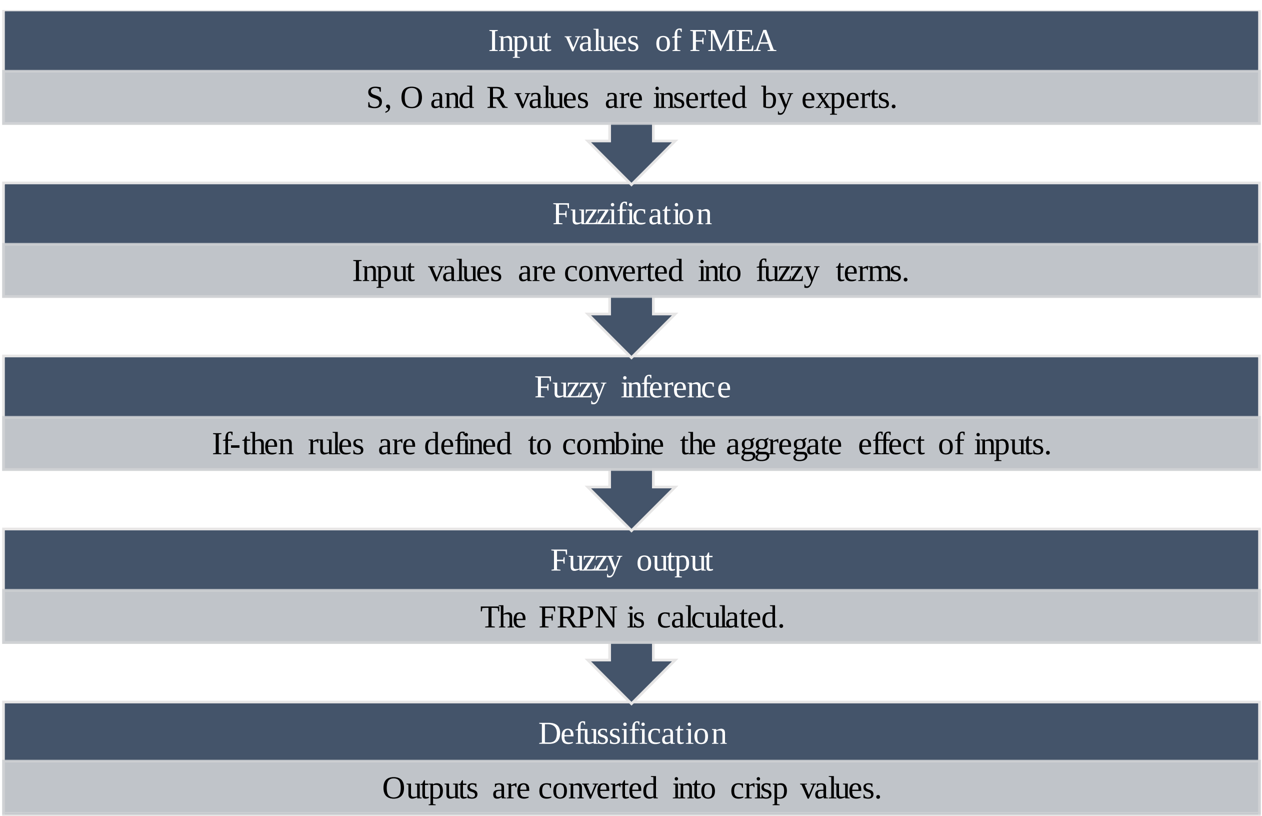


Figure 2.16. Fuzzy-FMEA process in brief

There is a large amount of research that have used fuzzy-FMEA as the risk analytical tool. Table 2.5 shows some of the researches that have been published as journal papers. :

Table 2.5. Examples of Applications of Fuzzy – FMEA in the literature

Author	Year	Brief description (Application)
Chin et al.	2008	Improving quality and reliability with the purpose of enhancing heftiness of new products at the stage of conceptual design
Guimaraes et al.	2004	Assessing risk in a nuclear reliability engineering problem related to chemical and volume control system
Xu et al.	2002	assessing the reliability of engine systems
Kumru et al.	2013	to improve purchasing process in a public hospital
Chen et al.	2009	Assuring that the design requirements have been fulfilled for the purpose of quality function deployment
Hu et al.	2009	to analyze the risks of green components in compliance with the European Union (EU)
Dinmohammadi et al.	2013	Risk and reliability analysis of wind turbines
Zaman et al.	2014	for risk evaluation of ship collisions in the Malacca Strait
Yang et al.	2011	To evaluate risk priority of the failure mode of rotor blades in an aircraft turbine while there is uncertainty in evaluating information

As mentioned before, the capabilities of fuzzy approach as a modern mathematical technique, makes it possible to be combined with various other mathematical methods. Therefore, there is an evolving trend in combining fuzzy logic with other methods. Chapter 3 explains in details how fuzzy logic is combined with failure mode and effect analysis to analyze the risk of delay during construction.

2.4.1.1. Fuzzy-FMEA for Delay-Risk Analysis

A fuzzy logic-based approach for prioritizing failures in FMEA uses fuzzy linguistic terms to describe S, O, D, and the risk of failures. The relationships between the risks and each of S, O, and R are characterized by fuzzy "IF-THEN rules" extracted with the help of experts' knowledge and expertise (Bowles and Pelaez, 1995).

The delay risk assessment model which is introduced in this research applies the fuzzy- FMEA method, which is supported by fuzzy-rule-based approximate inference methods. Inputs are mapped into outputs using a A fuzzy inference system (FIS) which is based on fuzzy set theory. Some examples of applications of fuzzy-FMEA in the literature are listed in table 2.6

As mentioned before, the capabilities of fuzzy approach as a modern mathematical technique makes it possible to be combined with various other mathematical methods. Therefore, there is an evolving trend in combining fuzzy logic with other methods. Chapter 3 explains in details how fuzzy logic is combined with failure mode and effect analysis to analyze the risk of delay during construction.

CHAPTER 3: METHODOLOGY

Since construction environment is full of uncertainties and risks, investing in controlling all roots and causes of delay is costly and impractical. Therefore, there is a need to decide without subjectivity that in *any certain phase* of *any construction project*, which causes of delay are the most critical and preventing which of them can more effectively mitigate the risk of delay in the project. In addition, it is essential to have an estimation of the expected delay with the current actual status of the project. In order to do so, there is a need to quantify and prioritize all potential causes by a method, which can generate reliable outputs. Doing so will help the construction team to clarify the most critical potential causes of delay; It also provides the chance of having a clear understanding of the risk of delay by having an estimation of the anticipated delay with the current status of the project.

The methodology used in this research is based on combining the Failure Mode Effect Analysis with fuzzy logic. At first, the most critical causes of delay are investigated through a national survey. Once these causes are identified, based on the concepts of Failure Mode Effect Analysis, certain criteria of risk should be measured to come up with a number that explains the riskiness of each of the causes. To overcome the shortcomings of the FMEA method, fuzzy logic is used to combine the elements of risk in FMEA and coming up with a number that is a representative of the aggregate effect of severity of causes, probability of their occurrence, and difficulty to resolve them before they can cause a delay. Once this number is calculated, using a designed fuzzy inference system, the potential causes can be ranked from the greatest to the smallest. This is a sorted list of the level of riskiness for all potential causes. A regression model will be also developed that shows the possible correlation between the fuzzy-risk priority number and the expected delay that it may cause. Based on this model, by evaluating a selected number of potential

causes of delay, the team can have an estimation about the percentage of the possible delay they would experience. This evaluation can happen at different stages of the project to reflect the project status in criteria of riskiness. The model presented in this research is expected to be used by project managers to provide an optimal risk-response strategy. The main applications of the tool are shown in the figure 3.1.

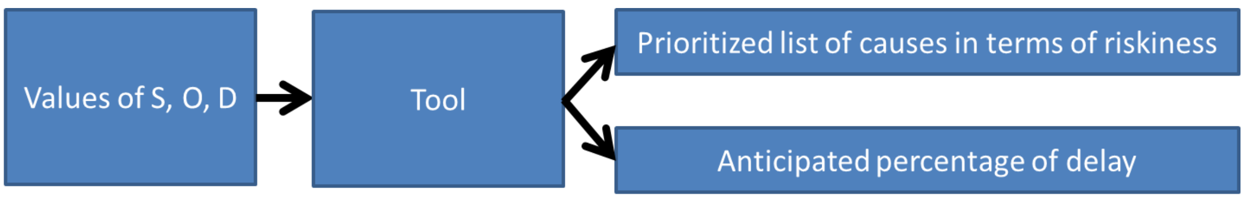


Figure 3.1. The two main applications of the tool developed in this research

3.1. Why fuzzy logic was chosen

There are several reasons why fuzzy logic was selected as the core method of doing this research; these reasons are listed below:

1. Fuzzy logic can be combined with traditional control techniques. It also has the capability of being combined with FMEA, which is a widespread risk assessment technique. This enhances the quality of risk assessment and improves the reliability of outputs of the model.
2. Risk assessment cannot be done based on crisp measurement values; in many cases, it is hard or impossible to assign a precise value to assess the riskiness of events. Fuzzy logic which is tolerant of imprecise data and does not require noise-free inputs, makes it possible to use approximate assessments to come up with reliable results in assessing the criticality of risks. Despite a wide range of input variations, the output of a fuzzy system is a smooth control function.

3. Fuzzy logic can combine numerous inputs to generate control outputs, which is the characteristic of causes of the risks. Some of the systems that would be difficult or impossible to model mathematically are modeled with fuzzy logic.
4. Fuzzy logic is based on natural language. It is capable of using human communications and linguistic terms, which are normally used to make approximate assessments. It simulates the decision making process in brain based on strong mathematical logic which prevents human errors while combining inputs to come up with conclusions (outputs).
5. Application of fuzzy logic has been widely accepted in many industries in the last decades. Fuzzy logic is now accepted and used as one of the main control systems in temperatures regulating, and/or water levels in air conditioners, washing machines, dishwashers, microwaves and more. It is used in digital image processing, robotics, and classification algorithms and medical diagnosis. In the literature review, it was also explained that fuzzy logic has been widely used in construction management as well.

3.2. Step by step methodology for dynamic risk analysis of delay in construction projects

In this part, the methodology, which is used for the dynamic risk analysis of construction delay, is explained step by step.

3.2.1. Selecting the most critical causes of delay for the analysis

The events that may lead to the occurrence of delay in construction projects are too many. Investigating and modeling all events that may have a contribution to delay is not practical. Therefore, to do the analysis, it is first required to identify which potential causes are more critical. In order to select these causes, a comprehensive study was conducted on the existing literature to find the causes that have been highlighted in previous research.

3.2.2. Conducting a national survey to evaluate the main causes of delay

In this step, a survey questionnaire is designed to ask experts of the construction industry in the United States. The purpose of this survey is to identify the relative importance of the causes. In other words, the results of this survey is intended to figure out the level of criticality between all the 30 selected causes for the study (which have been gained from the literature).

3.2.3. Identifying the Relative Importance Index (RII)

The relative importance of each of the causes is calculated in this step. This is to figure out which causes have a higher RII value to narrow down the number of causes that will be analyzed for the model in the next steps.

3.2.4. Selecting top-priority causes by running Wilcoxon Test

Since the tool needs input data for all the causes that it analyses, data collection is required to assess different aspects of riskiness for the causes. Assessment of all potential delay causes requires having too many questions (90 questions to measure S, O and R for 30 potential causes) and a very long survey, which has a very little chance to get adequate responses for the analysis. Therefore, a shortened list of causes should be selected from the 30 initial causes. Later on, if the tool is successful, it can be expanded, in future studies, to cover a greater number of causes and ideally to cover all potential causes. Based on this, by doing Wilcoxon ranking test, the causes that are significantly different from one another are selected to be included in the analysis.

3.2.5. Conducting the second national survey for the assessment of potential delay-causes with descriptive variables

Once it is clear that which causes are going to be selected for the design and the test of the tool, input data is required to test the quality of prediction that the tool is supposed to provide. The actual data of real completed projects that have been delayed is required for this purpose. When

this data is inserted into the tool, it predicts the percentage of delay using fuzzy inference system by combining numerous inputs to generate control outputs. Therefore, another dataset, which is collected through running the second survey, includes the amount of delay, occurred in certain projects. (Only delayed and completed projects are included in this survey).

Each potential cause is assessed in three aspects of: severity (S), occurrence (O) and difficulty of getting resolved or resolvability (R) by descriptive terms. The respondents are asked to have an evaluation based upon their information about the project to assess each cause in these three aspects. They are also asked to provide the data regarding percentage of delay in their project. All questions should be answered based on the data of a real completed project, which has been delayed.

Another consideration in designing this electronic questionnaire is the way the sliding bars are designed; all sliding bars have been designed in a way that sliding to the right (higher numbers) will be a representative of a more critical condition. It should be noted that about resolvability, the higher the number is, there is a higher chance of detection/control and so there will be less criticality. Though to keep consistency, for the questions that assess resolvability, instead of asking the chance of resolving the issue, difficulty of getting the cause resolved is assessed. This way, for all questions, moving the sliding bar to the right, will represent a more critical condition and there is less chance of confusion for the respondents. The electronic survey, which is designed for this assessment, facilitates answering the survey and minimizes the risk of human errors in data collection.

It should be noted that while assessing each of the S, O and R parameters, the assessment should be done independent of the other two parameters. For instance, when severity is being assessed, the chance of occurrence and the difficulty of resolving should not be considered. That is, severity

is not assessed based on the chance of occurrence and detection/control; even if there is a very low chance for occurrence, but in case an event happens, it will severely affect the project duration, the severity for the corresponding delay-cause will be high, regardless of the fact that it may almost never happen. Similarly, when difficulty of getting resolved and occurrence are being evaluated, the two other elements should not be considered. It is crucial to keep this in mind throughout the assessment because it can highly affect the quality of input data.

3.2.6. Fuzzification

Once the values for S, R and R are identified, fuzzy logic comes into play. Fuzzy logic consists of three steps: fuzzification, fuzzy rule-based inference, and defuzzification. The way these steps are taken is explained in brief.

3.2.6.1. Defining membership functions for S, O and R in Matlab® Software

As it was explained in chapter 2, membership functions are used to define the degree of membership to each fuzzy set. These functions are modifiable and help to simulate the human brain decision-making system. These functions can evolve throughout the years of application of a fuzzy-inference system to move towards precision.

Five functions are defined for each element of FMEA. These functions are labeled: 1) almost none, 2) low, 3) medium, 4) high, and 5) very high. The fuzzy inference systems will calculate the degree of membership for the inserted values in each of these five function. Graphically, the closer is the value of an inserted value to the peak of a plot for a function, the higher is degree of its membership to that function.

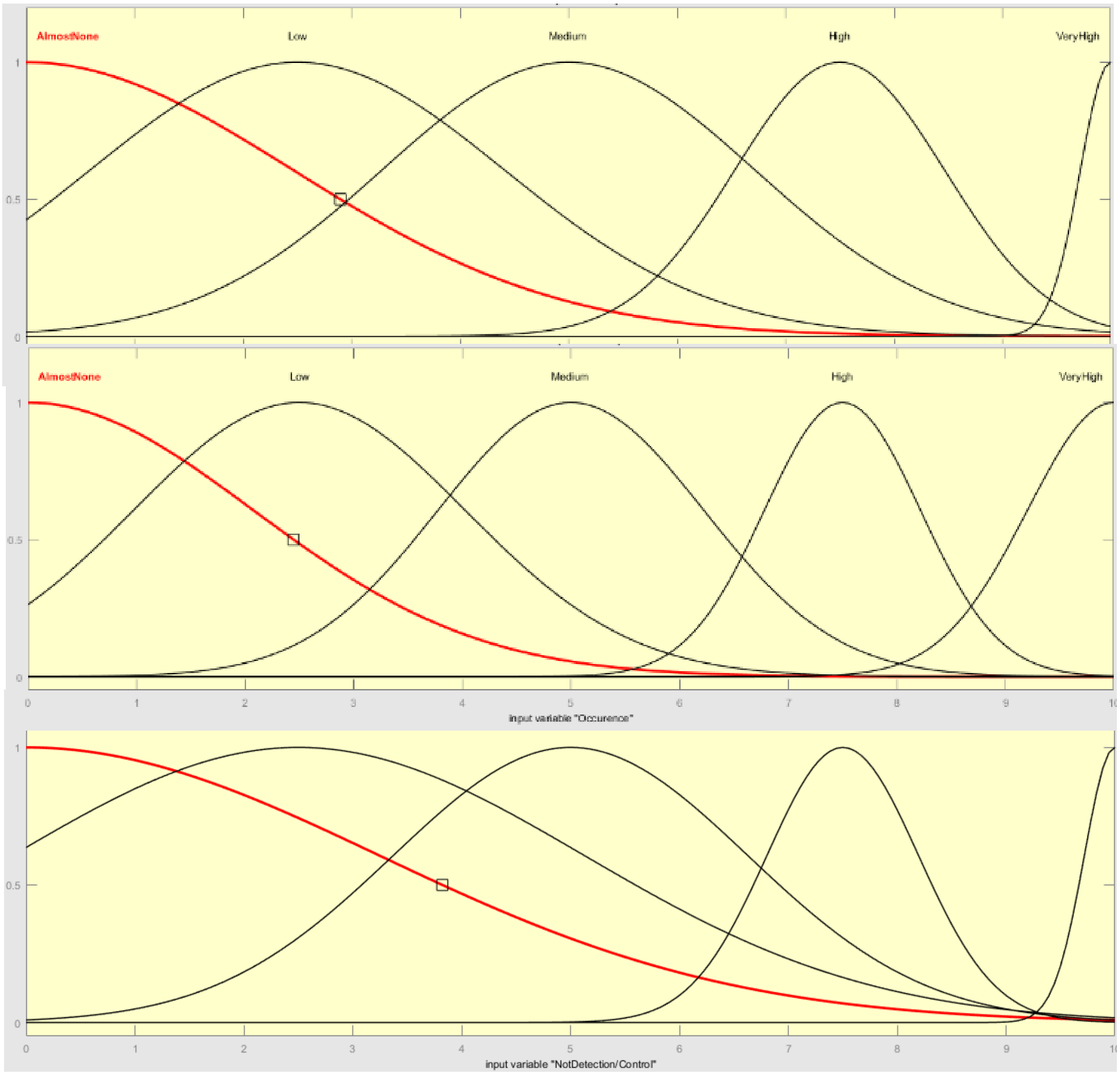


Figure 3.2. Defined membership functions for S, O and R in Matlab® Software

For recording the respondents' assessment of the project, Gaussian fuzzy function, which is one of the most widely used fuzzy function, is selected. This function translates the descriptive analysis of the causes into fuzzy values, which are later combined using fuzzy-based rules to generate the FRPN. The equation, which is used to calculate memberships, is shown below:

$$\mu_{A^i}(x) = \exp(-\frac{(c_{i}-x)^2}{2\sigma_i^2})$$

Where c_i and σ_i are respectively the center and width of the i^{th} fuzzy set A_i (See figure 3.3).

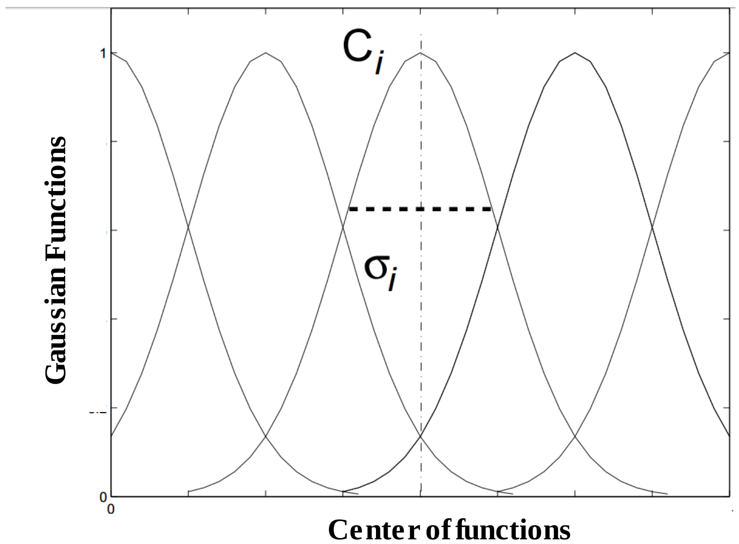


Figure 3.3. Parameters to Calculate degree of membership

3.2.6.2. Defining fuzzy-rules for the fuzzy inference system

One advantage of Fuzzy-FMEA system is its ability to define different rules for combining the aggregate riskiness of a potential cause by combining its severity, occurrence and resolvability. Despite FMEA, which considers the product of the risk elements as the risk priority number, in Fuzzy-FMEA, the fuzzy rules are used to combine the effects of these three elements and come up with the FRPN for each cause.

The Fuzzy-based rules will be tested to see how well they can generate an FRPN, which can effectively represent the riskiness of the causes. These rules are defined and inserted into Matlab. The structure of fuzzy rules is based on "If-then" conditional statements. Rules of this type, can be more easily formulated using linguistic terms (Chin, et al 2008). Each rule has two parts: an antecedent and a consequence. Antecedent which contains the "if" term, explains a unique combination of linguistic terms for S, O and R. The "consequence" explains the level of riskiness

for that certain composition. To make the fuzzy-based rules, the status for each of the assessment elements (S, O and R) should be combined to come up with an overall assessment.

Each rule explains how the effect of S, O and R should be combined and interpreted by the software. In this study since there are five different status of riskiness for each of the elements and since there are three elements, the number of different possible ways that these elements can be combined will be $5 \times 5 \times 5 = 125$. Therefore, 125 rules are used by the fuzzy inference system to come up with a single FRPN.

On the other hand, these rules make fuzzy process long and involve tones of calculations before an output value can be generated. Applying these rules requires using software to reduce the chance of human error in long calculations.

3.2.7. Defuzzification

The purpose of the defuzzification process is to create a crisp ranking from the fuzzy conclusion set which can show the riskiness of each of the potential causes of delay. This facilitates choosing the most efficient corrective actions to prevent or minimize the risk of delay. In other words, defuzzification process, decodes the fuzzy conclusions based on their degree of truth (membership function values) to come up with crisp (non-fuzzy) results. At this step, the results of calculations are translated to values that represent the riskiness of each of the potential causes of delay. The outcome of the defuzzification is the FRPN.

The software is capable of calculating the FRPN using the “centroid of area” defuzzification method for each of the causes (this was explained in chapter 2). The way it works, in simple words, is explained here: Each of the 125 rules consider the aggregated result of combining S, O, and R. In centroid of area method, the center of gravity for all results combined is calculated. In other

words, the center of gravity is calculated for the shape that is the result of combining all the outcomes of each rule. This is called the fuzzy centroid. The output is a number with a crisp value. The generated FRPN provides an assessment of the riskiness of each of the causes. The FRPNs are then sorted from greatest to smallest. This list provides the criticality of each of the potential causes and is useful for corrective actions. That is, the construction team can decide how to invest the budget more effectively in preventing delay by spending it on the more critical causes.

Since assessment of the project can be done during the construction, the tool can prevent or mitigate the risk of delay in a dynamic way. By calculating the FRPNs, the team will perform the corrective actions and then they can reassess the project to see how the FRPNs change (decrease). This is why it is claimed that the presented method provides a *dynamic* approach of assessing the risk of delay.

3.3. Correlating FRPN with the percentage of delay

The crisp FRPN values can provide an assessment of the risk of the delay. Another target of this research is to investigate the relationship between the FRPN and the percentage of delay. Based on this, the model can estimate a range-percentage of expected delay based on its assessment of the causes that contribute to delay. These causes are investigated individually. It was explained earlier that in the second survey, the respondents are asked to evaluate the three elements of FMEA and indicate the percentage of delay in a certain completed delayed project. The model correlates the amounts of FRPN generated from defuzzification with ranges of percentage for delay. To make this happen, the second survey asks the construction experts to select the main causes of delay in one actual completed delayed project. The amounts of FRPN for each specific cause will be mapped with the corresponding percentage of delay in that project to investigate the correlation between the FRPN (for a specific cause) and percentage of delay.

It is expected that there is a correlation between the FRPN and the percentage of delay in a way that, the greater the FRPN is, the greater the percentage of delay will be. If the results verify such a correlation, the tool can be also used for predicting the range of percentages of delay based on the status of project. In other words, the tool can measure the riskiness of a potential cause of delay based on the elements of FMEA, use a fuzzy inference system to combine and generate the FRPN, and based on this predict a range of delay in any project at any phase during construction.

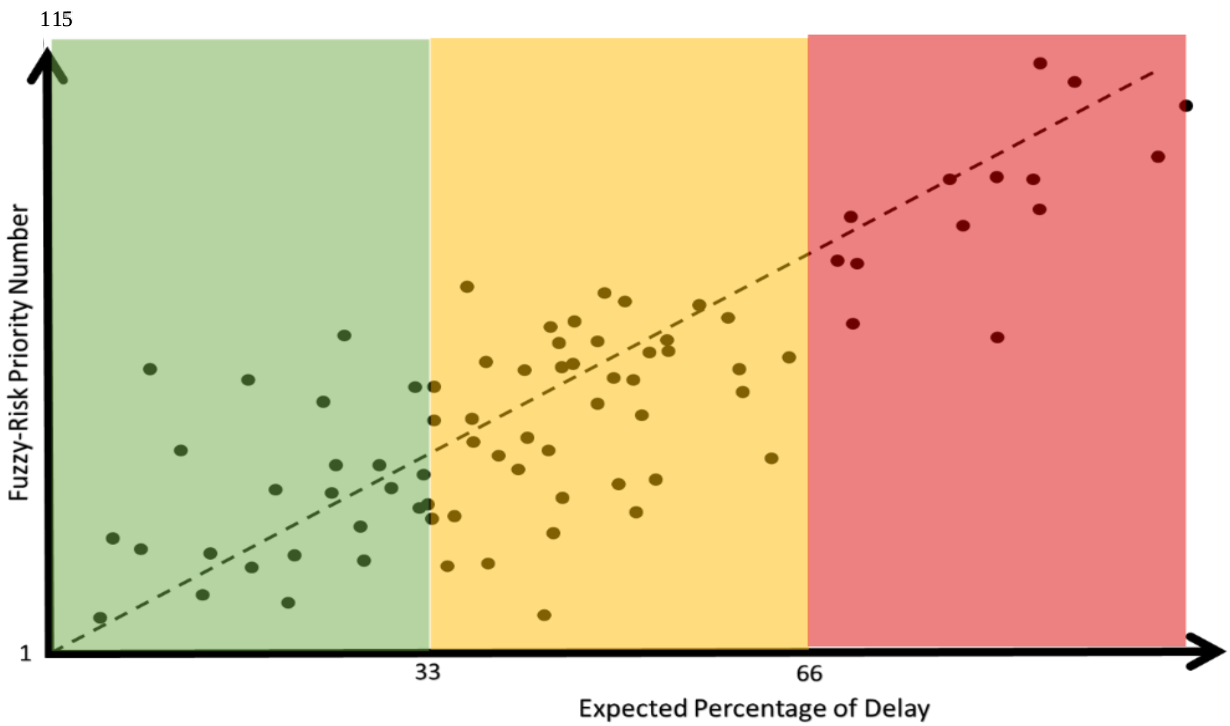


Figure 3.4. Expected correlation assumed between the FRPN and the percentage of delay (to be investigated after data collection)

3.4.Testing the Model

The model will be tested to evaluate its ability to predict the percentages of delay. To perform the test, the amount of S, O and R will be assessed in several finished construction project that have been delayed. To use the model, the input data are inserted in the designed fuzzy logic inference

system to generate a crisp fuzzy risk priority number. The model then uses this generated number in a formula to calculate the percentage of delay. This delay percentage is then compared with the actual delay that has happened in the project to see how close the model will be able to predict delays.

CHAPTER 4: ANALYSIS AND RESULTS

4.1. Results of the literature Review for identifying the potential cause of construction delay

To decide which causes of delay (from the numerous possible causes) should be selected for the initial analysis, it was required to investigate the common causes that have been mentioned by the majority of construction-delay studies. The research papers (that were mentioned in chapter 2) were studied. The result of the study was a list of 30 potential causes that are shown in table 4.1.

Table 4.1. The main causes of construction delay in the literature

C1	Unrealistic schedule (bid duration is too short)
C2	Ineffective delay penalties provisions in contract
C3	Errors in contract documents
C4	Selecting inappropriate project delivery method
C5	Excessive change orders by the owner during construction
C6	Delayed payments by the owner
C7	Delay in approving design documents by the owner
C8	Time consuming decision making process of the owner
C9	Unnecessary Interference by the owners
C10	Delay to furnish and deliver the site to the contractor
C11	Poor communication and coordination of the owner with designer and/ or contractor
C12	Poor Quality Assurance (QA) plan of the owner

C13	Lack of management staffs of the owner
C14	Inappropriate construction methods
C15	Contractor inefficiency (in providing the labor, equipment and material and handling sub-contractors
C16	Poor communication and coordination of the contractor with owner and/ or designer
C17	Inadequate contractor experience
C18	Financial difficulties and mismanagement by the contractor
C19	Poor site management and Quality Control (QC) by the contractor
C20	Legal disputes between designer and the owner
C21	Design errors
C22	Complexities and ambiguities of project design
C23	Delays in providing the design documents by the designer
C24	Inadequate experience of the designer
C25	Inadequate site assessment by the designer during design phase
C26	Misunderstandings between owner and designer about scope of the work
C27	Financial difficulties with the designer
C28	Poor communication and coordination of the designer with owner and/ or contractor
C29	Legal disputes between designer and the owner
C30	Delay in getting permits and acquisitions (Environmental, building, Right of way, utilities, etc.)

4.2. Results of the first national survey

As it was explained in chapter 3, the first national survey aims at the two following goals:

1) Investigating the comparative effectiveness of the common causes of construction delay or ,in other words, the level of riskiness for each of the potential causes of delay
2) Identifying a smaller list of the most critical causes of construction delay in the United States for the second round of analysis and model development.

The survey was done on-line in 96 days during summer 2016, by inviting almost 11,000 experts in the United Stated of which 219 completed the survey. What follows are the results of this survey:

4.2.1. The types of projects the respondents have been involved

The majority of the respondents (88%) have been involved in building projects. The second rank is infrastructure projects with 23%, and highway projects with 14%. Figure 4.1 shows the graph for these statistics.

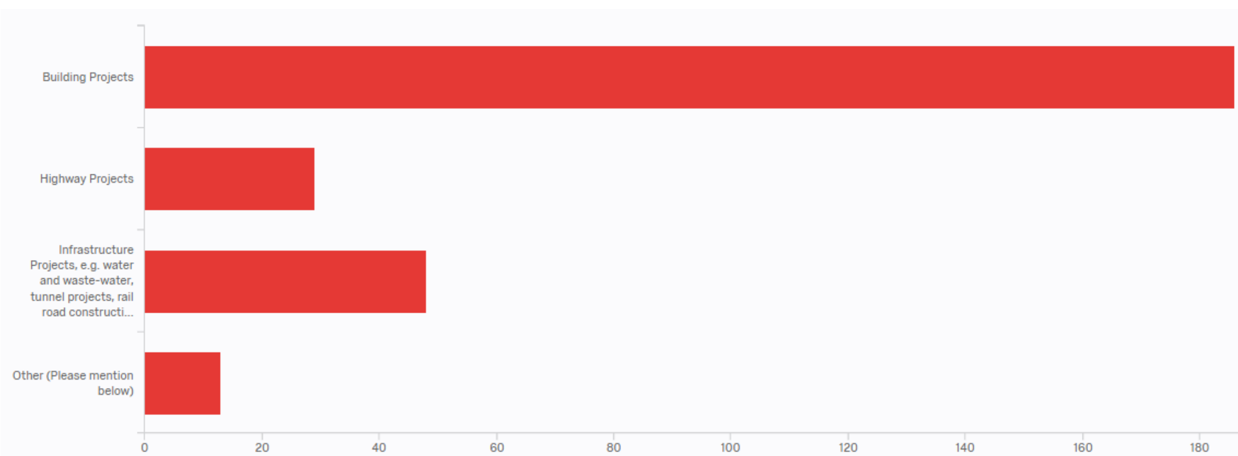


Figure 4.1. The types of projects the respondents have been involved

4.2.2. The types of ownership

The majority of respondents (87%) have been involved in private projects. The second rank is public projects (49%), and public-private ownerships (18%). Figure 4.2 shows the graph for these statistics.

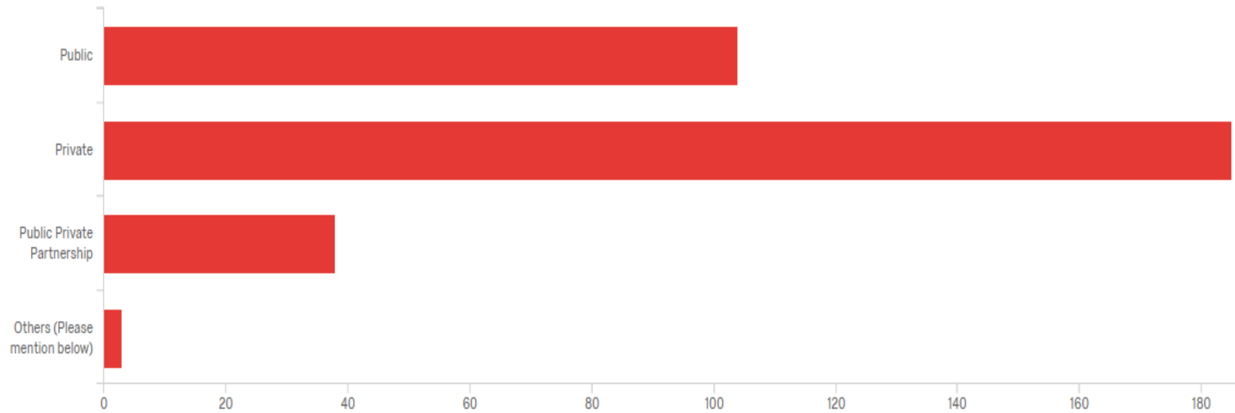


Figure 4.2. The types of ownership in projects the respondents have been involved

4.2.3. The types of project delivery method

The majority of respondents (68%) have been involved in 'design-bid-build' projects. The second rank is 'design-build' (66%), and 'construction manager at risk' (18%). Figure 4.3 shows the graph for these statistics.

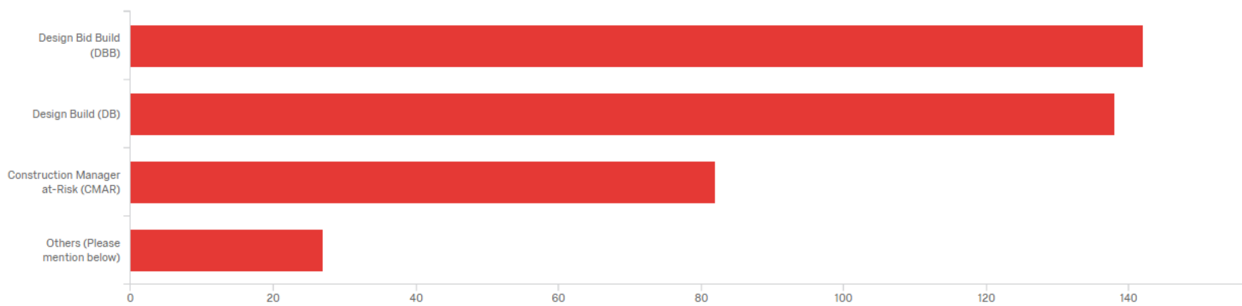


Figure 4.3. The types of project delivery method the respondents have been involved

4.2.4. The party the respondents worked for

The majority of respondents (83%) have been involved as owners of the projects. The second rank is the contractors (38%), and designers /consulting firm (32%). Figure 4.4 shows the graph for these statistics.

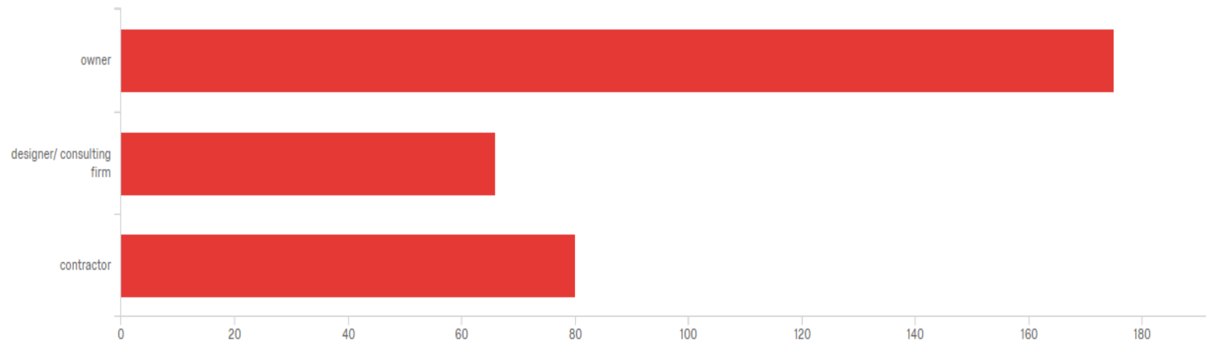


Figure 4.4. The types of party the respondents have worked for

4.2.5. The average years of experience of the respondents

The average years of experience of the respondents is 27.9 years. Considering the fact that 27 years indicates a great deal of experience for a person who has been involved in construction projects, the high average years of experience for the respondents is one of the strengths of this survey.

4.3. The effectiveness of different causes of delay

One of the major goals the surveys aims as measuring is the effectiveness of the 30 potential causes, in the occurrence of delay. The respondents were asked to evaluate the effectiveness of each of the causes by selecting a number between 1 to 5 in which 1 shows the least and 5 shows the most effectiveness.

The results of the survey for this question were then analyzed using relative importance index method. The equation below was used:

$$RII = \frac{\sum W}{A \times N} \qquad (0 \leq RII \leq 1)$$

Where:

- "W" is the weight given to each factor by respondents and ranges between 1 to 5 (where "1" is extremely ineffective and "5" is extremely effective).
- "A" is the highest weight (i.e. 5 in this case) and;
- "N" is the total number of respondents

Based on this, figure 4.5 shows the result of the analysis.

Figure 4.5. Results of the analysis for Relative Importance Index

4.3.1. Results of the Wilcoxon Ranking Test

To select the top causes, it was first necessary to make sure that these causes are significantly different from one another. In order to test this, the Wilcoxon non-parametric test was conducted. The P-value of 0.05 or less was required to reject the null hypothesis. This test is based on the equations below:

$$Z = \frac{R - \mu_R}{\sigma_R}$$

Where:

$$\mu_R = \frac{n_1 + (n_1 + n_2 + 1)}{2}$$

$$\sigma_R = \sqrt{\frac{n_1 n_2 (n_1 + n_1 + 1)}{12}}$$

R = sum of ranks for smaller sample size (n_1)

n_1 = smaller of sample sizes

n_1 = larger of sample sizes

$n_1 \geq 10$ and $n_2 \geq 10$

To make the calculations easier, starting from the cause with the highest RII value, every two causes that had the two consecutive values of RII, were first compared. If the P-value $\leq$ 0.05 in the Wilcoxon Test they were significantly different and since all other causes had a smaller RII, without calculations it could be claimed that the target cause is significantly different from the rest of the causes. In case P-value $\geq$ 0.05, the null-hypothesis could not be rejected and the next cause with the next highest RII value is compared with the target cause. This is repeated until the P-value $\leq$ 0.05, which shows that the target cause is significantly different from the rest of the causes on the list. Figure 4.6 shows the results of this comparison matrix. Since the bottom half of the matrix will be identical to its top-half, the bottom half has been eliminated. The black cells show the rest of the P-values in each row, that are equal or smaller than 0.05 after meeting this condition

	C5	C8	C21	C7	C3	C1	C30	C22	C11	C23	C15	C16	C9	C24	C6	C28	C25	C26	C17	C19	C18	C10	C4	C14	C13	C12	C20	C2	C29	C27
C5	1	0.080	0.000																											
C8		1	0.12	0.001																										
C21			1	0.887	0.286	0.345	0.345	0.186	0.068																					
C7				1	0.263	0.319	0.276	0.274	0.075	0.015																				
C3					1	0.869	0.991	0.702	0.467	0.183	0.050																			
C1						1	0.888	0.983	0.738	0.246	0.085	0.043																		
C30							1	0.885	0.644	0.158	0.054	0.087	0.011																	
C22								1	0.757	0.184	0.058	0.039	0.017	0.006	0.012															
C11									1	0.333	0.138	0.025																		
C23										1	0.367	0.608	0.141	0.028																
C15											1	0.966	0.715	0.423	0.496	0.219	0.041													
C16												1	0.553	0.304	0.439	0.093	0.007													
C9													1	0.719	0.785	0.682	0.154	0.108	0.052	0.032										
C24														1	0.995	0.79	0.222	0.186	0.039											
C6															1	0.779	0.266	0.126	0.073	0.004										
C28																1	0.297	0.306	0.099	0.057	0.004									
C25																	1	0.741	0.489	0.423	0.047									
C26																		1	0.34	0.313	0.039									
C17																			1	0.692	0.153	0.171	0.151	0.002						
C19																				1	0.344	0.229	0.188	0.007						
C18																					1	0.628	0.605	0.125	0.008					
C10																						1	0.981	0.37	0.02					
C4																							1	0.376	0.021					
C14																								1	0.228	0.07	0.034			
C13																									1	0.786	0.484	0.064	0.014	
C12																										1	0.52	0.045		
C20																											1	0.318	0.100	0.000
C2																												1	0.419	0.031
C29																													1	0.078
C27																														1

Figure 4.6. The P-values for the Wilcoxon Test

From this matrix, it can be inferred that it cannot be claimed that C5 is significantly different from C8. Similarly, it cannot be claimed that C21 is significantly different from C7, C3, C1, C30, C22, and C11. Accordingly, to select four major causes to design the tool, the causes in each of these 4 groups should be significantly different from other groups. Based on this, the four groups of significantly different causes are shown in table 4.2.

Table 4.2. Groups of causes that are significantly different

Group numbers	Group #1	Group #2	Group #3
Causes that belong to the group	C5, C8	C8, C21	C21, C7, C3, C1, C30, C22, C11

Based on this, the selected causes are C5, C8, C21, C7, C3, C1, C30, C22 and C11.

To conduct the survey, *Qualtrics* on-line tool was used. The link to the survey was sent to project managers across the country. There were almost 30 questions in the survey and participants were anonymous.

4.4. Results of the second national survey

The second national survey aimed at developing a model that can predict the percentage of delay based on evaluating the riskiness of the potential causes of delay. As mentioned above, the selected potential causes in this survey come from the results of the first survey in which thirty potential causes were ranked based on their criticality. In addition, using Wilcoxon Ranking test, it was confirmed that the selected causes are significantly different from other causes. The most important difference of the second survey with the first one are the following:

I. The fist survey asks the general opinion of the experts about the criticality of thirty different potential causes in the U.S construction industry while the second survey aims at evaluating the riskiness of the nine selected most critical causes in a certain and unique project.

II. The first survey ranks the thirty potential causes by defining their riskiness with a number between 1 to 5, while the second survey aims at evaluating the riskiness of the selected causes based on the experts' evaluation of the causes' likelihood of occurrence, severity in causing delays, and resolvability before they can contribute to delays.

4.4.1. The main causes of delay

The respondents were asked to identify the main cause of occurrence of delay in a specific delayed project. A total of 46 responses were collected for this question. The top five causes were identified as Time consuming decision making process by the owner (35%), Design errors, delay in getting permits and acquisitions, and unrealistic schedule (32% each), and excessive change orders by the owner during construction (28%). Figure 4.7 shows how other potential causes were ranked.

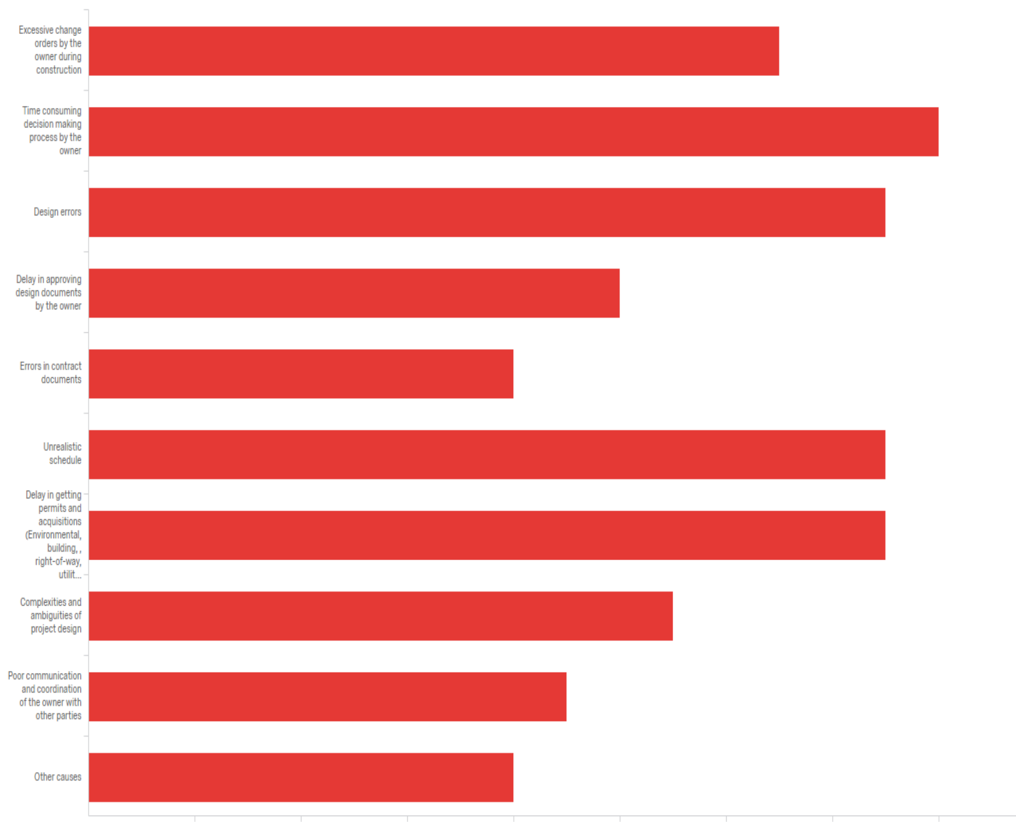


Figure 4.7. Responses for main cause of delay in a specific delayed project.

4.4.2. Type of construction project

Almost 70% of the respondents were involved in building projects. None of the responses came from experts involved in highway projects and almost 27% of the respondents were involved in infrastructure projects.

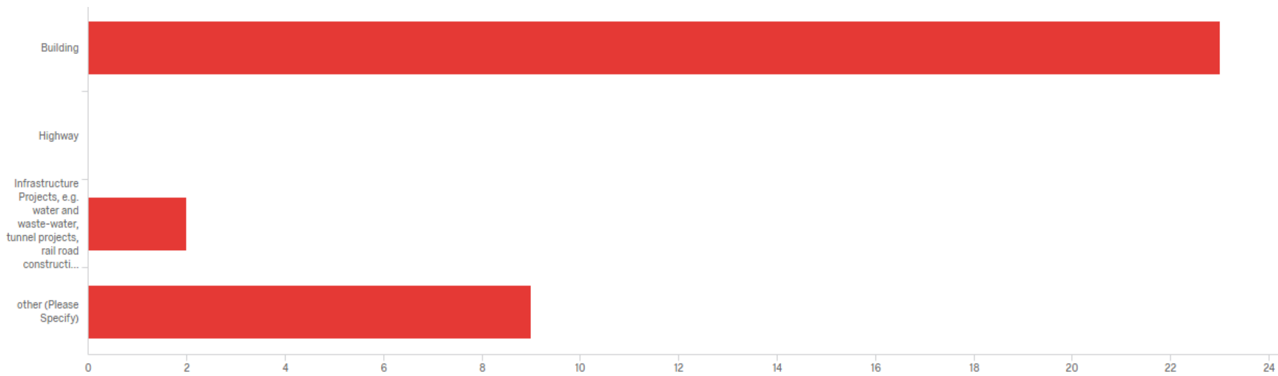


Figure 4.8. Responses for main cause of delay in a specific delayed project.

4.4.3. Type of ownership

The respondents were asked to identify the type of ownership for the type of the project they have been involved. The most frequent response was 'private ownership', which covered 64.65% of the population followed by public ownership covering 26.47% of the population. In addition, 5.88% of the experts have mentioned other types of ownership. Figure 4.9 shows how these types of ownership were ranked.

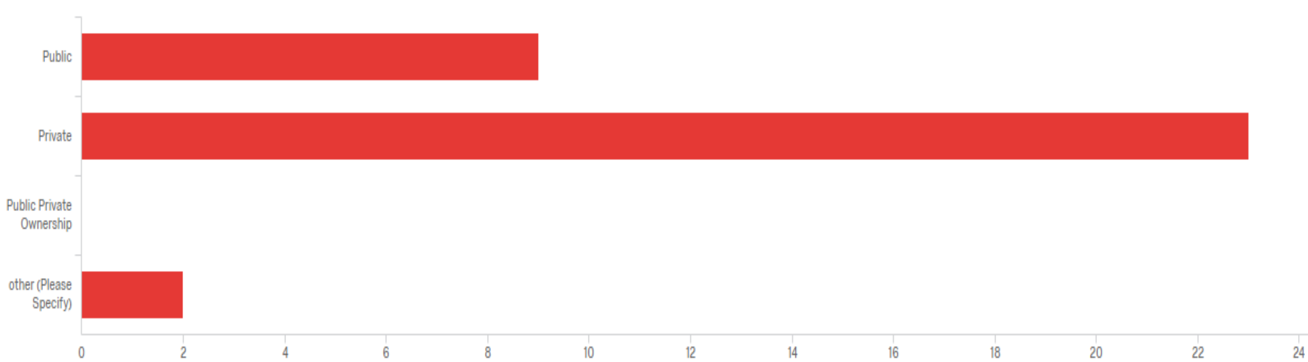


Figure 4.9. The type of ownership for the project the respondents have been involved

4.4.4. Project duration and extension of the substantial completion

The next question of the survey deals with calculating the percentage of delay in the project. The survey would invite experts to answer the question about a unique project that had been delayed; therefore, all responses included an extension in the intended date for the substantial completion. Figure 4.10 shows an example of measuring these two values by the survey. The percentage of delay is calculated through the following formula:

$$Delay\ (\%) = \frac{Project\ Delay\ Duration}{Contracted\ Substantial\ Completion\ Project\ Duration} \times 100$$

Both durations are measured in months. As a reminder, the respondents can only take the survey for a completed and delayed project.

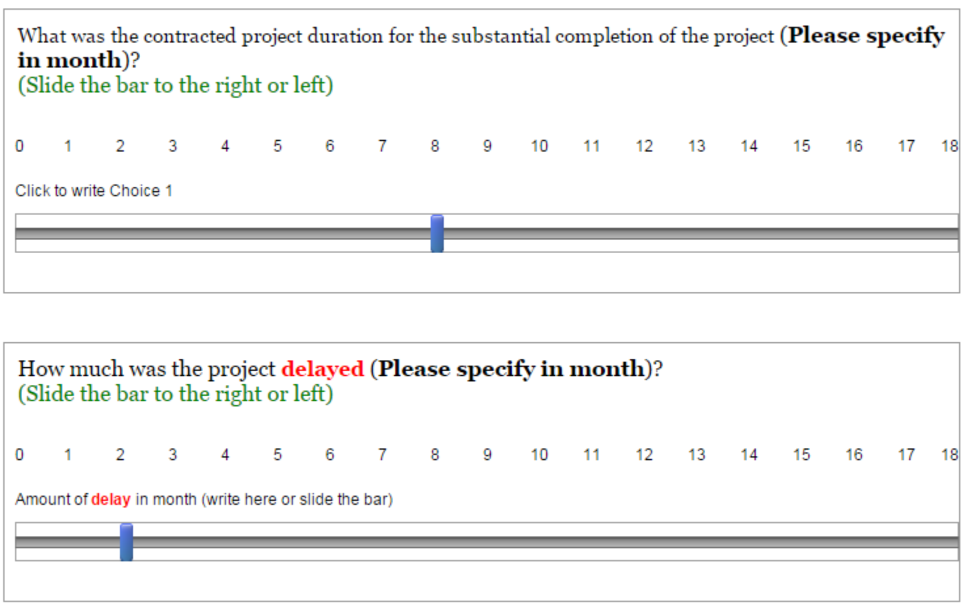


Figure 4.10. An example for measuring the project and delay durations by the survey

4.4.5. Assessing S, O and R for the causes

The online survey was capable of adjusting the remaining questions based on the responses provided by the survey-takers. For each potential cause of delay selected by the respondent, the

survey would show three follow-up questions to assess the riskiness of the cause. These three questions were designed to assess the three following elements of the risk in a descriptive way:

1- Occurrence (O), which measures the likelihood that a potential cause happens
2- Severity (S), which measures how effectively the selected cause could lead to delays in case it occurs
3- Resolvability (R), which measures the difficulty of resolving a potential cause before it can cause a delay.

All the three elements of delay evaluation are measured based on descriptive terms. Figure 4.11 shows an example of this measurement for the "excessive change orders".

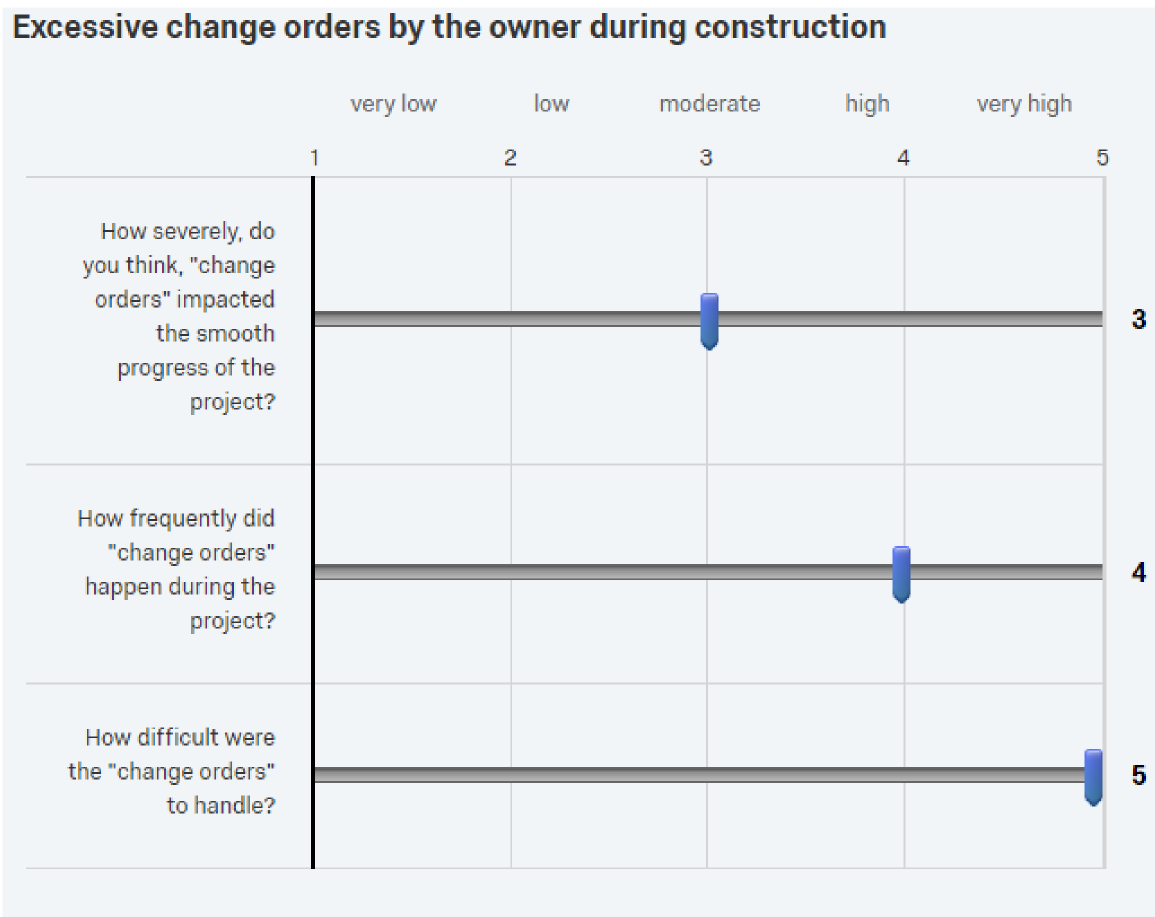


Figure 4.11. An example of measuring the values of O, S, and, R for one of the selected potential causes

4.5. Calculating the Fuzzy Risk Priority Number

The next step of the method is using the values inserted as O, S and R to generate a crisp value that is a representative of the riskiness of the cause. This value is labeled as the Fuzzy Risk Priority Number or FRPN.

As explained in details in chapter three, the developed tool to generate the FRPN in this study is based on a fuzzy inference system, which can calculate the membership of each element of risk and then through defuzzification translate the overall membership into a crisp value. The tool uses 125 different rules (figure 4.12) which explain how the combined effect of S, O, and R should be calculated to come up with a distribution that explains the overall membership of the event in the fuzzy set. The tool will be tested later to see how the defined rules and calculations manage to provide a prediction of the percentage of delay.

1. If (Occurence is VeryHigh) and (Severity is AlmostNone) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
2. If (Occurence is VeryHigh) and (Severity is AlmostNone) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
3. If (Occurence is VeryHigh) and (Severity is AlmostNone) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is VeryLow) (1)
4. If (Occurence is VeryHigh) and (Severity is AlmostNone) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is VeryLow) (1)
5. If (Occurence is VeryHigh) and (Severity is AlmostNone) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is Low) (1)
6. If (Occurence is VeryHigh) and (Severity is Low) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is VeryLow) (1)
7. If (Occurence is VeryHigh) and (Severity is Low) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is VeryLow) (1)
8. If (Occurence is VeryHigh) and (Severity is Low) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is Low) (1)
9. If (Occurence is VeryHigh) and (Severity is Low) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is HighLow) (1)
10. If (Occurence is VeryHigh) and (Severity is Low) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is LowMedium) (1)
11. If (Occurence is VeryHigh) and (Severity is Medium) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is VeryLow) (1)
12. If (Occurence is VeryHigh) and (Severity is Medium) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is Low) (1)
13. If (Occurence is VeryHigh) and (Severity is Medium) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is LowMedium) (1)
14. If (Occurence is VeryHigh) and (Severity is Medium) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is Medium) (1)
15. If (Occurence is VeryHigh) and (Severity is Medium) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is LowHigh) (1)
16. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is Low) (1)
17. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is LowMedium) (1)
18. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is HighMedium) (1)
19. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is High) (1)
20. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is High) (1)
21. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is LowHigh) (1)
22. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is LowHigh) (1)
23. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is High) (1)
24. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is High) (1)
25. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is High) (1)
26. If (Occurence is High) and (Severity is AlmostNone) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
27. If (Occurence is High) and (Severity is AlmostNone) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
28. If (Occurence is High) and (Severity is AlmostNone) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is VeryLow) (1)
29. If (Occurence is High) and (Severity is AlmostNone) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is VeryLow) (1)
30. If (Occurence is High) and (Severity is AlmostNone) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is VeryLow) (1)
31. If (Occurence is High) and (Severity is Low) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
32. If (Occurence is High) and (Severity is Low) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is VeryLow) (1)
33. If (Occurence is High) and (Severity is Low) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is Low) (1)
34. If (Occurence is High) and (Severity is Low) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is Low) (1)
35. If (Occurence is High) and (Severity is Low) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is HighLow) (1)
36. If (Occurence is High) and (Severity is Medium) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is VeryLow) (1)
37. If (Occurence is High) and (Severity is Medium) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is Low) (1)
38. If (Occurence is High) and (Severity is Medium) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is HighLow) (1)
39. If (Occurence is High) and (Severity is Medium) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is LowMedium) (1)
40. If (Occurence is High) and (Severity is Medium) then (FuzzyRiskPriorityNumber is Medium) (1)
41. If (Occurence is High) and (Severity is High) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is VeryLow) (1)
42. If (Occurence is High) and (Severity is High) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is HighLow) (1)
43. If (Occurence is High) and (Severity is High) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is LowMedium) (1)
44. If (Occurence is High) and (Severity is High) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is HighMedium) (1)
45. If (Occurence is High) and (Severity is High) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is LowHigh) (1)
46. If (Occurence is High) and (Severity is VeryHigh) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is Low) (1)
47. If (Occurence is High) and (Severity is VeryHigh) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is LowMedium) (1)
48. If (Occurence is High) and (Severity is VeryHigh) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is HighMedium) (1)
49. If (Occurence is High) and (Severity is VeryHigh) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is LowHigh) (1)
50. If (Occurence is High) and (Severity is VeryHigh) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is High) (1)
51. If (Occurence is Medium) and (Severity is AlmostNone) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
52. If (Occurence is Medium) and (Severity is AlmostNone) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
53. If (Occurence is Medium) and (Severity is AlmostNone) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
54. If (Occurence is Medium) and (Severity is AlmostNone) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
55. If (Occurence is Medium) and (Severity is AlmostNone) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is VeryLow) (1)
56. If (Occurence is Medium) and (Severity is Low) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
57. If (Occurence is Medium) and (Severity is Low) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is AlmostNone) (1)
58. If (Occurence is Medium) and (Severity is Low) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is VeryLow) (1)
59. If (Occurence is Medium) and (Severity is Low) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is Low) (1)

...

115. If (Occurence is VeryHigh) and (Severity is Medium) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is HighMedium) (1)
116. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is LowMedium) (1)
117. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is Medium) (1)
118. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is HighMedium) (1)
119. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is LowHigh) (1)
120. If (Occurence is VeryHigh) and (Severity is High) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is High) (1)
121. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is AlmostNone) then (FuzzyRiskPriorityNumber is HighMedium) (1)
122. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is Low) then (FuzzyRiskPriorityNumber is LowHigh) (1)
123. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is Medium) then (FuzzyRiskPriorityNumber is High) (1)
124. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is High) then (FuzzyRiskPriorityNumber is High) (1)
125. If (Occurence is VeryHigh) and (Severity is VeryHigh) and (NotDetection/Control is VeryHigh) then (FuzzyRiskPriorityNumber is High) (1)

Figure 4.12. Some of the defined rules to combine S, O, and R in Matlab Software

The values of S, O, and R were inserted to the software to be combined in the designed fuzzy inference system. Out of 46 respondents, only 30 respondents provided the delay data for this analysis. Table 4.3 shows the percentage of delay in the projects the respondents worked on and the corresponding FRPN for them.

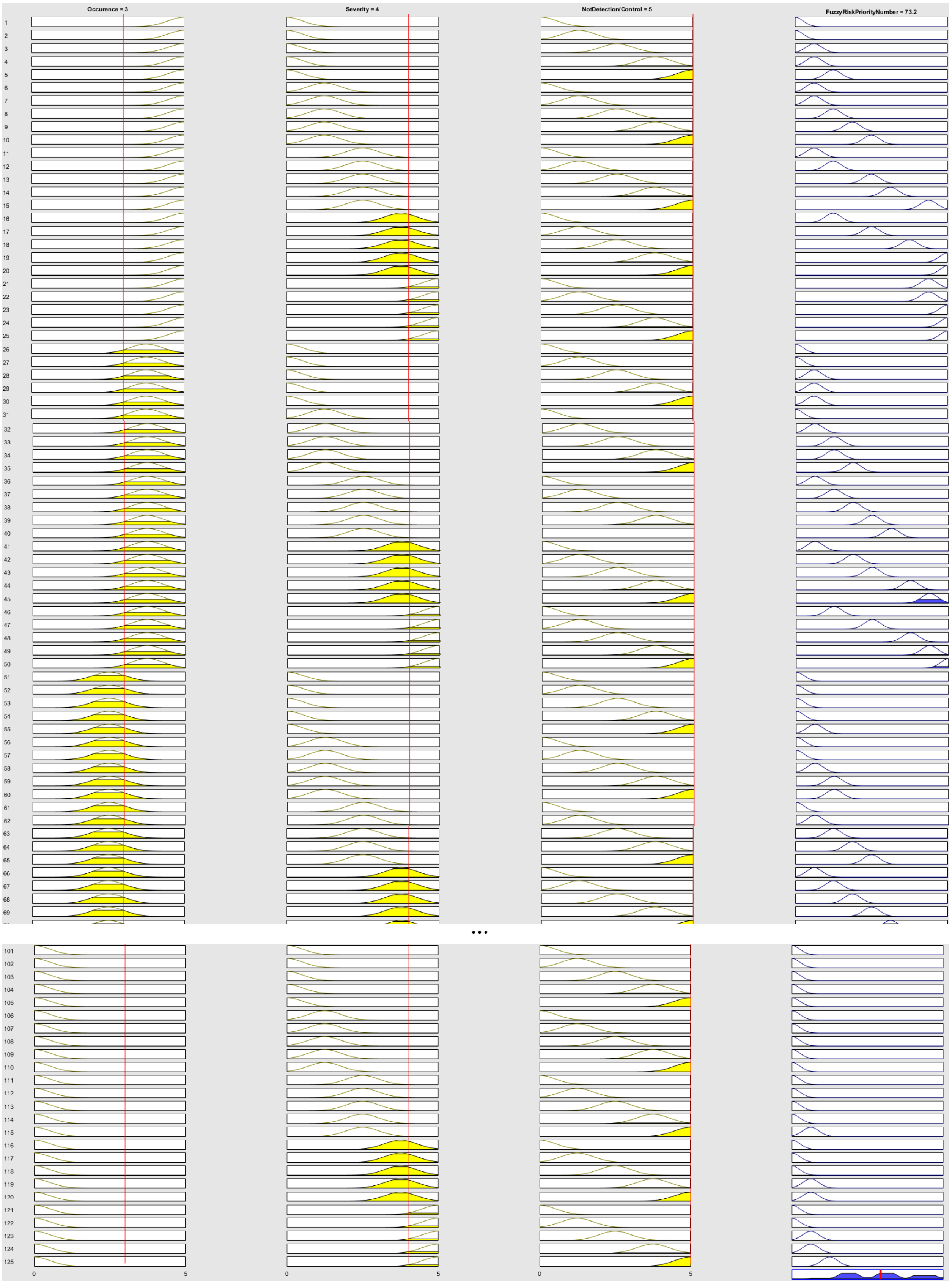


Figure 4.13. An example of how the tool calculates FRPN for O=3, S=4, and R= 5.

Table 4.3. Percentage of delay and FRPN for 30 construction projects

Project ID	FRPN	Intended Duration (months)	Extension (months)	Delay %
#1	83.8	12	4	33
#2	105	16	9	55
#3	65.6	5	4	73
#4	94.1	18	3	16
#5	86.5	4	4	99
#6	66.8	10	2	20
#7	104.2	6	6	100
#8	89.6	20	6	30
#9	28.5	12.5	3	24
#10	67.2	12	4	33
#11	38.475	24	4	17
#12	55.625	10	6	60
#13	64.35	18	10	56
#14	97.3	12	6	50
#15	94.5	24	4	16
#16	100.3	16	4	25
#17	95.6	14	10	70
#18	93	24	6	25
#19	55.2	12	3	25
#20	115	12	12	99
#21	110	12	11	91
#22	115	6	6	100
#23	115	6	6	100
#24	47.9	14	2	14
#25	93	11	5	45
#26	22	20	1	5
#27	45.6	15	3	20
#28	78	8	4	50
#29	115	7	8	114
#30	115	10	11	110

4.6. Combining FRPNs

As it can be seen from the table, for each project, a unique representative FRPN has been provided. Considering the fact that six of the respondents had identified more than a single cause for the occurrence of delay in their project, it was needed for these projects to combine the generated FRPNs to come up with a unique FRPN based on which the riskiness of delay in the project can be assessed. In doing so, there were two options; one was to calculate the simple average FRPN by adding up the FRPN values associated with different causes in a project and then dividing the total by the number of causes. This could lead to inaccurate results as not all the causes have the same weight in the occurrence of delay. Another method was to consider weights for each cause based on its severity in causing delay, which has been measured in the survey. It means the weights of FRPN for each cause depends on its share in the total weight of severity. The combined FRPN for the project is the summation of the all causes weighted FRPN values. An example of this is shown in table 4.4.

Table 4.4. An example of calculating FRPN for a project with three different causes

Cause ID	Severity	FRPN	weight	Weighted FRPN
I	3	60	3/12 = 0.25	0.25 * 60 = 15
II	4	90	4/12=0.33	0.33 * 90 = 30
III	5	115	5/12=0.42	0.42 * 115 = 48
Total	12			93

4.7. Descriptive analysis of the variables

The dataset created from the second survey provided an evaluation of the three elements of riskiness for the selected cause of delay, as well as the percentage of delay that has happened for

thirty different delayed and finished construction projects. Table 4.5 shows the average delay and the calculated FRPN for these projects.

Table 4.5. Descriptive Analysis

	Mean	Std. Deviation	N
Delay	52.5817	34.58605	30
FRPN	81.9171	27.50389	30

4.8. Investigating correlation between FRPNs and Delay Percentages

One of the major goals of the research is to investigate the relationship between the FRPN and the percentage of delay. The goal was to investigate the extent to which the percentage of delay depends on the FRPN. In other words, if the designed method of assessing the risk is correlated with the casual percentage of project delay.

If this correlation is verified, it can be utilized for a predictive relationship between the two variables. In other words, by assessing the riskiness of the causes through the designed method, the percentage of delay can be predicted with some approximation.

The test of correlation, in general, can be done via parametric and non-parametric tests. The Person Correlation test is performed for parametric test; Kendall's τ coefficient and the Spearman's ρ tests are performed for the non-parametric test.

4.8.1. Parametric-test of coefficient

One of the most familiar statistical methods for investigating the correlation is Pearson product-moment correlation coefficient. In order to calculate this correlation, the covariance of delay

percentages and FRPN values should be divided by the product of their standard deviations. The equation used for this is the following:

$$r = \frac{\sum_{i=0}^{30}((FRPN_i - \overline{FRPN})(Delay_i - \overline{Delay}))}{\sqrt{\sum_{i=0}^{30}(FRPN_i - \overline{FRPN})^2 \sum_{i=0}^{30}\left(Delay_i - \overline{Delay}\right)^2}}$$

Where:

r = correlation coefficient

$FRPN_i$= the value of FRPN (created by the tool) for the i^{th} project

$Delay_i$ = = the percentage of delay for the i^{th} project

$\overline{FRPN}$ *= the average FRPN for the thirty measured projects*

$\overline{Delay}$ *= the average percentage of delay for the thirty measured projects*

To test the correlation, a null-hypothesis is required. The selected confidence level is 95%. The results of investigating this correlation are presented in table 4.6, which is the output of the SPSS software.

Table 4.6. SPSS outputs Pearson's τ coefficient test

		Delay	FRPN
Pearson Correlation	Delay	1.000	0.675
	FRPN	0.675	1.000
Sig. (1-tailed)	Delay	.	0.000
	FRPN	0.000	.
N	Delay	30	30
	FRPN	30	30

As it can be seen from the table, the P-value is less than 0.001, therefore, the null-hypothesis can be rejected and it is verified by the parametric test that the two variables are significantly correlated.

4.9. Developing a model to predict delay percentages using FRPN values

After verifying the correlation between the FRPN and delay percentages, the next goal is to develop a model that can estimate the relationship between these two variables.

4.9.1. Regression Analysis

The regression analysis explains how the percentage of delay changes when the FRPN varies. In this analysis, it is assumed that the FRPN is an independent variable, which is a representative of the riskiness of the potential causes of delay, and the actual delay is the dependent variable. In other words, since delays are a result of risks created by the occurrence of the delay-causes, these causes are the independent and the delay is considered as the dependent variable. Therefore, in this analysis, the estimation target is the percentage of the delay and regression function is the value of FRPN. Regression analysis is able to evaluate how the values of FRPN correlate with the actual delay that has occurred. The reason for selecting this type of analysis is its widespread use, particularly when sample sizes are not large

The following assumptions, which are required to perform a regression analysis, are verified.

i. Both variables of FRPN and delay are continuous.

ii. Since the dependent and the independent variables are just one, there exists independence of observations.

iii. The data are normally distributed.

4.9.2. Selecting the best model

The technique for carrying out the regression analysis in this research is based on trying different types of regression models to identify the type of regression that can provide better statistical results. For this purpose, the linear regression model and the exponential regression model are compared. By plotting the data points for FRPN and delay percentage values, a scatter plot is obtained. The best fitting line for both models is then tested to see which one can provide a better approximation of the delay.

4.9.2.1.Linear regression model

A linear predictor function can be obtained by finding the best fitting straight-line for the data points of FRPN and delay. The equation that can generate this line by calculating the values of the dependent variable (delay percentage), when the values of the independent variable (FRPN) are inserted into it, will be the linear regression model. This model was developed by the SPSS software.

Table 4.7 shows the result of the regression analysis by the SPSS. The R-value, which shows the simple correlation, is 0.675. The R^2 value shows that almost 0.455 of the total variance in the delay can be explained by the values of FRPN.

Table 4.7. SPSS outputs for Regression Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.675	0.455	0.436	25.985

The next step to check how well the regression model predicts the delay is through Analysis of variance (ANOVA) of the model. Since there are two groups involved in the analysis a T-test

could also be performed but due to more conservative results of ANOVA, this method is selected. The null-hypothesis for this test is: The regression model cannot predict the outcome variable.

The results of the ANOVA are shown in table 4.8. As it can be seen, The P-value is smaller than 0.001. This means that the null hypothesis can be rejected and it can be concluded that at 95% of confidence level, the regression model statistically significantly predicts the percentage of delay by having FRPN values.

Table 4.8. SPSS outputs for ANOVA

Model	Su of squares	df	Mean square	F	Sig.
1	0.675	0.455	0.436	25.985	0.000

Table 4.9. SPSS outputs for Linear model Coefficient

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-16.902	15.134		-1.117	0.274	-47.903	14.100
	FRPN	0.848	0.175	0.675	4.835	0.000	0.489	1.208

Based on the outputs the linear regression model of delay prediction is:

$$\boldsymbol{Delay\ \% = 0.8482(FRPN) - 16.902}$$

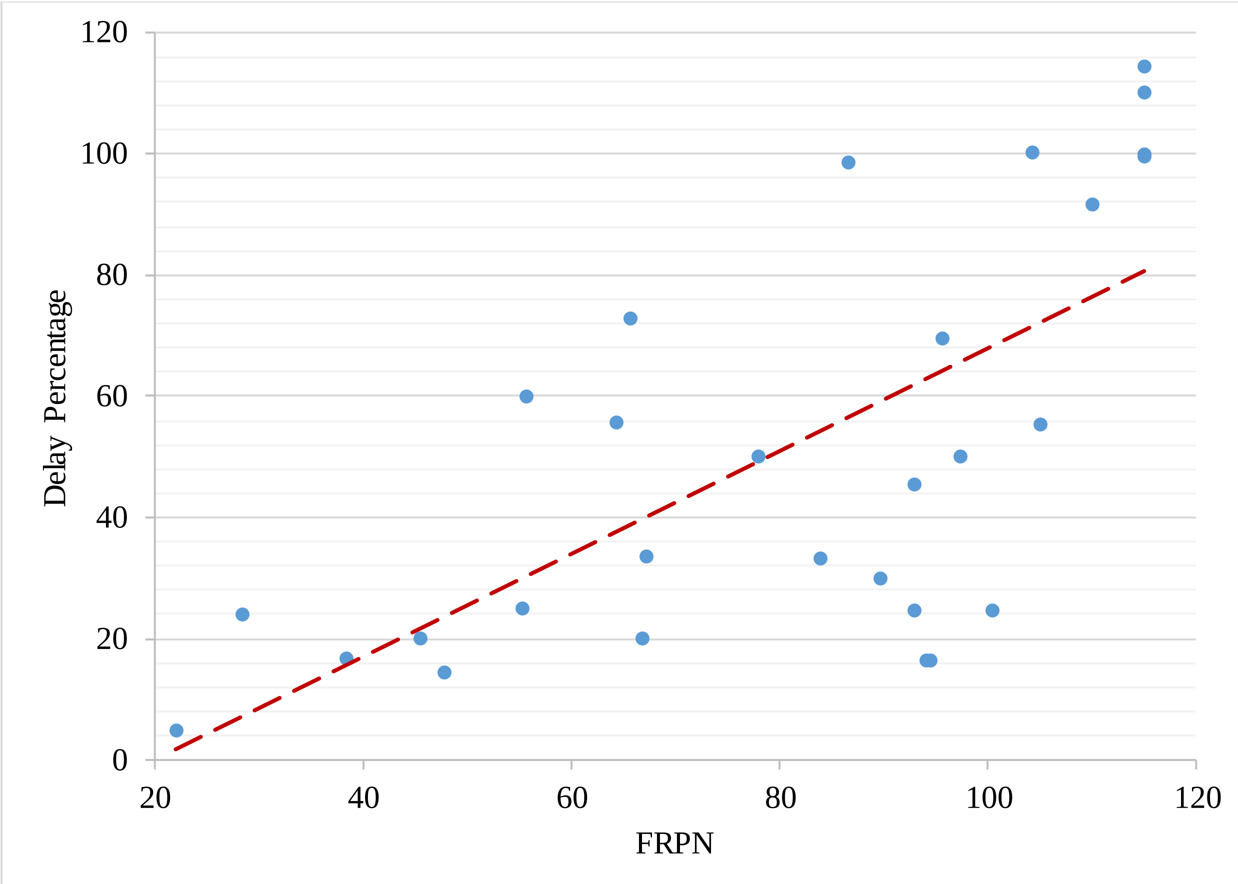


Figure 4.14. The scatter plot of data points and the best-fitted line for a linear regression model

4.9.3. Exponential regression model

While the linear regression model provided satisfactory results (statistically significant), to make sure if other models can provide better results, some other models were also tested. From these models, the results of the exponential regression model are explained here.

Similar to the linear regression model, the purpose of this model is to find an equation that fits best for the FRPN-Delay dataset. In this model, the equation is based on an exponential function. This non-linear model was investigated.

The model summary (table 4.10) shows an R-Value close to 0.7 which is slightly better than the R-value of the linear regression model.

Table 4. 10. SPSS outputs for Exponential model summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.696	0.485	0.467	0.574

**The independent variable is FRPN.*

The null-hypothesis for the ANOVA test is: *The regression model cannot predict the outcome variable*. The results of the ANOVA are shown in table 4.11. As it can be seen, The P-value is smaller than 0.001. This means that the null hypothesis can be rejected and it can be concluded that at 95% of confidence level, the exponential regression model statistically significantly predicts the percentage of delay by having FRPN values.

Table 4. 11. SPSS outputs for Exponential model ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	8.686	1	8.686	26.368	.000
Residual	9.224	28	0.329		
Total	17.910	29			

Table 4.12. SPSS outputs for Exponential model Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
FRPN	0.020	0.004	0.696	5.135	0.000
(Constant)	7.971	2.665		2.991	0.006

As it can be seen, the P-value of the exponential regression in less than 0.001 and the regression model is statistically significant at 95% of confidence interval. Based on the outputs, the exponential regression model of delay prediction is:

$$\boldsymbol{Delay = 7.9707e^{0.0199*FRPN}}$$

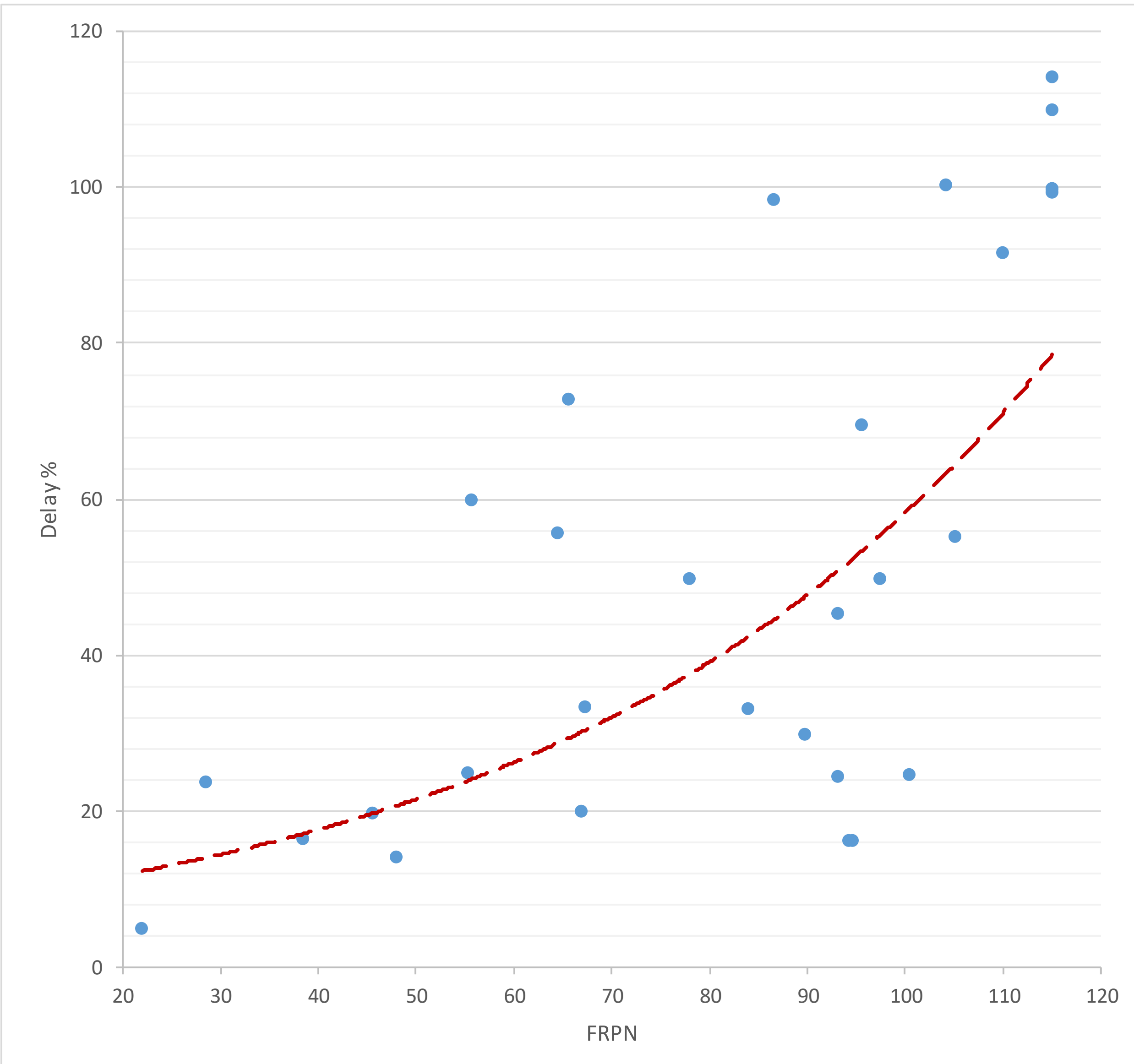


Figure 4.15. The scatter plot of data points and the best-fitted line for an exponential regression model

Comparing the graphical view of the two models indicates that the curve for the exponential model is closer to the observed values. This is also supported by comparing the R-values of both models.

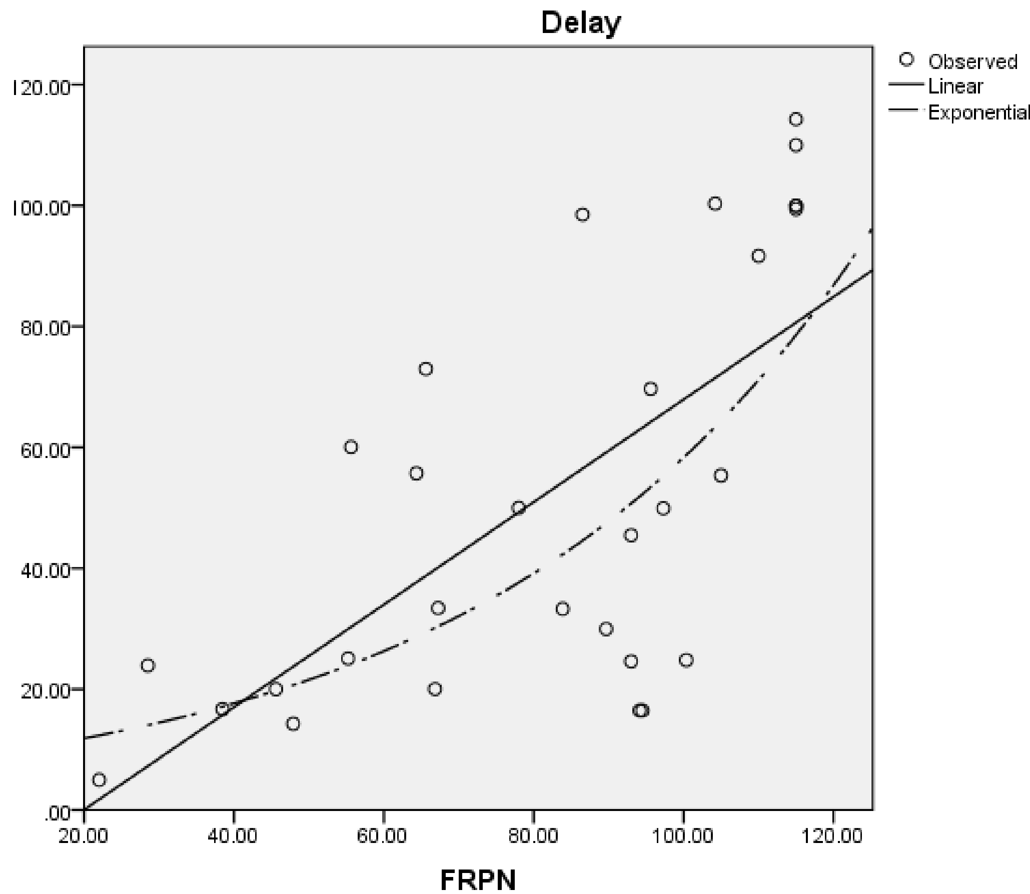


Figure 4.16. The scatter plot of comparing the linear and the exponential regression models

4.10. Testing the models

The models were designed using the collected data from 30 construction projects. To verify the models and to test which model is generating more accurate results, in the next step, the models needed to be tested. What follows shows how the testing process was performed.

4.10.1. Conducting the third survey

To test the model, a new data set that has not been used in developing the model was required. To do so, the third survey with questions identical to the second survey, was designed. The data of ten

projects were used in this survey to generate the FRPN and to see how the predicted percentage of delay by the models is close to the actual delay that had happened in these projects. Table 4.13 shows the results of collected data for 10 completed and delayed projects.

Table 4.13. The results of the third survey to test the model.

Project ID	Cause	Original duration	Project Extension	Delay %	S	O	D	FRPN
#1_test	Change orders	6	5	83	4	5	4	110
#2_test	Delayed permits	10	5	50	3	4	5	87.9
#3_test	Errors in contract	10	3	30	3	3	5	64
#4_test	Complex Design	5	2	40	2	2	4	37
#5_test	Design errors	4	4	100	5	5	4	112
#6_test	Unrealistic schedule	8	4	50	4	4	5	104
#7_test	Change orders	12	9	75	5	5	5	115
#8_test	Change orders	10	1	10	2	2	2	23.1
#9_test	Unrealistic schedule	12	4	33	3	3	4	48
#10_test	Change orders	8	4	50	3	4	5	87.9

4.10.2. Comparing the linear regression predicted delay with the actual delay

In the next step, the values of FRPN, which are based on the assessment of the respondents, were inserted into the linear regression model to generate the predicted delay. The predicted delay was then compared with the actual delay to see how close the results are. The result of this comparison is shown in table 4.14.

Table 4.14. The results of comparing the predicted delay by the linear regression model and the actual delay

Project ID	FRPN	Actual Delay	Predicted Delay
#1_test	110	83	76.40
#2_test	87.9	50	57.65
#3_test	64	30	37.38
#4_test	37	40	14.48
#5_test	112	100	78.10
#6_test	104	50	71.31
#7_test	115	75	80.64
#8_test	23.1	10	2.69
#9_test	48	33	23.81
#10_test	87.9	50	57.65

Based on the data of this table, figure 4.17 shows the scatter plot, which maps this data points. The yellow points are the delay percentages predicted by the model (*Delay % = 0.8482(FRPN) - 16.902*) and the blue points are the actual delay that has happened. Since both amounts of delay are related to a certain FRPN, for each measured projects both amounts of delay will appear on the same x-coordinate.

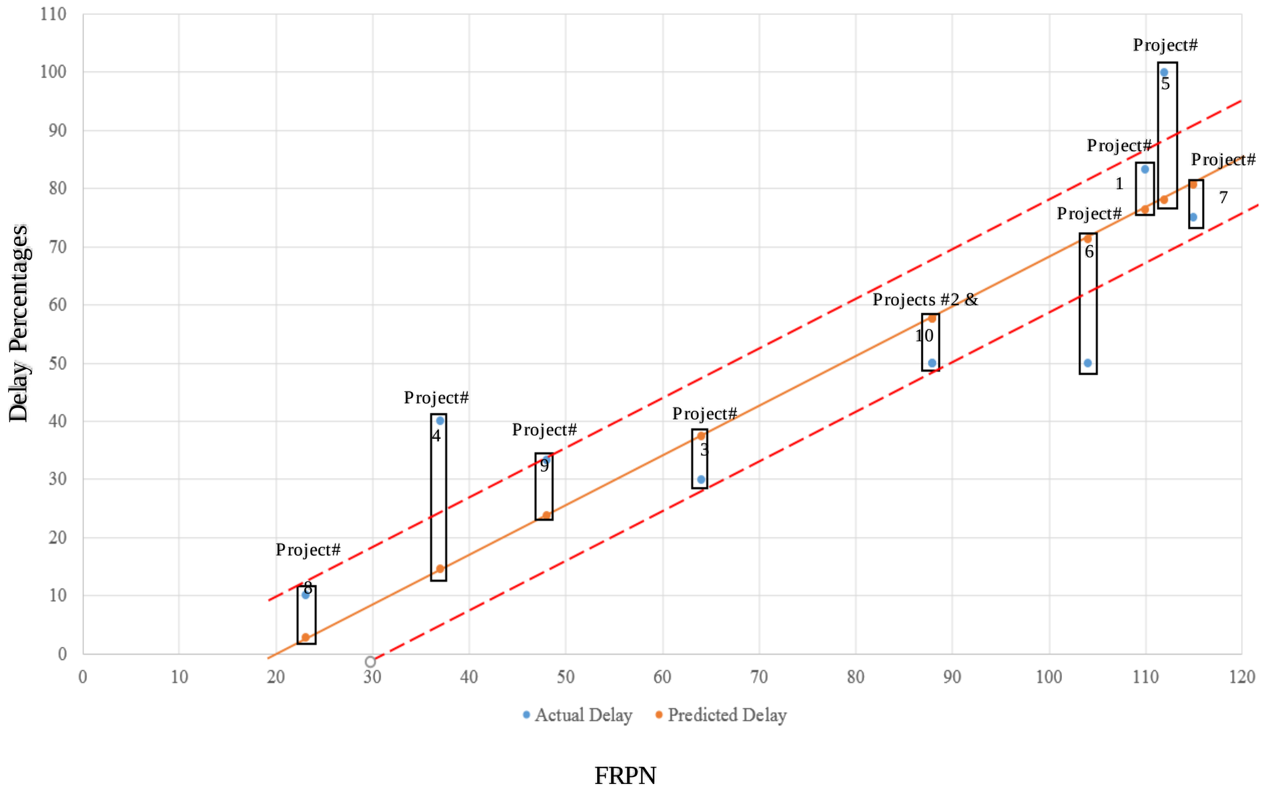


Figure 4.17. Comparing the actual delay with the predicted delay by the linear regression model

In this figure, the upper dotted red line is 10% higher than the prediction line (yellow line) and the lower dotted red line is 10% lower than the prediction line. As it can be seen, except projects four, five and six, other projects fall into the band of ±10% of error in prediction. Therefore, it is verified that the equation is providing satisfactory predictions for the percentage of delay.

4.10.3. Comparing the exponential regression predicted delay with the actual delay

The values of FRPN, which are based on the assessment of the respondents, were inserted into the exponential regression model to generate the predicted delay. The predicted delay was then compared with the actual delay to see how close the results are. The result of this comparison is shown in table 4.15.

Table 4.15. The results of comparing the predicted delay by the exponential regression model and the actual delay

Project ID	FRPN	Actual Delay	Predicted Delay
#1_test	110	83	71.15
#2_test	87.9	50	45.83
#3_test	64	30	28.48
#4_test	37	40	16.64
#5_test	112	100	74.04
#6_test	104	50	63.14
#7_test	115	75	78.59
#8_test	23.1	10	12.62
#9_test	48	33	20.72
#10_test	87.9	50	45.83

Based on the data of this table, figure 4.18 shows the scatter plot, which maps this data points. The yellow points are the delay percentages predicted by the model ($Delay = 7.9707e^{0.0199*FRPN}$) and the blue points are the actual delay that has happened. Since both amounts of delay are related to a certain FRPN, for each measured projects both amounts of delay will appear on the same x-coordinate.

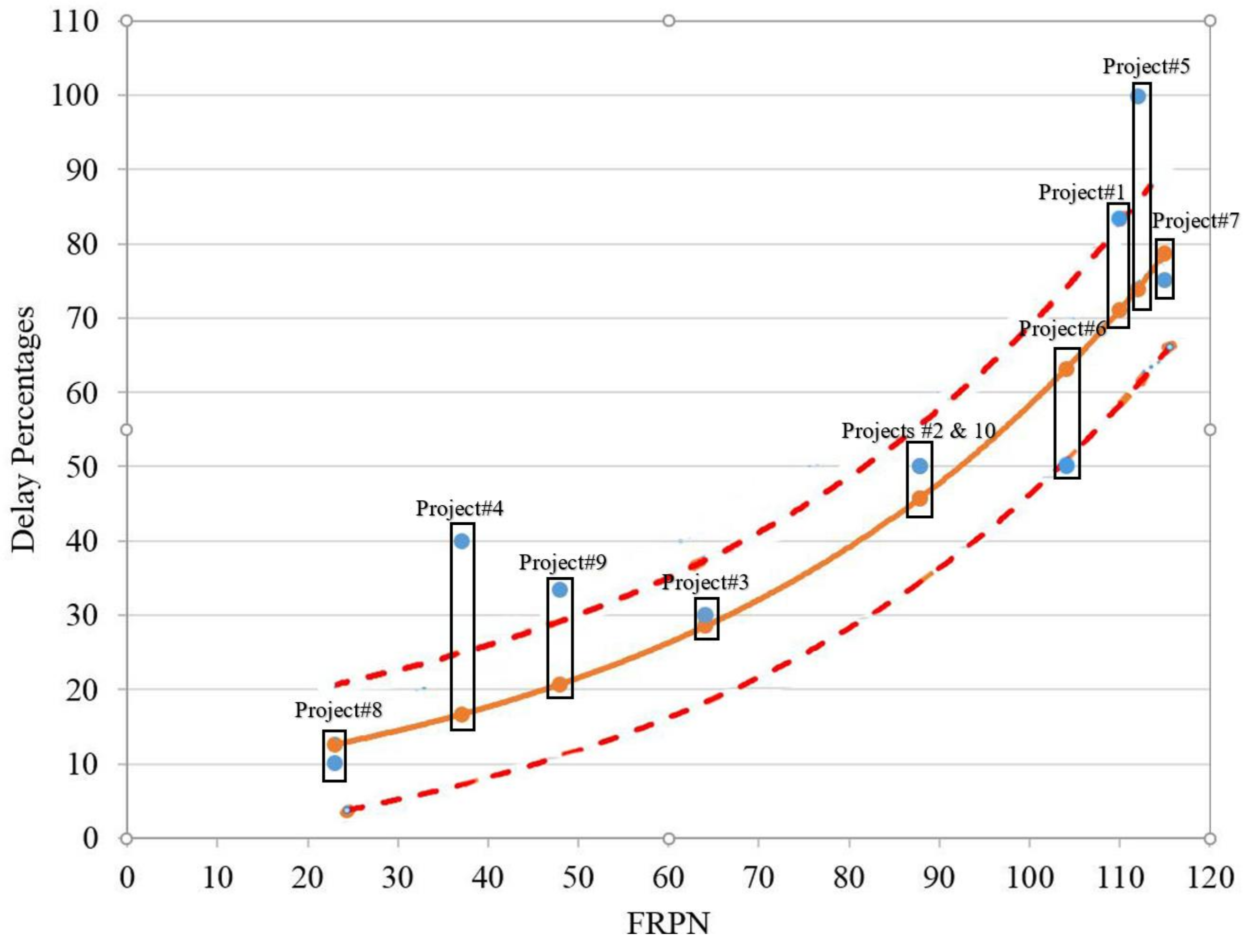


Figure 4.18. Comparing the actual delay with the predicted delay by the exponential model

In this figure, the upper dotted red line is 10% higher than the prediction line (yellow line) and the lower dotted red line is 10% lower than the prediction line. As it can be seen, except projects four, five and nine, other projects fall into the band of ±10% of error in prediction. Therefore, it is verified that the equation is providing satisfactory predictions for the percentage of delay.

4.11. Selecting between the two models

While both the linear regression model and the exponential model provided statistically significant results, one model should be selected as one of the products of the research. To select one of the two, one statistical method is to calculate the root mean square error created by each model and

then to compare them. This method is commonly used to measure the differences between the forecasted and observed values. What it does is that it considers the sample standard deviation of the differences between predicted values and observed values.

The equation to calculate this error is as follows:

$$RMSE = \sqrt{\frac{1}{10}\sum_{1=1}^{10}(f_i - O_i)^2}$$

RSME = Root Mean Square Error

10 = Number of forecast and observed pairs for each model

Fi= forecasted delay for the i^{th} project

Oi= observed delay for the i^{th} project

Based on this, table 4.16 shows the results of comparing the RSME value resulted from using each of the models. The model with a smaller RMSE value can be selected as the delay prediction model.

Table 4.16. RSME of the two models

Project ID	FRPN	Actual Delay (%)	Predicted Delay (%)		$(f_i-O_i)^2$	
			Linear Regression Model	Exponential Regression Model	Linear Regression Model	Exponential Regression Model
#1_test	110	83	76.40	71.15	48.07	148.46
#2_test	87.9	50	57.65	45.83	58.60	17.37
#3_test	64	30	37.38	28.48	54.51	2.30
#4_test	37	40	14.48	16.64	651.20	545.49
#5_test	112	100	78.10	74.04	479.77	674.05
#6_test	104	50	71.31	63.14	454.15	172.69
#7_test	115	75	80.64	78.59	31.82	12.90
#8_test	23.1	10	2.69	12.62	53.42	6.88
#9_test	48	33	23.81	20.72	90.66	159.16
#10_test	87.9	50	57.65	45.83	58.60	17.37
RMSE					14.07	13.25

As it can be seen from the table, the value of Root Mean Square Error (RMSE) in the exponential model is slightly smaller than that of the linear model. Therefore, the exponential regression model is selected as the final model to predict the percentage of delay by having the FRPN.

4.12. Research Limitations

The research has some limitations. One limitation is the role of human judgment is assessing the risk of potential causes. This may cause inaccurate assessments. As the construction industry gets

more standardized and controllable, data collection is facilitated. This, in turn, opens the ways to qualitative assessments. That is, performances and evaluations can be based more on recorded numbers and collected data than the human judgment.

Another limitation with the research method was the low number of the projects that were studied. Since construction projects commonly take several months to complete and most of the construction experts are not willing to share the data regarding the causes of delay in their project, it was very difficult to collect data of delay. As an example, the first survey was sent to almost 11,000 construction experts throughout the country while only 219 of which participated. With a larger population and more extensive data collection in several years, the quality of the model is expected to increase.

CHAPTER 5: CONCLUSIONS AND DISCUSSION

5.1. Main causes of delay in the U.S construction industry

Based on the results of the first survey the top cause of the occurrence of delay in the American construction industry is excessive change orders by the owner during construction. In order to control the risk of delay, measures to mitigate the need for change orders should be taken more seriously by the construction team.

Another consideration is that the top three causes of delays are related to owners. While on-time completion of the project is commonly to the benefit of the owner, due to making excessive change orders, time-consuming decision-making process and delay in approving design documents owners are putting their interests at risk.

The results also indicate the need for improving the quality of design as design errors, complexities, and ambiguities of design, and delays in providing the design documents have all been ranked among the main causes of delay.

The next interpretation of the first survey results, highlight the impact of poor communication and coordination between different parties that are involved in the construction. The role of the construction manager in facilitating this communication and maximizing collaboration between different individuals and teams is essential in preventing these type of delays.

5.2. The benefits of the model

The proposed model is a decision-making support tool to mitigate the risk of delay caused by the defined potential causes in construction projects. Considering the huge losses caused by construction-delays, if the model is successful, it can have a huge contribution in making construction industries more profitable. Some of the strengths of the proposed model are reviewed in the following.

5.2.1. A Dynamic Analysis of Potential Risks Based on Project's Actual Status

Based on the literature review, one of the main novelties of the proposed model in the prevention of the construction delay is its dynamic nature. This model is based on the actual status of the project and has the flexibility to be applied at any phase of the construction. It uses the actual conditions of the project to do the delay risk analysis. No pre-defined weights, which may not apply for the target project, are used in this model. Moreover, the model provides the flexibility for the user to modify the rules of the assessment based on the construction manager's knowledge about the ongoing status of the project. This is expected to make the outputs of the model more realistic.

5.2.2. Preventive-Based Method

The proposed model is based on making an assessment to detect the potential causes of delay before they can put the normal duration of the projects at risk. This can provide the project team with sufficient time to respond to the critical risks.

5.2.3. Prevention Based on Risk Criticality

Considering the limited budget for taking care of all the potential causes of delay, the proposed model is expected to be able to optimize taking corrective measures to identify and resolve the most critical causes first. This makes budgeting for risk mitigation efficient since a higher level of confidence to prevent delays is obtained by investing a lower amount of budget.

5.2.4. Delay prediction

The model provided in this study is capable of predicting the delay based on risk assessment of causes with satisfactory accuracy. The dynamic nature of the model can be used to track and maintain the estimated delay within the desired level. Since this prediction is based on the risk

assessment, the model provides clear solutions and detects the hot spots of risk (between all potential causes).

5.3. Primary Contribution to Body of Knowledge

The major contribution of this research is to apply the fuzzy logic FRPN number in determining the percentage of delay in the construction projects. Fuzzy logic have been used in various forms in construction management research, however the use of fuzzy logic with FRPN number is an innovative approach to develop a model by combining qualitative and quantitative data in predicting the delays in construction projects. This research shows that the model can be used for predicting a delay in future construction projects.

5.4. Future Research

This research can evolve through the following recommended approached:

I. Finding ways to minimize the human judgment while risk assessment: As mentioned above, with the help of more effective ways of performance measurement it is possible to make evaluations based on the recorded data. The application of image processing technologies and building information modeling during construction as well as paying more attention to recording performance data and providing more quantitative progress reports is a key solution to approach this goal.

II. Evolving the model requires involving more projects for the data collection. If time is not a concern, data collection can be followed for several years to improve the model. This is particularly helpful to revise the rules that the fuzzy inference system uses to generate the FRPN.

III. If the data collection methods improve to be more based on quantitative data specifically by the Building Information Modeling, the model can get revised to define a new method for evaluating the riskiness of the causes based on the collected data.; in addition the model can get expanded to be connected to a client server in which the data is automatically sent to the model, and the model uses these inputs to generate a ranked list of most critical potential causes of delay as well as the anticipated delay percentage.

APPENDIX A: SURVEYS

Survey 1: National Survey of Causes of Delay in Construction

You are one of our few selected experts for our pilot survey. We thank you for participating in this survey. This survey is intended to investigate the effectiveness of different causes in the occurrence of delay (postponement in the substantial completion date) in construction projects in the United States.

The confidentiality of the respondents' information will be strictly maintained. The survey data will not be placed in any type of permanent record and will be destroyed when no longer needed by the researchers. The identity of persons responding to this survey will remain anonymous.

If you wish to get the results of this survey (most important causes of delay in the US), please provide an Email address.

Thank you in advance for your time.

1- Type of projects you are/were involved in (Choose all that applies):

◯ Building Projects

◯ Highway Projects

◯ Infrastructure Projects, e.g. water and waste-water, tunnel projects, rail road construction, etc.

◯ Other (Please mention) ……………………………………………………………………

2- Please select a type of ownership in the projects, you were involved in (Choose all that applies):

◯ Public ◯ Private ◯ Public Private Partnership

Others (Please mention)---

3- Please select a type of project delivery method you are/were involved with (Choose all that applies):

◯ Design Bid Build (DBB) ◯ Design Build (DB) ◯ Construction Manager at-Risk (CMAR)

Others (Please mention)---

4- Please choose which of following parties you worked for (Choose all that applies)

◯ owner ◯ designer/ consulting firm ◯ contractor

5- Years of experience in construction ---------------------------------

6- If you wish, provide us an Email and we will send you the results of the study once it is completed.

Email address:---

Please **rate the effectiveness** of the **occurrence of the following issues** in **causing a delay** in a construction project.

Please select a rating on the scale of 1 to 5. (**1 very ineffective and 5 extremely effective**).

Unrealistic schedule (bid duration is too short)	1	2	3	4	5
Ineffective delay penalties provisions in contract	1	2	3	4	5
Errors in contract documents	1	2	3	4	5
Selecting inappropriate project delivery method	1	2	3	4	5
Excessive change orders by the owner during construction	1	2	3	4	5
Delayed payments by the owner	1	2	3	4	5
Delay in approving design documents by the owner	1	2	3	4	5
Time consuming decision making process of the owner	1	2	3	4	5
Unnecessary Interference by the owners	1	2	3	4	5
Delay to furnish and deliver the site to the contractor	1	2	3	4	5
Poor communication and coordination of the owner with designer and/ or contractor	1	2	3	4	5
Poor Quality Assurance (QA) plan of the owner	1	2	3	4	5
Lack of management staffs of the owner	1	2	3	4	5
Inappropriate construction methods	1	2	3	4	5
Contractor inefficiency (in providing the labor, equipment and material and handling sub-contractors	1	2	3	4	5
Poor communication and coordination of the contractor with owner and/ or designer	1	2	3	4	5
Inadequate contractor's experience	1	2	3	4	5
Financial difficulties and mismanagement by the contractor	1	2	3	4	5
Poor site management and Quality Control (QC) by the contractor	1	2	3	4	5
Legal disputes between designer and the owner	1	2	3	4	5
Design errors	1	2	3	4	5
Complexities and ambiguities of project design	1	2	3	4	5
Delays in providing the design documents by the designer	1	2	3	4	5
Inadequate experience of the designer	1	2	3	4	5
Inadequate site assessment by the designer during design phase	1	2	3	4	5
Misunderstandings between owner and designer about scope of the work	1	2	3	4	5
Financial difficulties with the designer	1	2	3	4	5
Poor communication and coordination of the designer with owner and/ or contractor	1	2	3	4	5
Legal disputes between designer and the owner	1	2	3	4	5

Survey 2: Assessing the Causes of Delay in a Project

You are one of our few selected experts for our nationwide survey. We do appreciate your participation.

This survey is intended to develop a tool for prediction of risk of delay in the U.S construction projects. For this purpose, we need our respondents to answer the few following questions about a completed construction project that has finished with a delay.

The confidentiality of the respondents' information will be strictly maintained. The survey data will not be placed in any type of permanent record and will be destroyed when no longer needed by the researchers. The identity of persons responding to this survey will remain anonymous.

If you wish to get our tool for free you may provide an Email address at the end of this survey (This is optional).

Thank you in advance for your time and precision in answering this survey.

1- What was the original time decided for the substantial completion of the project?

2- How much was the project delayed?

3- What type of construction project was this project?

◯ Building Projects ◯ Highway Projects ◯ Infrastructure Projects, e.g. water and wastewater, tunnel projects, rail road construction, etc.
◯ Other (Please mention) ……………………………………………………………………

4- What was the type of ownership in this project??

◯ Public ◯ Private ◯ Public Private Partnership
Others (Please mention)--

Change Orders

How severely, do you assume, the change orders affected the smooth progress of the project?

◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did change orders happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of NOT detecting and managing change orders before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Time Consuming Decision Making by the Owner

How severely, do you assume, time-consuming decision making by the owner, impacted the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did the project encounter time-consuming decision making by the owner?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing change orders before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Delay in Approving Design Documents

How severely, do you assume, delay in approving design documents affected the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently, did delay in approving design documents happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing, delay in approving design documents before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Design Errors

How severely, do you assume, design errors affected the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did design errors happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing design errors before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Unrealistic schedule

How severely, do you assume, design errors affected the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did design errors happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing design errors before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Errors in contract documents

How severely, do you assume, design errors affected the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did design errors happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing design errors before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Poor communication and coordination of owner with other parties

How severely, do you assume, design errors affected the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did design errors happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing design errors before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

Complexities and ambiguities in project design

How severely, do you assume, design errors affected the smooth progress of the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

How frequently did design errors happen during the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

What was the chance of detecting and managing design errors before they could cause a delay in the project?
◯ very low ◯ Low ◯ Moderate ◯ High ◯ Very High

BIBLIOGRAPHY

Abdelgawad, M., & Fayek, A. R. (2010). Risk management in the construction industry using combined fuzzy FMEA and fuzzy AHP. Journal of Construction Engineering and Management, 136(9), 1028-1036.

Abdelgawad, M., & Fayek, A. R. (2011). Comprehensive hybrid framework for risk analysis in the construction industry using combined failure mode and effect analysis, fault trees, event trees, and fuzzy logic. Journal of Construction Engineering and Management, 138(5), 642-651. Accuracy. Int J Adv Manuf Technol 27(3–4):321–328

Abudayyeh, O. Y. (1997). A multimedia construction delay management system. Computer-Aided Civil and Infrastructure Engineering, 12(3), 183-192.

Abudayyeh, O. Y. (1997). A multimedia construction delay management system. *Computer-Aided Civil and Infrastructure Engineering*, *12*(3), 183-192.

Ahmed, S. M., Azhar, S., Castillo, M., & Kappagantula, P. (2002). Construction delays in Florida: An empirical study. Final report. Department of Community Affairs, Florida, US.

Al-Humaidi, H. M., & Hadipriono Tan, F. (2010). A fuzzy logic approach to model delays in construction projects using translational models. Civil engineering and environmental systems, 27(4), 353-364.

Alkass S, Mazerolle M, Harris F. Construction delay analysis techniques. Construction Manage Econ 1996; 14(5):375–94.

Al-Momani, A. H. (2000). Construction delay: a quantitative analysis. *International journal of project management*, *18*(1), 51-59.

Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International journal of project management*, *24*(4), 349-357.

Baloi, D., and Price, A. D. F. (2003). "Modeling global risk factors affecting construction cost performance." *Int. J. Proj. Manage.* 21(4), 261–269.

Bowels, J. B. and Pelaez, C. E. (1995). "Fuzzy logic prioritization of failure in a system failure mode, effects and criticality analysis." *Reliability Engineering and System Safety*, Vol. 50, No. 2, pp. 203- 213.

Bubshait AA, Cunningham MJ. Comparison of delay analysis methodologies. J Constr Eng Manage ASCE 1998; 124(4):315–22.

Carlson, C. S. (2014, January). Understanding and Applying the Fundamentals of FMEAs. In *Proceedings of the 2014 Annual Reliability and Maintainability Symposium*.)

Castro, A., & Arcay, B. (2009). Fuzzy Logic Applied to Biomedical Image Analysis. In Encyclopedia of Artificial Intelligence (pp. 710-718). IGI Global. Chan, A. P., Chan, D. W., & Yeung, J. F. (2009). Overview of the application of "fuzzy techniques" in construction management research. *Journal of construction engineering and management*.

Chan, A. P., Chan, D. W., & Yeung, J. F. (2009). Overview of the application of "fuzzy techniques" in construction management research. Journal of construction engineering and management, 135(11), 1241-1252.

Chan, D. W., and Kumaraswamy, M. M. (1997). "A comparative study of causes of time delays in Hong Kong construction projects." Int. J. Project Manage. 15(1), 55–63.

Chao, L. C., and Skibniewski, M. J. (1998). "Fuzzy logic for evaluating new construction technology *Journal of Construction Engineering Management*, 124(4), 297–304.

Chaudhari, S., Patil, M., & Bambhori, J. (2014). Study and review of fuzzy inference systems for decision-making and control. *AIJRSTEM*, *5*(1), 88-92.

Chen, G., & Joo, Y. H. (2009). Fuzzy control systems: An introduction. In Encyclopedia of artificial intelligence (pp. 688-695). IGI Global.

Chen, L. H., & Ko, W. C. (2009). Fuzzy linear programming models for new product design using QFD with FMEA. *Applied Mathematical Modelling*, *33*(2), 633-647.

Cheng, C. L., He, K. C., & Yen, C. J. (2008). Decision-making and assessment tool for design and construction of high-rise building drainage systems. *Automation in Construction*, *17*(8), 897-906.

Cheng, C. L., He, K. C., & Yen, C. J. (2008). Decision-making and assessment tool for design and construction of high-rise building drainage systems. Automation in Construction, 17(8), 897-906.

Chin, K. S., Chan, A., & Yang, J. B. (2008). Development of a fuzzy FMEA based product design system. *The International Journal of Advanced Manufacturing Technology*, *36*(7-8), 633-649.

Choi, H. H., Cho, H. N., & Seo, J. W. (2004). Risk assessment methodology for underground construction projects. Journal of Construction Engineering and Management, 130(2), 258-272.

Diaz-Hermida, F., Losada, D. E., Bugarín, A., & Barro, S. (2005). A probabilistic quantifier fuzzification mechanism: The model and its evaluation for information retrieval. IEEE transactions on Fuzzy Systems, 13(5), 688-700.

Dinmohammadi, F., & Shafiee, M. (2013). A fuzzy-FMEA risk assessment approach for offshore wind turbines. *IJPHM Special Issue on Wind Turbine PHM (Color)*, 59.

Dubois, D. (2007). Applied Fuzzy Arithmetic: An Introduction with Engineering Applications (Michael Hanss). SIAM REVIEW, 49(3), 520.

Ebrahimnejad, S., Mousavi, S. M., & Mojtahedi, S. M. H. (2008, September). A model for risk evaluation in construction projects based on fuzzy MADM. In*Management of Innovation and Technology, 2008. ICMIT 2008. Fourth IEEE International Conference on* (pp. 305-310). IEEE.

El Razek, M. E., Basssioni, H. A., and Mobarak, A. M. (2008). “Causes of delay in building construction projects in Eygpt.” J. Constr. Eng. Manage., 134(11), 831–841.

Fadlovich, Erik. *Performing Failure Mode and Effect Analysis* [Online] 2007 [cited 2010; Available from: http://www.embeddedtechmag.com/component/content/article/6134, Embedded Technology.

Faridi, A. S., & El-Sayegh, S. M. (2006). Significant factors causing delay in the UAE construction industry. *Construction Management and Economics*, *24*(11), 1167-1176.

Fayek, A. R., and Oduba, A. (2005). “Predicting industrial construction labor productivity using fuzzy expert systems.” *J. Constr. Eng. Manage.*, 131(8), 938–941.

Filip, F. C. (2011). Theoretical Research on the Failure Mode and Effects Analysis (FMEA) Method and Structure. In *fourth International Conference on Manufacturing Engineering, Quality and Production Systems* (pp. 176-181).

Frimpong, Y., Oluwoye, J., and Crawford, L. (2003). “Causes of delay and cost overruns in construction of groundwater projects in developing countries: Ghana as a case study.” Int. J. Project Manage. 21(5), 321–326.

Garg, H., Rani, M., & Sharma, S. P. (2013). Predicting uncertain behavior and performance analysis of the pulping system in a paper industry using PSO and Fuzzy methodology. Handbook of Research on Novel Soft Computing Intelligent Algorithms: Theory and Practical Applications, 414-449.

George J, K. L. I. R., & Bo, Y. (2008). Fuzzy sets and fuzzy logic, theory and applications.

Goguen, J. A. (1967). L-fuzzy sets. Journal of mathematical analysis and applications, 18(1), 145-174.

Hamzah, N., Khoiry, M. A., Arshad, I., Tawil, N. M., & Ani, A. C. (2011). Cause of construction delay-Theoretical framework. *Procedia Engineering*, *20*, 490-495.

Holt, G. D. (1998). "Which contractor selection methodology?" *International Journal of Project Management*, 16(3), 153–164.

Hu, A. H., Hsu, C. W., Kuo, T. C., & Wu, W. C. (2009). Risk evaluation of green components to hazardous substance using FMEA and FAHP. *Expert Systems with Applications*, *36*(3), 7142-7147.

Ibáñez, Ó., & Castro, A. (2009). Genetic Fuzzy Systems Applied to Ports and Coasts Engineering. In Encyclopedia of Artificial Intelligence (pp. 759-766). IGI Global.

Jang, J. S. R., Sun, C. T., & Mizutani, E. (1997). Neuro-fuzzy and soft computing; a computational approach to learning and machine intelligence.

Kartam, S. (1999). Generic methodology for analyzing delay claims. *Journal of construction engineering and management*, *125*(6), 409-419.

Kazaz, A., Ulubeyli, S., and Tuncbilekli, N. A. (2012). "Causes of delays in construction projects in Turkey." J. Civ. Eng. Manage., 18(3), 426–435.

Kenneth W. Dailey, (2004). *The FMEA Pocket Handbook, Publisher DW Publishing*. ISBN 0-947221-2-X, United State of America.

Knight, K., and Fayek, A. R. (2002). "Use of fuzzy logic for predicting design cost overruns on building projects." J. Constr. Eng. Manage., 128(6), 503–512.

Koushki, P. A., Al-Rashid, K., and Kartam, N. (2005). “Delays and cost increase in the construction of private residential projects in Kuwait.” Constr. Manage. Econ., 23(3), 285–294.

Kumar, V. S. S., Hanna, A. S., and Adams, T. (2000). “Assessment of working capital requirements by fuzzy set theory.” *Engineering Construction and Architecture Management*, 7(1), 93–103.

Kumru, M., & Kumru, P. Y. (2013). Fuzzy FMEA application to improve purchasing process in a public hospital. *Applied Soft Computing*, *13*(1), 721-733.

Kutlu, A. C., & Ekmekçioğlu, M. (2012). Fuzzy failure modes and effects analysis by using fuzzy TOPSIS-based fuzzy AHP. *Expert Systems with Applications*, *39*(1), 61-67.

Leu, S. S., Chen, A. T., and Yang, C. H. (2001). “A GA-based fuzzy optimal model for construction time-cost trade off.” *International Journal of Project Management*, 19(1), 47 -58.

Li, D. C., Wu, C., & Chang, F. M. (2005). Using data-fuzzification technology in small data set learning to improve FMS scheduling accuracy. The International Journal of Advanced Manufacturing Technology, 27(3), 321-328.

Liang, L. R., Lu, S., Wang, X., Lu, Y., Mandal, V., Patacsil, D., & Kumar, D. (2006). FM-test: a fuzzy-set-theory-based approach to differential gene expression data analysis. *BMC bioinformatics*, *7* (Suppl 4), S7.

Ma, H., Deng, Z., and Solvang, W. D. (2004). “An online approach for distributor benchmarking.” International Journal of *Benchmarking*, 11(4), 385–402.

Mahamid, I., Bruland, A., & Dmaidi, N. (2012). Causes of delay in road construction projects. *Journal of Management in Engineering*, *28*(3), 300-310.

Mamdani, E.H. and S. Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller," *International Journal of Man-Machine Studies*, Vol. 7, No. 1, pp. 1-13, 1975.

McDermott, R., Mikulak, R. J., & Beauregard, M. (1996). The basics of FMEA. SteinerBooks.

Meng Tay, K., & Peng Lim, C. (2006). Fuzzy FMEA with a guided rules reduction system for prioritization of failures. *International Journal of Quality & Reliability Management*, *23*(8), 1047-1066.

Mohammadi, A., & Tavakolan, M. (2013, June). Construction project risk assessment using combined fuzzy and FMEA. In *IFSA World Congress and NAFIPS Annual Meeting (IFSA/NAFIPS), 2013 Joint* (pp. 232-237). IEEE.

Murphy, M., Heaney, G., & Perera, S. (2011). A methodology for evaluating construction innovation constraints through project stakeholder competencies and FMEA. *Construction Innovation*, *11*(4), 416-440.

Ng, S. T., Luu, D. T., Chen, S. E., and Lam, K. C. _2002_. "Fuzzy membership functions of procurement selection criteria." *Constr. Manage. Econom.*, 20(3), 285–296.

Noulmanee, A., Wachirathamrojn, J., Tantichattanont, P., and Sittivijan, P. (1999). "Internal causes of delays in highway construction projects in Thailand." 〈www.ait.c1et.com〉 (Jul. 1, 1999).

Odeh, A. M., & Battaineh, H. T. (2002). Causes of construction delay: traditional contracts. *International journal of project management*, *20*(1), 67-73.

Odeyinka, H. A., and Yusif, A. (1997). "The causes and effects of construction delays on completion cost of housing project in Nigeria." J. Financ. Manage. Property Constr., 2(3), 31–44.

Ogunlana, S. O., Promkuntong, K., and Jearkjirm, V. (1996). "Construction delays in a fast-growing economy: Comparing Thailand with other economies." Int. J. Proj. Manage., 14(1), 37–45.

Okoroh, M. I., and Torrance, V. B. (1999). "A model for subcontractor selection in refurbishment projects." *Construction Management Economics*, 17(3), 315–327.

Oliveros, A. V. O., and Fayek, A. R. (2005). "Fuzzy logic approach for activity delay analysis and schedule updating." J. Constr. Eng. Manage., 131(1), 42–51.

Pillay, A. and Wang, J. (2003). "Modified failure mode and effects analysis using approximate reasoning." *Reliability Engineering and System Safety*, Vol. 79, No. 1, pp. 69-85

Rhee, S. J., & Ishii, K. (2003). Using cost based FMEA to enhance reliability and serviceability. *Advanced Engineering Informatics*, *17*(3), 179-188.

Sambasivan, M., & Soon, Y. W. (2007). Causes and effects of delays in Malaysian construction industry. *International Journal of project management*, *25*(5), 517-526.

Sánchez, M., Prats, F., Agell, N., and Ormazabal, G. (2005). "Multiple criteria evaluation for value management in civil engineering." *Journal of Management Engineering*, 21(3), 131–137.

Seo, S., Aramaki, T., Hwang, Y., and Hanaki, K. (2004). "Fuzzy decisionmaking tool for environmental sustainable buildings." *J. Constr. Eng. Manage.*, 130(3), 415–423.

Shang, H. P., Anumba, C. J., Bouchlaghem, D. M., and Miles, J. C., (2005). "An intelligent risk assessment for distributed construction teams." *Engineering Construction and Architecture Management*, 12(4), 391–409.

Sharma, R. K., Kumar, D., & Kumar, P. (2007). Modeling and analysing system failure behaviour using RCA, FMEA and NHPPP models. *International Journal of Quality & Reliability Management*, *24*(5), 525-546.

Silva, I. N., & Flauzino, R. A. (2009). Multilayer Optimization Approach for Fuzzy Systems. In Encyclopedia of Artificial Intelligence (pp. 1121-1129). IGI Global.

Singh, D., and Tong, R. L. K. 2005. "A fuzzy decision framework for contractor selection." Journal of Construction Engineering Management, 131-1, 62–69.

Stamatis, D. H. (2003). *Failure mode and effect analysis: FMEA from theory to execution*. ASQ Quality Press.

Tah, J. H. M., and Carr, V. (2000). "A proposal for construction project risk assessment using fuzzy logic." *Construction Management Economics*, 18(4), 491–500.

Tseng, B. T. L., Huang, C. C., Chu, H. W., and Cung, R. R. (2004), "Novel approach to multi-functional project team formation." *International Journal of Project Management*, 22(2), 147–159.

Tumi, S. A. H., Omran, A., & Pakir, A. H. K. (2009). Causes of delay in construction industry in Libya. In *The International Conference on Economics and Administration* (pp. 265-272).

United States Military, 1949, Mil-P 1629 "Procedure for performing a failure mode effect and criticality analysis".

Venkatesh, M. P., Umarani, C., Renuga, S. M., & Malathi, B. (2012). Analysis and identification of critical factors of delay in construction projects. NICMAR Journal of Construction Management, 27, 83-91.

Wang, C. H. (2011, December). A novel approach to conduct risk analysis of FMEA for PCB fabrication process. In Industrial Engineering and Engineering Management (IEEM), 2011 IEEE International Conference on (pp. 1275-1278). IEEE.

Wei, C. C., and Wang, M. M. J. (2004). "A comprehensive framework for selecting and ERP system." *International Journal of Project Management*, 22(2), 161–169.

Wiguna, I. P. A., and Scott, S. (2005). “Analyzing the risks affecting construction delay and cost overruns in Indonesia building projects.” Proc., 3rd Int. Conf. on Innovation in Architecture, Engineering and Construction, Vol. 3, Dept. of Civil and Building Engineering, Loughborough Univ., Loughborough, Leicestershire, U.K., 841–849.

Xu, K., Tang, L. C., Xie, M., Ho, S. L., and Zhu, M. L. (2002). “Fuzzy assessment of FMEA for engine systems.” *Reliability Engineering and System Safety*, Vol. 75, No. 1, pp. 17-29.

Yang, J., Huang, H. Z., He, L. P., Zhu, S. P., & Wen, D. (2011). Risk evaluation in failure mode and effects analysis of aircraft turbine rotor blades using Dempster–Shafer evidence theory under uncertainty. *Engineering Failure Analysis*, *18*(8), 2084-2092.

Yeh, R. H. and Hsieh, M. H. (2007). “Fuzzy assessment of FMEA for a sewage plant.” *Journal of the Chinese Institute of Industrial Engineers*, Vol. 24, No. 6, pp. 505-512.

Zadeh, L.A. (1999). “Fuzzy set as a basis for a theory of possibility.” *Fuzzy Sets System*, Vol. 100, No. 1, pp. 9-23.

Zaman, M. B., Kobayashi, E., Wakabayashi, N., Khanfir, S., Pitana, T., & Maimun, A. (2014). Fuzzy FMEA model for risk evaluation of ship collisions in the Malacca Strait: based on AIS data. *Journal of Simulation*, *8*(1), 91-104.

Zayed, T. M., and Halpin, D. W. (2004). “Quantitative assessment for piles productivity factors.” *Journal of Construction Engineering Management*, 130(3), 405–414.

Zhang, H., and Tam, C. M. (2003). “Fuzzy decision-making for dynamic resource allocation.” Constr. Manage. Economy.21(1), 31–41.

Zheng, D. X. M., and Ng, T. (2005). “Stochastic time-cost optimization model incorporating fuzzy sets theory and non-replacement.” *J. Construction Engineering Management* 131(2), 176–186.

Zheng, D. X. M., and Ng, T. (2005). "Stochastic time-cost optimization mode incorporating fuzzy sets theory and non-replacement." J. Constr. Eng. Manage., 131(2), 176–186.

Zimmermann, H. J. (2001). *Fuzzy set theory and its application*, Kluwer, Dordrecht, The Netherlands.

CURRICULUM VITAE

Graduate College

University of Nevada, Las Vegas

Mohammadsoroush Tafazzoli

Email address:
tafazzol@unlv.nevada.edu
mohammadsoroushtafazzoli1@gmail.com

Degrees:

- Bachelor of Engineering in Civil Engineering, 2008, Qazvin Azad University

- Master of Science in Transportation Engineering, 2011 Tehran Azad University
  Dissertation Title: Introducing and Prioritizing of Sustainable Transportation Indicators Using Multiple Criteria Decision Making (MCDM) Methods

Certificates

- LEED AP (BD+C)
  Leadership in Energy and Environmental Design (Building Design and Construction)

- ENV SP
  Envision Sustainability Professional Institute for Sustainable Infrastructure

Dissertation Examination Committee:
Pramen P. Shrestha, Ph.D.
Examination Committee Chair

Donald Hayes, Ph.D.
Examination Committee Member

Mosses Karakouzian, Ph.D.
Examination Committee Member

Huliang Teng, Ph.D.
Examination Committee Member

E. Lee Bernick
Graduate College Faculty Representative