ABSTRACT

Residential buildings are usually designed to withstand earthquake damage through their elastic and plastic deformations. The damage causes the buildings to be unoccupiable for a period of time, called the *downtime*. This report introduces a methodology to predict the downtime of buildings given an earthquake through the use of Fuzzy logic. Generally, the downtime can be divided into three main components: downtime due to the actual damage (DT1); downtime due to rational and irrational delays (DT2); and downtime due to utilities disruption (DT3). DT1 is evaluated by relating the building damageability of the building's components to pre-defined repair times. A rapid visual screening questionnaire form has been designed to acquire information about the analyzed building. Then, a fuzzy logic is implemented using a hierarchical scheme to determine the building damageability taking into account the earthquake intensity. DT2 and DT3 are estimated using the REDi^{TM} Guidelines.

DT2 considers irrational components through a specific sequence, which defines the order of components repair. DT3 depends on the site seismic hazard and on the infrastructure vulnerability. Due to the fact that the complex network of utilities is widely distributed geographically and, thus, there are different seismic intensities and local site effects, DT3 is computed from data about past earthquake. The Downtime of the building is finally obtained by combining the three components.

The proposed method also allows identifying the downtime corresponding to three different recovery states: re-occupancy; functional recovery; and full recovery. Furthermore, the methodology is extended to give a resilience index, which is computed through the combination between the downtime and the building damage.

The fuzzy logic system is developed and implemented in Matlab Fuzzy Logic toolbox and Simulink in order to lead a rapid damage evaluation of a given building

and in order to realize a sensitivity analysis for evaluating the impact of components towards the building damageability.

The thesis also presents a graphical interpolation method to define the fuzzy base rules for the inference step in the fuzzy logic system.

Finally, the methodology is illustrated using an unrealistic residential building example, in which the earthquake that hit Northridge in 1994 is considered as the hazard event.

Keywords: Downtime, Residential Building, Fuzzy logic, Earthquake Resilience.

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CHAPTER 1 .

INTRODUCTION

1.1 BACKGROUND

This study addresses towards the creation of a new methodology on Downtime estimation and develops a framework that uses the combination between the Downtime and the Building Damage in order to compute the Seismic Resilience parameter for a given building.

Recent disasters around the world have prompted increased attention in the resilience-engineering field. In fact, the engineering community is developing new methodologies to quantify impact of natural and man-made disasters (e.g. earthquakes, tsunami or floods) on buildings and infrastructures. Over the years, the study has shifted to managing (e.g. recovery through resiliency) and minimizing the natural disaster risk, as it is prohibitively expensive (often impossible) to prevent it.

Currently, existing methodologies consider probabilistic type uncertainty. However, the decision-making framework is complex and it is subject to ignorance, imprecision, vagueness, and vagueness type uncertainties. Using such methodologies, quantification of Downtime, and therefore Resilience, uses historical data and resources that are usually not readily available. The main reason is that, such parameters (e.g. topology and site seismic characteristics) are not simple to capture using traditional models, because they are different in nature and lead to complex mathematical formulation. Consequently, existing methodologies are inappropriate for cases with high-uncertainty. Therefore, it is crucial to have a simple method for predicting the Downtime for building structures.

The thesis proposes a methodology that considers concepts of Fuzzy Logic to evaluate information of building specifications and irregularities. Such information is organized into a hierarchical structure, which follows a logical way to lead to building damageability, which is the main parameter to quantify the downtime. The hierarchical scheme provides a simple organization of the system combining specific contributors at every level of the system. In the methodology, building information is provided in linguistic terms and is obtained through a walk down survey (Rapid Visual Screening), which is performed by an expert.

The proposed methodology can be used by owners, engineers, architects, and decision makers for post-earthquakes management, for minimizing the impacts of the earthquakes and allowing the damaged building to recover as soon as possible.

1.2 OBJECTIVE

The main objective of this thesis is to develop a consistent and rapid methodology for evaluating the Downtime, and therefore the Resilience of a given building. The study is focused on the use of Fuzzy Logic into a hierarchical scheme, which permits a fast and economical estimation of parameters that involve uncertainties. The study includes:

- Review existing methodologies to evaluate the Downtime and Seismic Resilience parameter;
- Establish a framework taking into account the Building Vulnerability and the Site Seismic Hazard, on which the Downtime assessment is based;
- Create a hierarchical scheme that includes all the variables contributing to the Building Damage;

- Apply the Fuzzy Logic to aggregate all the variables presented in the hierarchical scheme;

- Combine repair times of structural and no-structural components (rational components), repair times of delays (irrational components), and repair duration of utilities to evaluate the total repair time;

- Extend the methodology to evaluate the Seismic Resilience index;

- Realize a sensitivity analysis of the system by using MATLAB® software;

- Illustrate the methodology using a case study for a residential building damaged by the 1994 Northridge earthquake.

1.3 ORGANIZATION OF THE THESIS

Chapter 2 reviews the state of knowledge about existing frameworks in earthquake risk evaluation. Chapter 3 introduces the concept of the Fuzzy Logic starting from the early theory of the system formulated in 1976 by Zadeh. The methodology to quantify the Downtime is detailed in Chapter 4, in which the procedure for evaluating the Building Damageability is described. Chapter 5 defines the three sources that determine and may increase the Downtime: repairs, delays and utilities disruption. The downtime methodology is extended in Chapter 6 in order to obtain the Seismic Resilience parameter through the combination between the Downtime and the Building Damage. The illustrative example for an unreal three story residential building, which is damaged by the 1994 Northridge earthquake, and the implementation of the fuzzy system on MATLAB® are shown in Chapter 7.

Conclusions, limitations of the work, and recommendations for future work are presented in Chapter 8. References are presented in Chapter 9.

Appendix A presents component repair times for structural components. Finally, appendix B details component repairs times for non-structural components.

CHAPTER 2 .

LITERATURE REVIEW

The chapter provides a review of existing frameworks available in literature for evaluating the Seismic Resilience and the Downtime. Although the literature review is not exhaustive, it is adequate for the reader to classify the different methodologies.

2.1 STATE-OF-ART IN SEISMIC RESILIENCE

The improvement of regulations and design practice is allowing many studies on risk evaluation and on several parameters, which describe the behavior of building and infrastructures during and after earthquakes, such as the resilience.

The concept of resilience finds its application in several fields, thus different definitions available in literature and different methods to evaluate it are listed.

Bruneau et al. (2003) defined seismic resilience as "*the ability of both physical and social systems to reduce the change of a shock, to absorb such a shock if it occurs and to quickly re-establish normal performance*" (Figure 2.1).

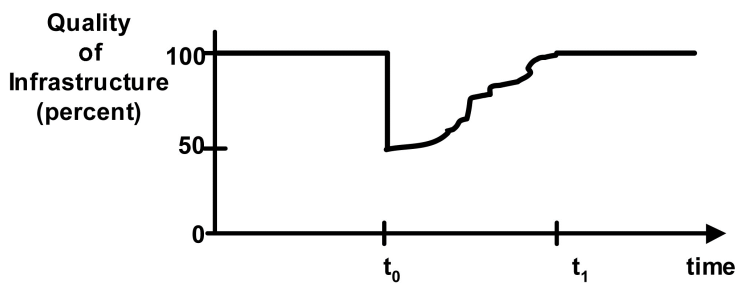

Figure 2.1: Measure of Seismic Resilience Bruneau et al. (2003)

Cimellaro et al. (2010) introduced the concept of functionality recovery and suggested that resilience is "*the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out* *recovery activities in ways to minimize social disruption and mitigate the effects of further earthquakes*". In engineering, resilience is the ability to "*withstand stress, survive, adapt, and bounce back from a crisis or a disaster and rapidly move on*" (Wagner and Breil 2013).

Several resilience frameworks can be found in literature. Some tackled the engineering resilience on the country level (Kammouh et al. 2017; Kammouh et al. 2018) and some on the local and community levels (Kammouh and Cimellaro 2018; Kammouh et al. 2018; Kammouh et al. under review; Kammouh et al. 2017).

Liu et al. (2017) proposed a framework that combines dynamic modeling with resilience analysis. Two interconnected critical infrastructures have been analyzed using the framework by performing a numerical calculation of the resilience conditions in terms of design, operation, and control parameter values for given failure scenarios.

A quantitative method to evaluate resilience at the state level was introduced by Kammouh et al. In their approach, which is inspired by the classical risk analysis, resilience-based risk is a function of resilience, hazard, and exposure. Resilience parameter is carried out using the data of Hyogo Framework for Action (HFA) (ISDR 2005), which is a work developed by the United Nations (UN). HFA evaluates the resilience of countries based on a number of equally weighted indicators (Kammouh et al. 2017).

Another quantitative framework for evaluating community resilience is the PEOPLES framework (Cimellaro et al. 2016). PEOPLES is an expansion of the resilience research at the Multidisciplinary Center of Earthquake Engineering Research (MCEER). PEOPLES framework involves seven dimensions: Population, Environment, Organized government services, Physical infrastructures, Lifestyle, Economic, and Social capital (Renschler et al. 2010).

Recently, different organizations have shown that one of the majors recommendations and need from the earthquake community is the introduction of a resilience rating system (United States Resiliency Council 2015). This rating system should communicate risk in consistent, reliable terms and also benefit building owners, lenders, and government jurisdictions by providing a means to quantify risk. USRC also presented a certification program for rating professionals and a methodology for standardization and verification of existing resilience rating systems. The rating system is not itself an evaluation methodology, rather it is a set of definitions and procedures by which the results of existing evaluations are translated into consistent terms. The USRC Building Rating System provides star ratings over three dimensions, which are: safety, damage expressed as repair cost, and recovery expressed as time to regain basic functions (Figure 2.2).

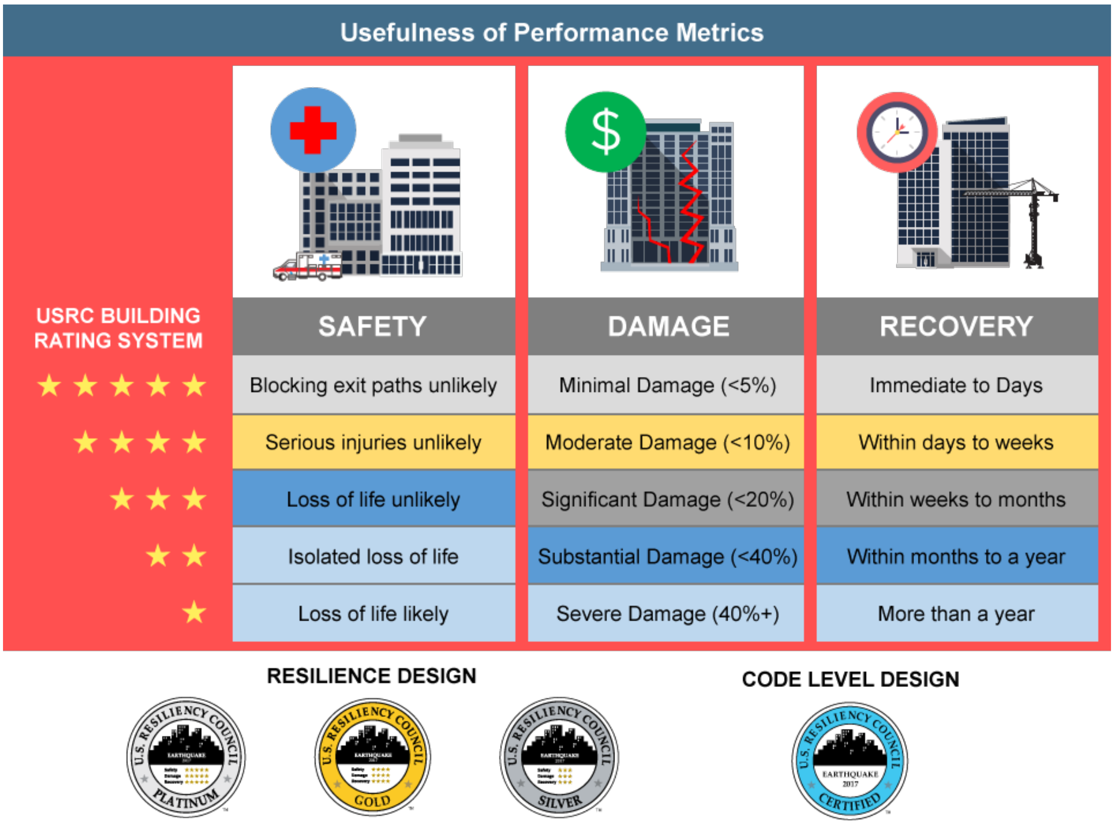

Figure 2.2: The three dimensions of Safety, Damage and Recovery (http://usrc.org/rating-definitions)

2.2 STATE-OF-ART IN DOWNTIME

The absence of concise approach makes the resilience quite difficult to determine, above all because the concept of resilience involves different elements ((Cimellaro et al. 2016), (Chang et al. 2014), (Bonstrom and Corotis 2014)), such as seismic prediction, vulnerability assessment, and downtime estimation.

In the context of seismic risk assessment, quantification of downtime is of importance to decision makers and owners. In fact, the downtime is an essential parameter of loss modelling to estimate resilience but also it is the most difficult to evaluate due to the fact that it includes rational and irrational factors, and consequently, it is complex and uncertain.

In seismic resilience evaluation, downtime is "*the time necessary to plan, finance and complete repair facilities damaged and is composed by rational and irrational components*"(Comerio 2006) (Figure 2.3). The "rational" components are predictable and easily quantifiable, such as construction costs and the time needed to repair damaged facilities. The "irrational" components, instead, take into account the time needed to mobilize for repairs (financing, workforce availability and, regulatoryand economic uncertainty).

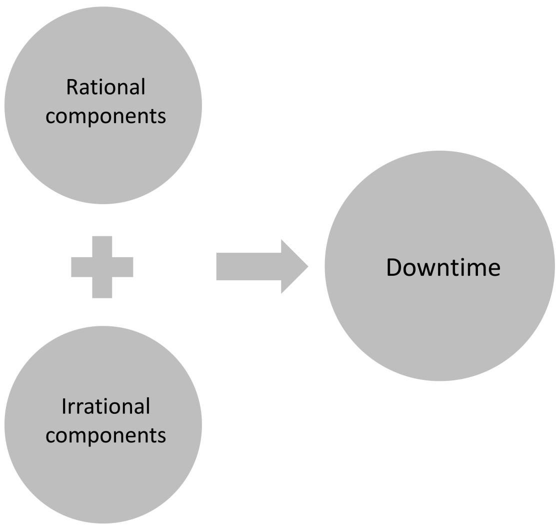

Figure 2.3: The Downtime by (Comerio 2006)

Several studies, which focused on implementing earthquake loss estimation techniques, were funded by The Federal Emergency Management Agency (FEMA) and resulted in the development of a loss estimation software "HAZUS" (Kircher et al. 2006). HAZUS 97 was the first edition of the risk assessment software, built using GIS technology. HAZUS, in which downtime is derived from the structural and nonstructural damage probabilities, provides an estimate for the damage caused by extreme events. HAZUS treats downtime evaluation as an interim step for assessing the long- term economic impact, so median values apply for large inventories. Downtime for essential facilities (e.g. schools and hospitals) is also derived from the estimates of dollar losses. For the transportation systems and the utility lifeline systems, an algorithm based on the number of breaks in the system is used for estimating the time needed for repairs.

Porter et al. (2001) introduced a new methodology called *Assembly-Based Vulnerability* (ABV), which extends the School and Kustu approach for developing theoretical damage relationships. ABV is a framework based on probability distribution for evaluating the seismic vulnerability. In the ABV, seismic vulnerability functions were created for each building component using the related structural response and damage state to estimate earthquake losses. A schematic vulnerability function is illustrated in

Figure 2.4, in which three curves are shown: the mean total earthquake loss as a fraction of a replacement cost, and two dashes lines representing the standard deviation. Thus, at level of spectral acceleration Sa, loss is uncertain and has a probability distribution fY|Sa (y|s). Steps of ABV methodology can be summarized as follows: first determination of the building location, site conditions and, building design; the second step is to select or simulate an acceleration time history appropriate to the building site; then a structural analysis to determine the building's peak structural response is performed and from the structural response different parameters are recorder such as peak floor accelerations and, peak member forces. The structural response is an input to determine the probability that each assembly in the building will be damaged and require repair. Finally, using a probability distribution on both unit cost and time to repair, the fifth step simulates the cost and the time to repair all the damaged assemblies.

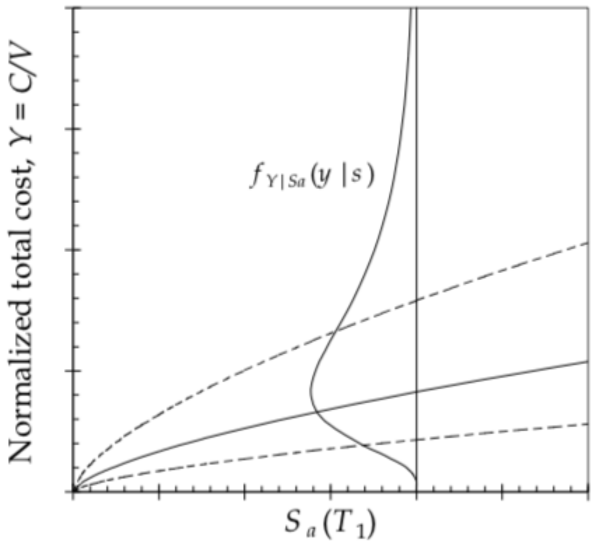

Figure 2.4: A seismic vulnerability function in schematic form from (Porter et al. 2001)

Moreover, Federal Emergency Management Agency (FEMA) recently released the *Performance Assessment Calculation Tool* (PACT), which is an electronic tool for performing probabilistic computation and accumulation of losses for individual buildings (FEMA 2012). It includes several utilities used to specify building properties and uses a methodology to assess the seismic performance of individual buildings accounting for uncertainty in the building response. The methodology is related to the damage that a building may experience and to the consequences of such damage. The PACT methodology is divided into five steps. The first one consists in assembling building performance model through collection of data on building exposure to seismic hazards. The building components are categorized into fragility and performance groups. Then, the earthquake hazards are defined by quantifying the probability that effects of a given intensity will be experienced. From this analysis, it is possible to analyze building response, which usually includes peak values of story drift ratio, floor velocity, floor acceleration, and residual drift ratio.

Once the building response has been analyzed, the collapse fragility functions and the consequence functions are developed to define the probability of incurring structural collapse as a function of ground motion intensity. Instead, the consequence functions indicate the potential distribution of losses and repair time as a function of damage state.

Later on, Almufti and Willford (2013) presented the *Resilience-based Earthquake Design Initiative* (REDi™), which is a tool developed by Arup in 2013 based on the result coming from PACT. It aims to provide owners, architects and engineers a framework for implementing resilience-based earthquake design and for achieving much higher performance. The REDi™ guidelines provide also a detailed downtime assessment methodology (Figure 2.5) for individual buildings and identify the likely causes of downtime through the introduction of repair classes. Repair classes, assigned to each damage state for each building component, evaluate whether the damage in the component hinders building re-occupancy, functional recovery, or full recovery. Thus, the component needs to be repaired before a recovery state can be achieved, if the damage prevents such recovery state. All the three recovery states introduced by SEAONC can be estimated through REDI™.

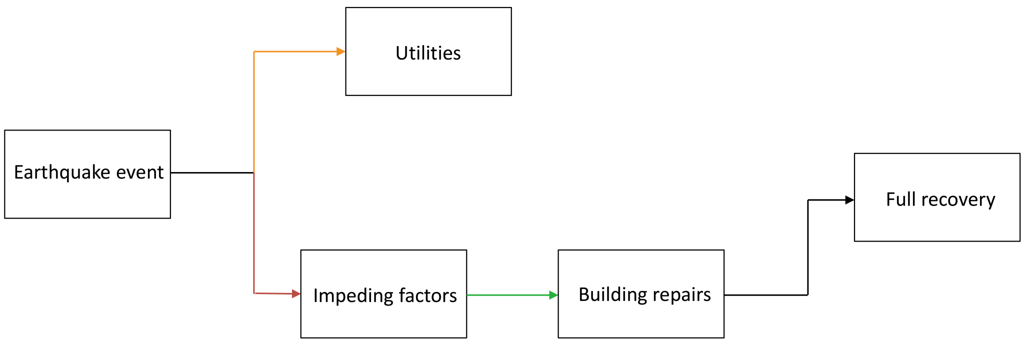

Figure 2.5: Downtime framework for full recovery by REDi^T

Once the components that need repairs to achieve a certain recovery state have been identified, the methodology includes delay estimates called impeding factors, defined as those factors, which may impede the initiation of repairs. Impeding factors include post-earthquake inspection, engineering mobilization, contractor mobilization, financing, permitting, and long-lead-time components. Impeding factors are presented in the form of lognormal cumulative distribution functions (impeding curves).

Another approach on recovery concept was introduced by Miles and Chang (2006). They developed robust model for community recovery after earthquakes. This model, which establishes the relationships among a community's household business, lifeline networks, and neighborhoods, is able to consider decisions made prior and subsequent to an earthquake.

Mitrani-Reiser (2007) developed and implemented an analytical approach for *Performance-Based Earthquake Engineering* (PBEE) to evaluate the performance of new reinforced-concrete moment resisting frame office buildings. The methodology estimates the direct economic losses due to repair costs as well as two types of indirect economic losses, which are produced by the building downtime and by human facilities.

CHAPTER 3 .

FUZZY LOGIC

The chapter provides general information on the concept of Fuzzy Logic, which was introduced by Zadeh in 1965. Some important applications of the theory in different fields are described, such as the industrial and seismic engineering applications. Moreover, the chapter details the three fundamental steps to apply the Fuzzy logic, which are: fuzzification, inference and defuzzification. Finally, a graphical interpolation method is illustrated in order to set the fuzzy base rules that are necessary in the fuzzy logic application.

3.1 INTRODUCTION TO THE FUZZY LOGIC

Zadeh (1965) introduced the concept of fuzzy set and the theory behind it, which comes with the absence of any mathematical framework. While in classical binary logic, a statement can be valued by an integer number, zero or one, corresponding to true or false, in the fuzzy logic a variable x can be a member of several classes (fuzzy sets) with different membership grades (μ) ranging between 0 (x does not belong to the fuzzy set) and 1 (x completely belongs to the fuzzy set) (

Figure 3.1)(Tesfamariam and Saatcioglu 2008).

Later on, fuzzy sets were implemented to new approaches in which linguistic variables were used instead or in addition to numerical variables (Zadeh 1973).

The use of the linguistic values changed completely the way of considering the human systems. The first application of the fuzzy logic was in the design of Fuzzy Logic Controller (FLC) for industrial plants. Mamdani (1974) showed that the hierarchical approach and the fuzzy rules need to be set. Fuzzy logic became a key factor in several fields such as industrial applications in the early 1980's in Europe and

Japan and, Machine Intelligence Quotient (MIQ) to mimic the ability of human, and earthquake engineering.

The most important applications in the earthquake-engineering field have been developed in recent years: Sanchez-Silva and Garcia (2001);Carreño et al. (2007);Demartinos and Dritsos (2006).

Another work that deserves to be described was presented by Tesfamaraim and Saatcioglu (2008), in which a knowledge-based fuzzy rule was developed for evaluating a risk-based seismic for reinforced concrete buildings through a hierarchical scheme. Most recent, the work was extended to considerate the life-cycle cost (LCC).

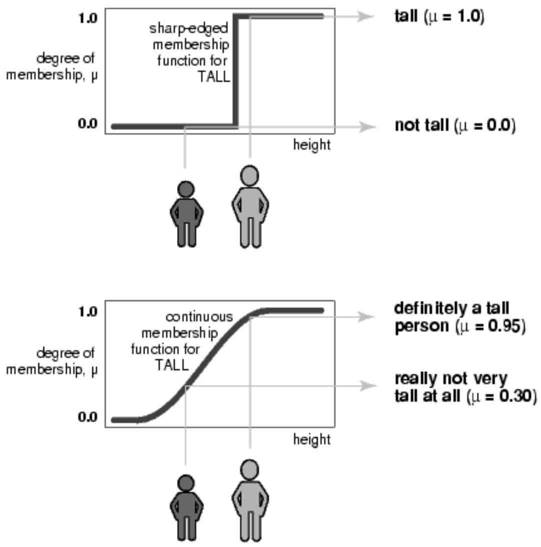

Figure 3.1: Classical binary logic and Fuzzy logic

3.2 THE FUZZY LOGIC

The fuzzy logic consists of three main steps (Figure 3.2):

1. Fuzzification of all input values into fuzzy membership functions;

2. Execute fuzzy rules in the inference system to compute the fuzzy output functions;

3. Defuzzify the fuzzy output functions to get crisp output values.

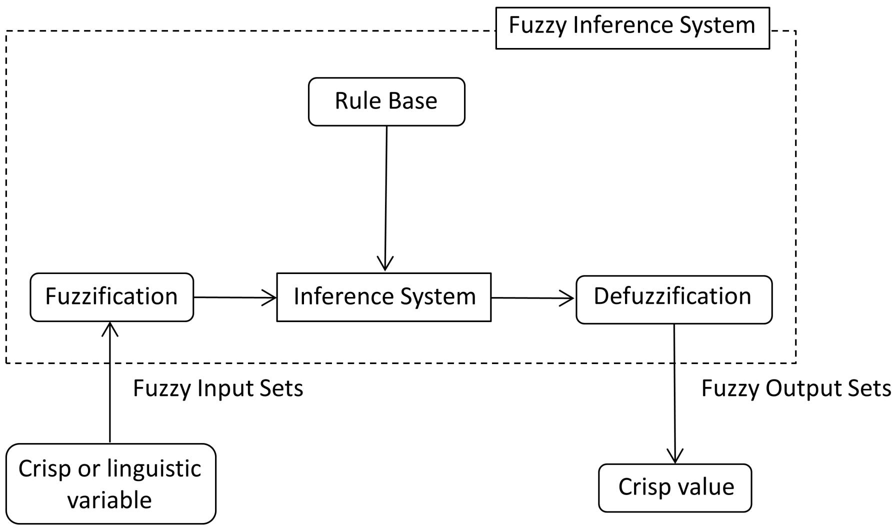

Figure 3.2: Fuzzy Inference System (FIS)

3.2.1 FUZZIFICATION

Every basic input parameters have a range of values that can be clustered into linguistic quantifiers, for instance, very low (VL), low (L), medium (M), high (H) and very high (VH). The process of assigning linguistic values is a form of data compression called *granulation*. The fuzzification step converts the input values into a homogeneous scale by assigning corresponding membership functions with respect to their specified granularities (Tesfamariam and Saatcioglu 2008).

A membership function is a curve that defines how input point is represented by a membership value between 0 and 1 and it is used to quantify a linguistic term. There are different forms of membership functions but the most common types are triangular, trapezoidal, and Gaussian shapes (Figure 3.3). The type of the membership function can be context dependent and it is generally chosen according to the user experience (Mendel 1995).

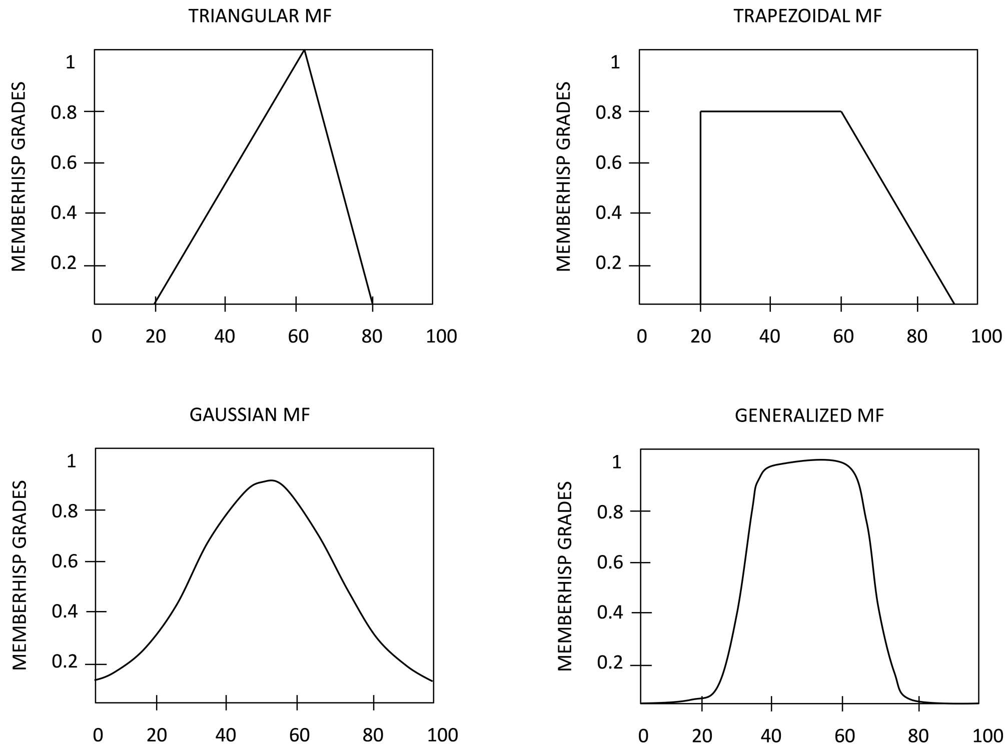

Figure 3.3: Different membership functions shapes

3.2.2 FUZZY RULE

The *fuzzy rule base* (FRB) is derived from heuristic knowledge of experts or historical data to define the relationships between inputs and outputs. The most common type is the *Mamdani* type (Mamdani 1976), which is a simple IF-THEN rule with a condition and a conclusion. For instance, considering two inputs x_i and x_2, the i^{th} rule R_i, has the following formulation:

$$R_i : \ IF \ x_1 \ is \ A_{i1} \ AND \ x_2 \ is \ A_{i2} \ THEN \ y \ is \ B_i \quad i = 1,...,n \tag{1}$$

where x_1 and x_2 are the input linguistic variables (antecedent), A_{i1} and A_{i2} are the input sets, n is the total number of rules, y is the output linguistic variable (consequent), B_i is the consequent fuzzy set. IF-THEN rule involves both the evaluation of the antecedent by fuzzifying the input and applying any necessary operator, and the application of this result to the consequent, known as implication.

3.2.3 WEIGHTED METHOD

The fuzzy rules are assigned using a proposed interpolation method in order to systematize the process. A weighting factor, for instance 1 or 2, is assigned to each input. This value represents the impact of the input towards the output (e.g. a weighting factor 1 signifies a higher impact of the input towards the output). The output is then identified by interpolating the weights and the states of the inputs.

As an example, two fuzzy rules with different granularity, assessed through interpolation method, are shown in Figure 3.4. Consider the following fuzzy rules base: a) IF input x_1 is *Low* AND input x_2 is *Medium* and the corresponding weights are 1 and 2 respectively, THEN the output y is *Medium* (i.e., the intersection of the influence line and the horizontal line is closer to the *medium*; b) IF x_1 is *Low* AND x_2 is *Very High* and their relative weights are 1 and 2, THEN the output y is *High*. In both examples the output y is *medium* (example 'a') and is *high* (example 'b') because x_2 has more weight than x_1.

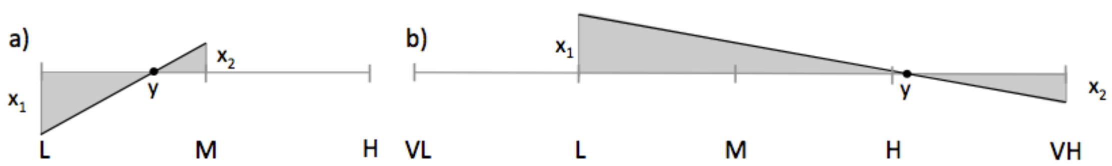

Figure 3.4: Graphical method for fuzzy rules aggregation

3.2.4 FUZZY INFERENCE SYSTEM (FIS)

The results of the rules are combined to obtain a final output (*inference* process). The evaluations of the fuzzy rules and the combination of the results of the individual rules are performed using fuzzy set operations to describe the behavior of a complex system for all values of the inputs. Different aggregation procedures are available: intersection, minimum, product, union, maximum, and summation (Klir and Yuan 1995). For example, Mamdani's inference system consists of three connectives: the aggregation of antecedents in each rule (AND connectives), implication (IF-THEN connectives), and aggregation of the rules (ALSO connectives). In Mamdani's model the fuzzy implication is modeled by Mamdani's minimum operator (the t-norm from compositional rule is min) whereas for the aggregation of the rules the max operator is used. This system is expressed as:

$$\mu_{R,i} = max(min\,\mu_{R,i} = [min(\mu k_{Ai}, \mu k_{Bi}), min(\mu k_{Ai}, \mu k_{Bi})]) \quad (2)$$

where $\mu_{R,i}$ represents the membership value of membership i of the output C_i, μk_{Ai} is the memberhsip value of membership k of the input fuzzy set A_i, μk_{Bi} is the membership value of membership k of the input fuzzy set B_i, and k can be any membership of the granularity defined, determined by the rule based.

3.2.5 DEFUZZIFICATION

The output of the inference step is a fuzzy value, which is defuzzified to obtain a final crisp output. This is the purpose of the defuzzifier component of an FLS. The defuzzification represents the inverse of the fuzzification process and it is performed according to the membership function of the output variable. Many different techniques to perform defuzzification are available in literature, such as: center of the area (COA), center of gravity (COG), bisector of area (BOA), etc (

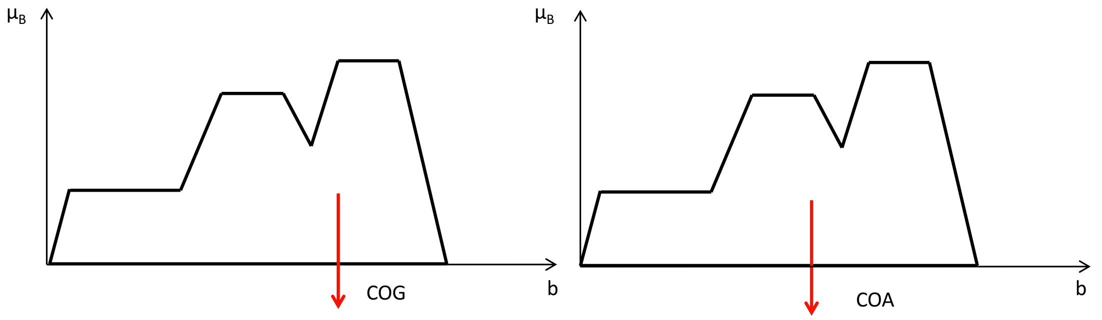

Figure 3.5) (Klir and Yuan 1995).

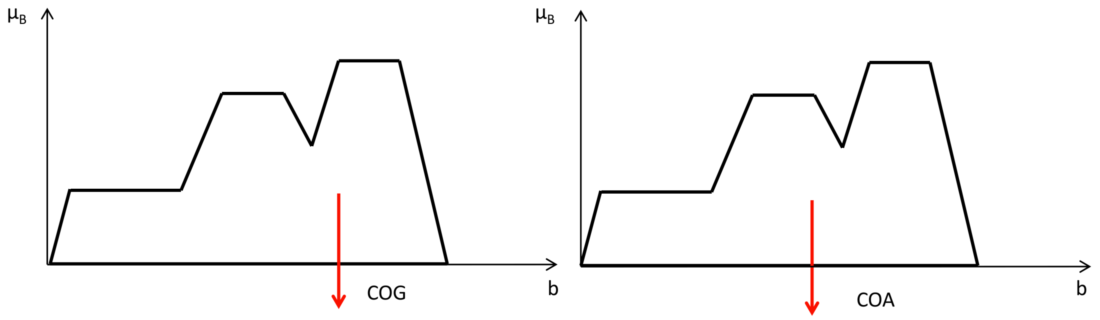

Figure 3.5: Different defuzzification methods

CHAPTER 4 .

METHODOLOGY TO QUANTIFY THE DOWNTIME

This chapter describes the downtime methodology starting from a Rapid Visual Screening (RVS), which is a questionnaire used to collect information of the buildings. The fuzzy logic is applied into a hierarchical scheme to transform information from the RVS into numerical data. Building information from RVS is the input to evaluate the building damage, on which the downtime analysis is based. Finally, the fuzzy numbers that describe the damage expected as a result of a given earthquake are used to calculate the *repairs*, *delays* and *utilities disruption*, which determine the total repair time.

4.1 INTRODUCTION TO THE METHODOLOGY

The evaluation on the downtime can be handled through a comprehensive framework (Figure 4.1), which follows a logical path combining the parameters that contribute in the downtime analysis.

The methodology starts with a Rapid Visual Screening (RVS) of the potentially damaged buildings based on a survey form performed by an expert. The RVS aims to analyze the building and to collect information on the building design characteristics and on the building's components that are subject to damage after an earthquake, and also helps identifying whether or not an earthquake recovery plan exists. This process is affected by subjective and qualitative judgments (Hadipriono and Ross 1991), which can be handle through the fuzzy set theory. A Fuzzy system is implemented in the procedure to translate the RVS results from linguistic terms into numerical data and it consists in three steps: fuzzification, inferencing, and defuzzification,

Building information from the RVS is incorporated through a comprehensive framework, which follows a logical order for combining specific contributors (e.g. site seismic hazard and building vulnerability modules) to estimate the building damage (Figure 4.1).

The building damageability is carried out as five-tuple membership values (μ_{VL}^{BD}, μ_{L}^{BD}, μ_{M}^{BD}, μ_{H}^{BD}, μ_{VH}^{BD}) and each membership value is associated with five damage states, *very low* (VL), *low* (L), *medium* (M), *high* (H), *and very high* (VH). The building membership can be considered as the limit state in which the structure may be for a given site seismic hazard and building vulnerability. For this reason, the downtime analysis is carried out for the degrees of damage membership that are greater than zero, which represents the possibility of the building being in a limit state. For instance, if the damage membership is (μ_{VL}^{BD}, μ_{L}^{BD}, μ_{M}^{BD}, μ_{H}^{BD}, μ_{VH}^{BD}) = (0, 0, 0.37, 0.63, 0), the downtime is quantified for damage = *Medium (0.37)* and damage = *High (0.63)* (Tesfamariam and Sanchez-Silva 2011).

These fuzzy numbers describe the damage expected as a result of a given earthquake and are used to calculate the *repairs, delays,* and *utilities disruption*. That is, the downtime is the combination of the time required for *repairs* (rational components), *delays* (irrational components), and the time of *utilities* disruption (Figure 4.1). This combination depends on the chosen recovery state. (Bonowitz 2010) Identifies three recovery states:

- Re-occupancy: the building is safe enough to be used as shelter;
- Functional recovery: the building can be re-occupated and can regain its primary function;
- Full recovery: the building is restored to its pre-earthquake condition.

In the re-occupancy recovery state, consideration of utilities disruption is not required. Therefore, the downtime is evaluated through the sum between (*DT repairs* + *DT delays*). Instead, downtime for functional and full recovery is the time needed to complete all three sources of downtime. It is the maximum between (*DT repairs + DT delays)* and *DT utilities*, as follows:

$$DT = \max((DTrepairs+DTdelays);DTutilities) \quad (3)$$

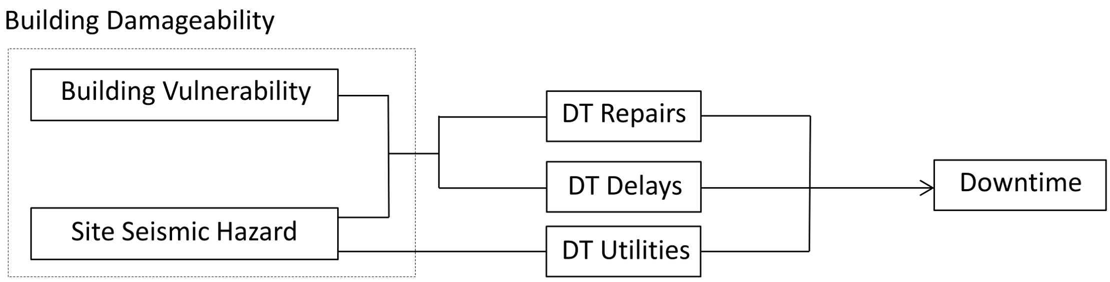

Figure 4.1: Evaluation of Downtime

Downtime due to repair and due to delay is computed from the Building Damageability, which is composed of the Building Vulnerability and the Site Seismic Hazard, while downtime due to utilities disruption is evaluated from the Site Seismic Hazard and from the Infrastructure Vulnerability (Note: the infrastructure vulnerability is not included in the research because it is out of the thesis scope).

To estimate the downtime due to *repairs*, it is necessary to define the repair time for each component of the analyzed building and the number of workers assigned for the repair. A repair scheme is used to identify the sequence of repairs that are to be conducted. In fact, repairs can occur in series one floor at a time starting from the bottom or simultaneously at all floors. The repair sequences introduced in REDI^{TM} (Almufti and Willford 2013) have been used in this work.

Downtime due to *delays* is based on irrational components (Comerio 2006). The irrational components considered in this paper are a selection from the components used by REDI^{TM}: post-earthquake inspection, engineering mobilization, financing, contractor's mobilization, and permitting. They need to be combined through a specific sequence, shown in Figure 4.2, which represents the path of delays in the recovery plan. As it is shown, after the earthquake event building inspection is necessary to define the presence or not of structural and non-structural damages. Such step is crucial to determine the following parameters. In fact, engineer mobilization, which occurs simultaneously with financing and contractor mobilization, and consequently permitting, are necessary only for structural damage.

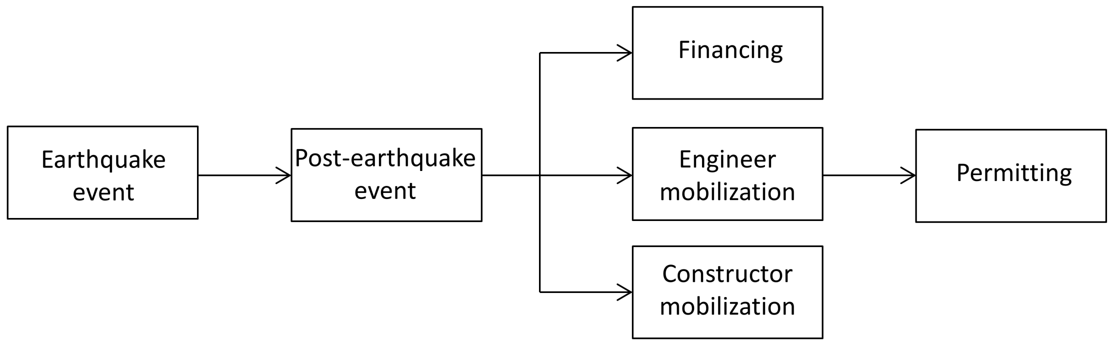

Figure 4.2: Delays sequences

Downtime due to *utilities* depends on the site seismic hazard and on infrastructure systems that are likely to be disrupted after an earthquake (e.g. electricity, water, gas, etc). The evaluation of utilities disruption is necessary since functional and full recovery of the building cannot be reached while utilities are disrupted.

Finally, once the rational components, the irrational components, and the utilities disruption are known, the total repair time can be estimated. A downtime value is computed for each damage membership as follows:

$$DT = \sum_{i=1}^{n} DT_i * \mu_i \qquad (4)$$

where DT_{i} is the downtime for a certain granulation, i is the granulation assigned to the damage membership, μ_i is the damage membership degree of granulation i.

4.2 RAPID VISUAL SCREENING (RVS)

The Rapid visual screening is the starting point of the methodology. The RVS, based on a survey form, is used to observe, from the exterior and from the interior, buildings that are seismically hazardous and to provide details on the building's geometry and design.

Information obtained during the visual inspection can be divided in three groups:

- Information of building design, such as: building basic attributes, building structural system, vertical and plan irregularities (topography), and construction quality;

- Information of building components that are located in each floor (rational components);

- Information about pre-earthquake recovery planning (irrational components): prearrangement of post-earthquake inspection program, existence of engineer on contract and contractor on contract, and finally the type of financing.

To collect information on building design and recovery planning, a survey form is performed by an expert (Figure 4.3), which lists information on building components per floor as well as the area per floor.

However, visual inspections are influenced by subjective uncertainties and judgments, which depend on the screener professional experience and knowledge. A qualification and quality control is therefore needed to establish the correct criteria of RVS. For example, the Proceeding for a Workshop on a Rating System (Rojahn et al. 2011) takes into account the criteria for the RVS procedure, as follows:

- Screeners should be licensed engineers and certified for commercial buildings;

- Screeners not need to be licensed engineers but should be certified for residential buildings.

RAPID VISUAL SCREENING OF BUILDINGS

INSPECTION INFORMATION

Screener(s): ____________ Date/Time: ____________

BUILDING INFORMATION

State: ________ City/Town: ________ Address: ____________________

Zip code: ______ Latitude: _________ Longitude: __________

SKETCHES

Scale:

PHOTOGRAPH

BUILDING DESIGN INFORMATION

No. stories: ____ Building height (ft.): ____ Total floor area (sq. ft.): ____ Year of construction: ____

Occupancy: Assembly Commercial Emer.Services Historic **Units:** ____

Industrial Office School Government

Utility Warehouse Residential Shelter

Structural system: C1 ☐ C2 ☐ C3 ☐

Vertical irregularity: Yes ☐ No ☐ Plan irregularity: Yes ☐ No ☐

Construction quality: Poor ☐ Average ☐ Good ☐

PRE-EARTHQUAKE RECOVERY PLANNING INFORMATION

Post earthquake inspection program: Yes ☐ No ☐

Engineer on contract: Yes ☐ No ☐ Conctractor on contract: Yes ☐ No ☐

Type of financing:

No ☐ Pre-arranged credit line ☐ SBA-backed loans ☐ Private loan ☐

Insurance ☐

Comments:

Figure 4.3: Rapid Visual Screening (RVS) survey form

4.3 DAMAGE ESTIMATION

The building damage is estimated through a hierarchical scheme that includes all variables contributing to the building damage (Figure 4.4). The proposed hierarchical scheme for building damageability is an adaptation from Tesfamariam and Saatcioglu (2008), in which aggregation of the variables is done through the fuzzy model introduced before, and the granularity assigned to the fuzzification is associated with the level of damage state.

In the hierarchical scheme, the basic components, which are assessed using the RVS, are:

- Site seismicity
- Site condition
- Building height
- Vertical irregularity
- Plan irregularity
- Construction quality
- Year of construction
- Structural system

The other components, which do not need inputs but rather they are obtained through the aggregation of the basic components, are:

- Building damageability
- Site seismic hazard
- Building vulnerability

- Structural deficiency
- Increase in demand
- Decrease in resistance

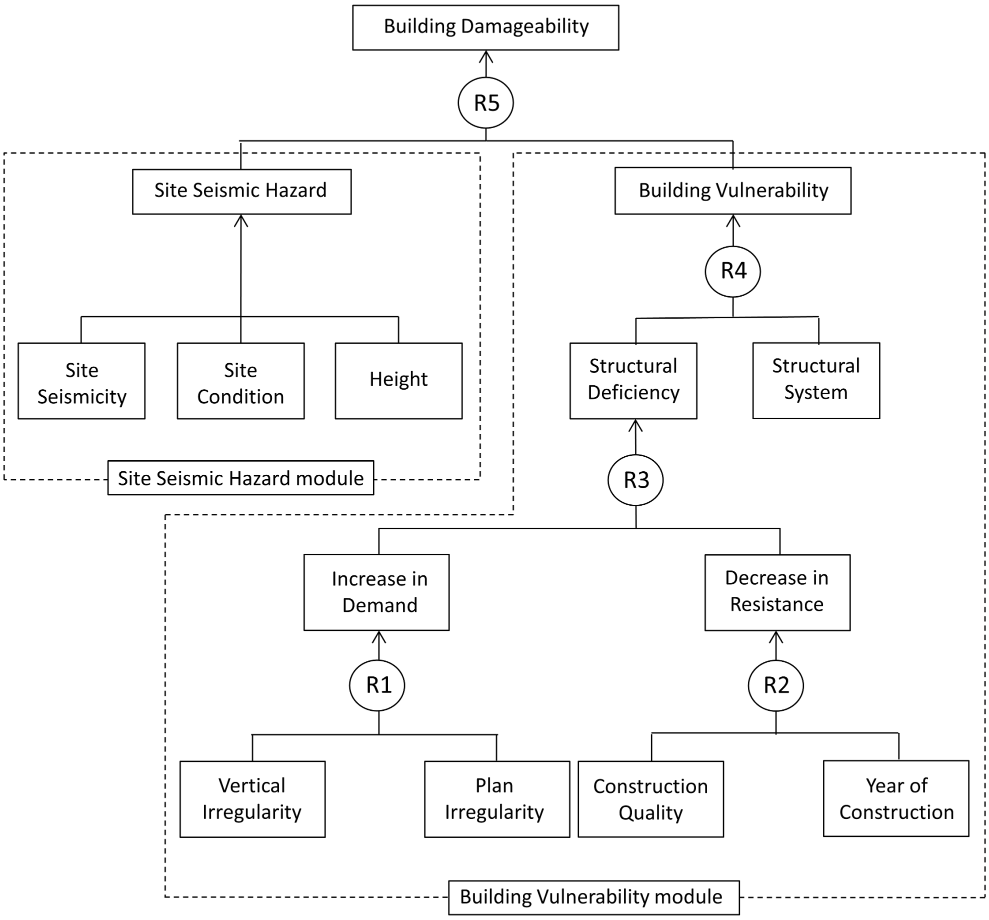

Figure 4.4: The building damageability hierarchical scheme, adapted from Tesfamariam and Saatcioglu (2008)

As mentioned before, the hierarchical scheme is used to represent the system in a logic and simple way combining parameters through the Fuzzy logic. In the methodology, the Fuzzy Logic is applied using a heuristic model to assign membership values starting from linguistic information, which can generate membership functions using our intelligence.

The membership functions considered in the methodology are those introduced by Tesfamariam and Saatcioglu (2008), which are based on triangular fuzzy numbers (TFNs) that are expressed by three vertices (a;b;c) where a,b, and c represents the minimum and the maximum respectively. The triangular fuzzy numbers are suitable to describe linguistic parameters since they can refer to three possible scenarios: pessimistic, most probable and optimistic. Their mathematical expression is:

$$\mu(x:a,b,c)=\begin{Bmatrix} 0 & \text{for } 0<x<a \\ \dfrac{x-a}{b-a} & \text{for } a<x<b \\ \dfrac{c-x}{c-b} & \text{for } b<x<c \\ 0 & \text{for } x>c \end{Bmatrix} \tag{5}$$

The weighting method introduced before is used to define fuzzy rules in the inference system and to connect inputs and outputs of the system. That is, associating a weighing value, which represents the impact of the input towards the output, it is possible to get all the necessary fuzzy rules for applying fuzzy logic.

Finally, at each level of hierarchical scheme (Figure 4.4), the weighted average method is used for defuzzification to obtain an index I, as follows:

$$I=\sum_{i=1}^{n} q_i * \mu_{R,i} \tag{6}$$

where q_i is the quality-ordered weights, $\mu_{R,\mathrm{i}}$ is the degree of membership, i is the tuple fuzzy set (Liou and Lo 2005; Sadiq et al. 2004).

The quality-ordered weights used in the methodology are established through the calibration based on the 1991 Northridge Earthquake observed damages (Tesfamariam and Saatcioglu 2008). They are listed below:

$$\begin{aligned}
&\text{For } R_1\ q_i = (i=1,2,3) = (0.25, 0.5, 0.1)\\
&\text{For } R_2\ q_i = (i=1,2,3) = (0.1, 0.6, 0.7)\\
&\text{For } R_3\ q_i = (i=1,2,3) = (0.1, 0.6, 0.9)\\
&\text{For } R_4\ q_i = (i=1,2,3) = (0.01, 0.5, 0.9)
\end{aligned} \tag{7}$$

For the Building Damageability (level 5 of the hierarchical scheme), defuzzification is not required. Each damage membership grade that is greater than zero is used independently in the downtime analysis. The resulting downtimes corresponding to the different memberships are combined to obtain a final downtime value, as described before.

In the following, components presented in the hierarchical scheme, which are assessed in the RVS, are described in detail.

4.3.1 BUILDING DAMAGEABILITY (Level 5)

According to the logical path proposed in the hierarchical scheme, the Building Damageability index (I^{BD}) is computed by integrating Site Seismic Hazard (SSH) and Building Vulnerability (BV). The fuzzy rule base, obtained from the interpolation method, contains twenty-five rules as the granulation of inputs is wider (Table 1).

Table 1. Fuzzy rule for Building Damageability

Rule	*SSH* *W=2*	*BV* *W=1*	*BD*
1	VL	VL	VL
2	VL	L	VL
3	VL	M	L
4	VL	H	L
5	VL	VH	L
6	L	VL	L
7	L	L	L
8	L	M	L
9	L	H	M
10	L	VH	M

11	M	VL	L
12	M	L	M
13	M	M	M
14	M	H	M
15	M	VH	H
16	H	VL	M
17	H	L	M
18	H	M	H
19	H	H	H
20	H	VH	H
21	VH	VL	H
22	VH	L	H
23	VH	M	H
24	VH	H	VH
25	VH	VH	VH

The index (I^{BD}) is fuzzified into five granules: VL, L, M, H, VH as it is illustrated In
Figure 4.5.

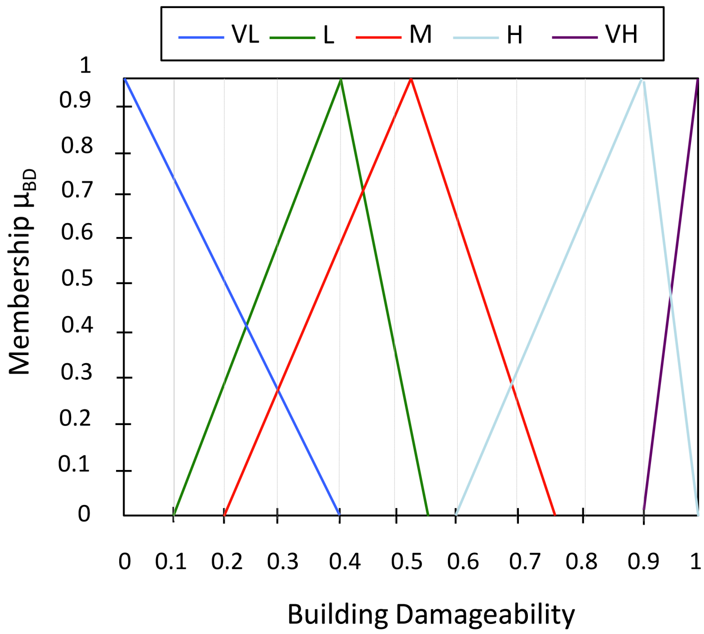

Figure 4.5: Building Damageability fuzzy sets

4.3.2 BUILDING VULNERABILITY (Level 4)

Building Vulnerability index (I^{BV}) is obtained through the integration of the two components: Structural Deficiency (SD) and Structural System (SS). Building vulnerability index (I^{BV}) is fuzzified using the building vulnerability fuzzy sets (Figure 4.6) into three granules: L, M, and H. The fuzzy rule base for Building Vulnerability is shown in Table 2.

Table 2. Fuzzy rule for Building Vulnerability

Rule	*SD* *W=2*	*SS* *W=1*	*BV*
1	L	L	L
2	L	M	L
3	L	H	M
4	M	L	M
5	M	M	M
6	M	H	M
7	H	L	M
8	H	M	H
9	H	H	H

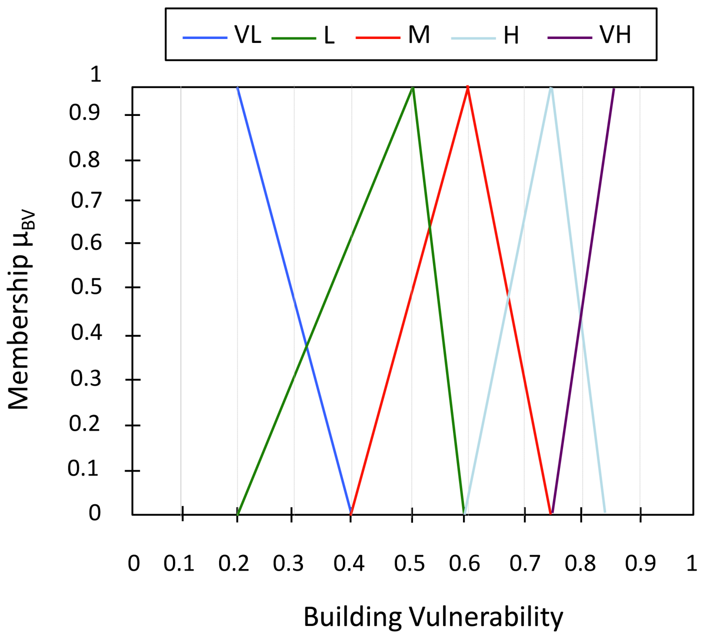

Figure 4.6: Building Vulnerability fuzzy sets

4.3.3 STRUCTURAL DEFICIENCY (Level 3)

Structural Deficiency can be divided into two categories (Saatcioglu et al. 2001): factors contributing to an increase in seismic demand (*Increase in Demand*) and factors contributing to a reduction in ductility and energy absorption (*Decrease in Resistance*). Basic risk items presented in FEMA 154 (FEMA 2002) have been adopted in the methodology to evaluate building vulnerability, which are inputs contributing to increase in demand (*vertical irregularity* and the *plan irregularity*) and inputs contributing towards the decrease in resistance (*construction quality* and *year of construction)*.

Structural Deficiency index (I^{SD}) is computed through the aggregation of the Increase in Seismic Demand (I^{ID}) and the Decrease in Resistance (I^{DR}) indexes. I^{SD} is fuzzified into three granules: L, M, H (Figure 4.7). The fuzzy rules base for Structural Deficiency are shown in Table 3.

Table 3. Fuzzy rule for Structural Deficiency

Rule	*ID* *W=2*	*DR* *W=1*	*SD*
1	L	L	L
2	L	M	M
3	L	H	M
4	M	L	L
5	M	M	M
6	M	H	H
7	H	L	M
8	H	M	M
9	H	H	H

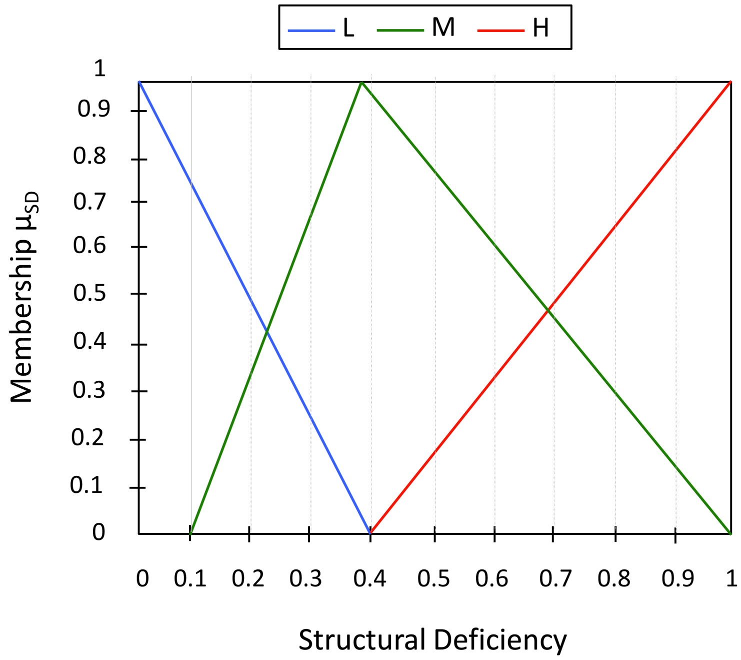

Figure 4.7: Structural Deficiency fuzzy sets

In the following, factors contributing to Increase in Seismic Demand and factors contributing to Decrease in Resistance are described.

4.3.4 DECREASE IN RESISTANCE (Level 2)

Decrease in Resistance index (I^{DR}) can be computed after the assessment of Construction Quality (CQ) and Year of Construction (YC) (Figure 4.8). The index is fuzzified into three granules that are: L, M, and H. The fuzzy rule base for decrease in resistance is shown in Table 4.

Table 4. Fuzzy rule for Decrease in Resistance

Rule	*CQ W=2*	*YC W=1*	*DR*
1	L	L	L
2	L	M	L
3	L	H	M
4	M	L	M
5	M	M	M

6	M	H	M
7	H	L	M
8	H	M	H
9	H	H	H

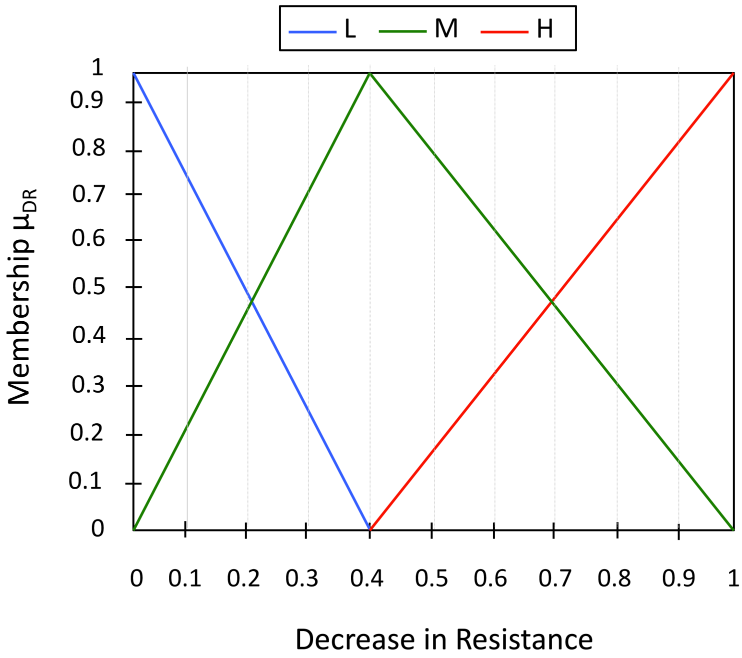

Figure 4.8: Decrease in Resistance fuzzy sets

4.3.4.1 CONSTUCTION QUALITY

To determine construction quality in the RVS, the screener can define it using linguistic terms as poor, average, and good quality. Construction errors, the lack of beam and column reinforcement, the use of non-seismic hooks may affect the quality of the building.

The transformation values for construction quality evaluation are: 0.99 for poor, 0.70 for average, and 0.01 for good.

Fuzzification of these values is done through the year of construction fuzzy sets (Figure 4.9).

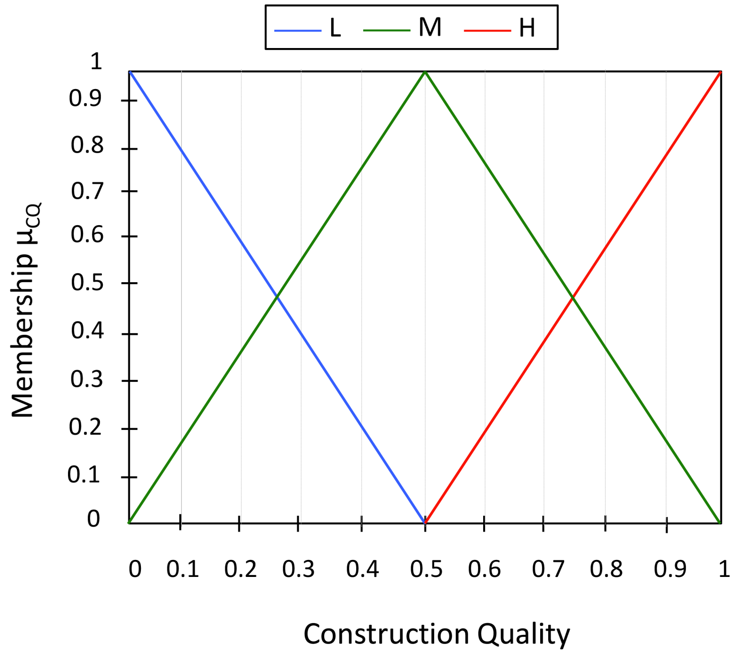

Figure 4.9: Construction Quality fuzzy sets

4.3.4.2 YEAR OF CONSTRUCTION

Year of Construction (YC) is used to convey important information about the seismic design code provision. Such information allows identifying the building behaviour in ductility, strength and detailing.

In general, the year of construction can be classified into three distinct states (Hazus 1999): low code ($YC \leq 1941$), moderate code ($1941 \leq YC \geq 1975$), and high code ($YC \geq 1975$). These threshold values are derived from the North America practice. The transformation values are computed through the following linear transformation functions:

$$\begin{cases} 0.90 & YC < Low\,code \\ -0.01\,YC + 20.25 & Low\,code < YC < High\,code \\ -0.02\,YC + 39.9 & YC > High\,code \end{cases}$$

Fuzzification of these values is done through the year of construction fuzzy sets (Figure 4.10).

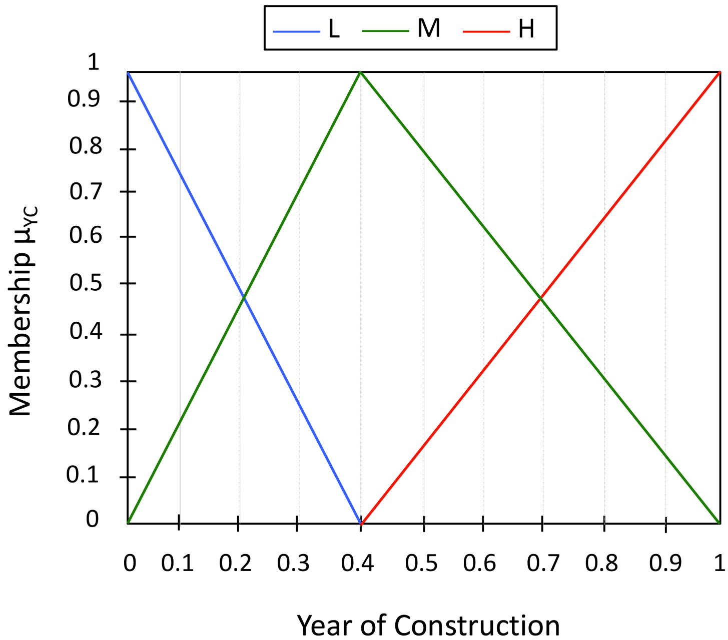

Figure 4.10: Year of Construction fuzzy sets

4.3.5 INCREASE IN DEMAND (Level 1)

Increase in Demand index (I^{ID}) is computed by defuzzifying vertical and plan irregularities. The index is fuzzified into three granules that are: L, M, and H (

Figure 4.11). The fuzzy rule base for Increase in Demand is listed in Table 5.

Table 5. Fuzzy rule for Increase in Demand

Rule	*VI* *W=2*	*PI* *W=1*	*ID*
1	L	L	L
2	L	M	L
3	L	H	M
4	M	L	M
5	M	M	M
6	M	H	M
7	H	L	M

8	H	M	H
9	H	H	H

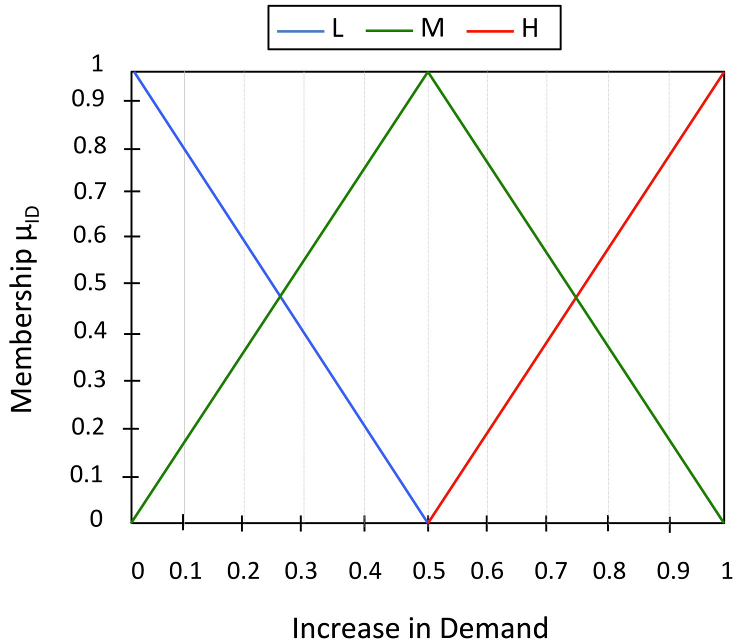

Figure 4.11: Increase in Demand fuzzy set

4.3.5.1 VERTICAL IRREGULARITIES

Vertical irregularity (VI) reflects the presence of discontinuity and/or irregular distributions of mass, strength and stiffness along the building height. It is mainly of five types: stiffness irregularity, mass irregularity, and vertical geometric irregularity. In the RVS, vertical irregularity is determined by “yes” when it is present and “no” when it is not present. The corresponding transformation is: 0.80 for present and 0.10 for not present. Fuzzification of these values is done through the vertical irregularity fuzzy sets (

Figure 4.12).

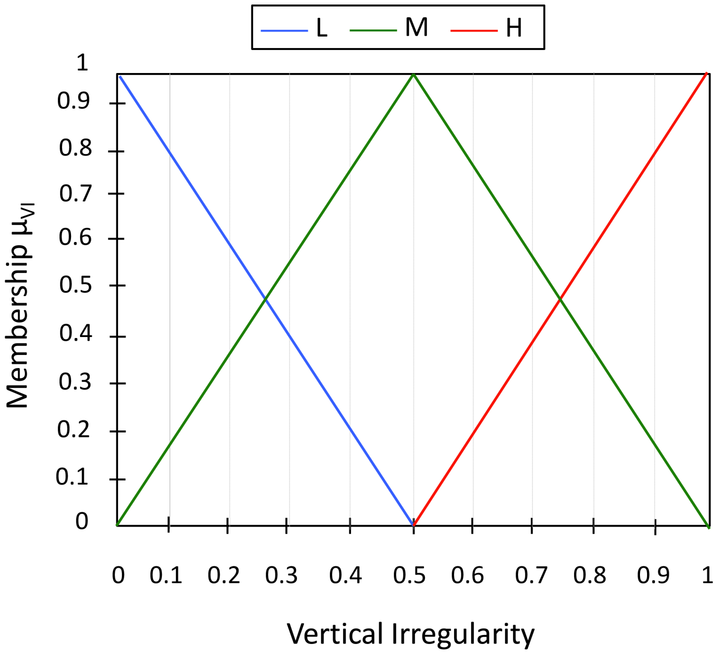

Figure 4.12: Vertical irregularity fuzzy sets

4.3.5.2 PLAN IRREGULARITY

Plan irregularity (PI) is determined by the presence of discontinuity and/or irregular distributions of mass, strength and stiffness in plan. Plan irregularities mainly concern torsion irregularity, plan geometric irregularity, and diaphragm discontinuity. The transformation values assigned to plan irregularity are: 0.80 for "yes" when it is present and 0.20 for "no" when it is not present. Fuzzification of these values is done through the plan irregularity fuzzy sets (Figure 4.13).

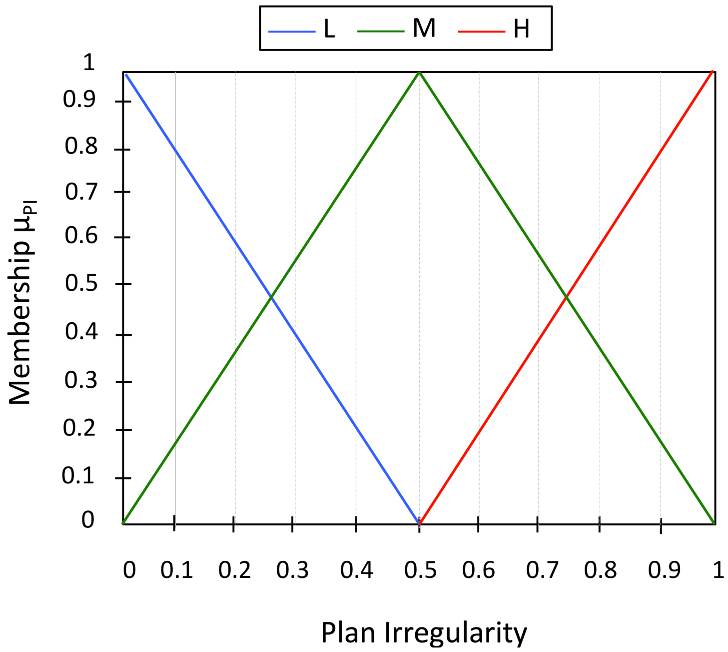

Figure 4.13: Plan Irregularity fuzzy sets

4.3.6 STRUCTURAL SYSTEM (Level 4)

Three popular reinforced concrete building types are identified for the evaluation of the structural system component: moment resisting frames (C1), shear walls (C2), and moment resisting frames with infill masonry walls (C3) (

Figure 4.14).

Moment resisting frame (C1) is a rectilinear structure with beams and columns rigidly connected, in which the resistance to lateral forces is provided by rigid frame action (Bruneau et al. 2011).

Shear wall (C2) is a structural system with shear panels used to resist lateral forces. The panels generally start at foundation level and are continuous throughout the building height. Shear wall structures are efficient in construction cost and in reduction of earthquake damage structural and non-structural elements.

The behavior of the construction is widely influenced by the shape and the plan position of shear wall. Generally, the best position is in the center of each half of the building, especially in high-rise buildings subject to lateral wind and seismic forces.

Moment resisting frames with infill masonry walls (C3) are largely presented in older buildings. They may work as shear walls in controlling deformations until the elastic limit of non-ductile concrete frames is exceeded.

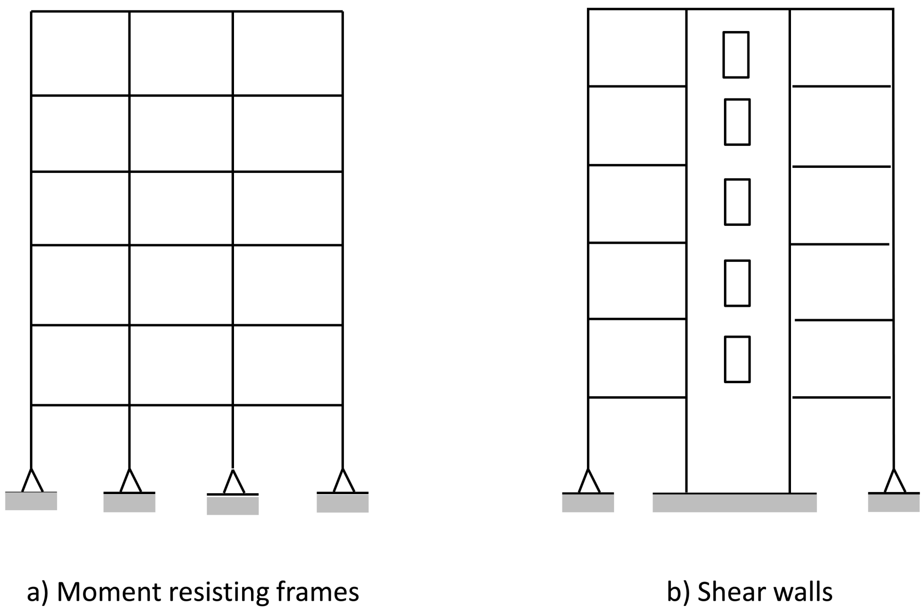

Figure 4.14: Structural system

The transformation values used for structural system are: 0.70 for moment resisting frames (C1), 0.2 for shear walls (C2), and 0.4 for moment resisting frames with infill masonry (C3). The granulation assigned to the structural system (SS) is shown in

Figure 4.15.

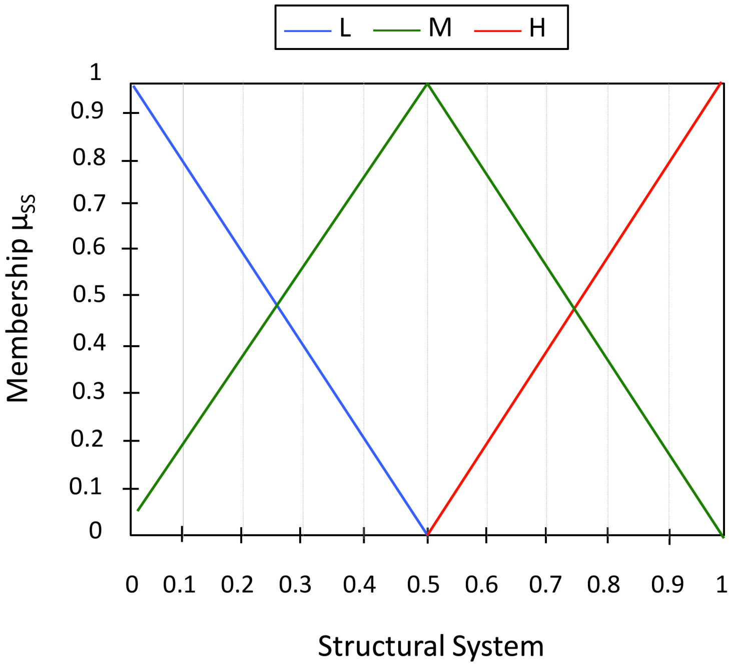

Figure 4.15: Structural System fuzzy sets

4.3.7 SITE SEISMIC HAZARD MODULE

Seismic hazard is affected by earthquake source conditions, source-to-site transmission path properties, and site conditions. The source conditions include the stress drop, source depth, size of the rupture area, slip distribution (amount and distribution of static displacement on the fault plane), rise time (time for the fault slip to complete at a given point on the fault plane), type of faulting, and rupture directivity. The transmission path of properties regards the crustal structure and the shear-wave velocity and damping characteristic of the crustal rock. Finally, the site conditions cover the rock properties beneath the site to depths of up about 2 km, the local soil conditions at the site to depths of up to several hundred feet, and the topography of the site. Landslide and liquefaction, in this work, are classified as consequences of ground shaking (Adams and Atkinson 2003). Therefore, in the seismic hazard analysis, to predict the site seismic hazard index (I^{SH}) it is only necessary to consider site ground motions.

Seismic hazard is expressed in terms of building response acceleration, which can be obtained from response spectra that describes maximum spectral accelerations as a function of building period (T). Building period evaluation is the first step in the seismic hazard assessment. It is dependent on mass, stiffness and damping, and consequently on all the factors which affect them (e.g. irregularities, dimensions, morphology, etc.).

The period-height expressions for concrete frame buildings and shear walls from Saatcioglu et al. (2001) are used as follows:

$$\begin{aligned} &T = 0.075(H)^{3/4} \quad \text{concrete frame building} \\ &T = 0.05(H)^{3/4} \quad \text{shear wall building} \end{aligned} \tag{8}$$

where H is the overall height of the building in meter above the base.

The spectral acceleration *(Sa)* can be obtained from site-specific response spectrum or from building codes through site-specific response spectrum by using the period of the structure T, determined in the previous step. Final step in site seismic hazard assessment consists in the fuzzification of the spectral acceleration through the site seismic hazard fuzzy sets (Figure 4.16).

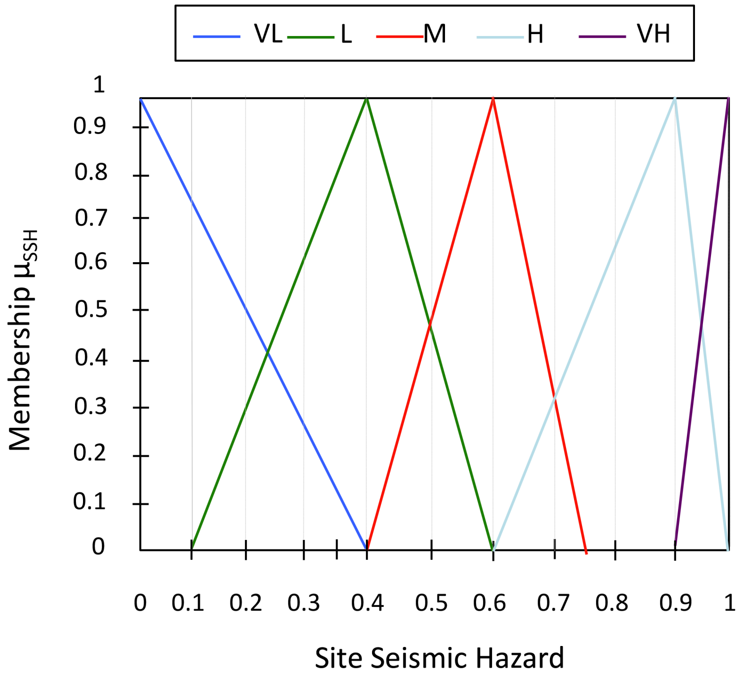

Figure 4.16: Site Seismic Hazard fuzzy sets

CHAPTER 5 .

THE DOWNTIME

This chapter describes the downtime analysis from the building damage state, which allows to understand for what recovery state the evaluation is carried out, to the total repair time. The chapter analyzes three sources that contribute to quantify the total repair time according to the chosen recovery state and to the damage membership values that are greater than zero: downtime due to *repairs* (rational components), downtime due to *delays* (irrational components) and downtime due to *utilities disruption*. A simple scheme for each downtime is illustrated and different factors that may increase downtimes are described in detail in the chapter.

5.1 DOWNTIME DUE TO REPAIRS

Downtime due to repairs depends on the state of the damaged components as well as on the number of workers assigned (Figure 5.1). These are the rational parameters contributing in the downtime evaluation.

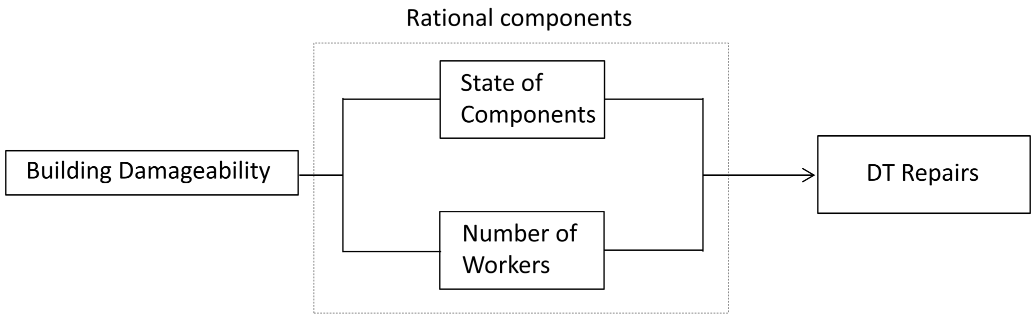

Figure 5.1: Downtime due to *Repairs* (Rational components)

5.1.1 STATE OF COMPONENTS

PACT, an electronic calculation tool released by FEMA (2012), evaluates the repair times from consequence functions that indicate the distribution of losses as a function of damage state. The distribution (and dispersion) for potential repair time was derived from data representing 10th, 50th, and 90th percentile estimates of labor effort. Both lognormal and normal distributions are developed from available data, and the curve with the best fit is used in each case. However, in this work, only data representing the 50th and 90th percentile is used, as the 10th percentile is not desirable for downtime assessment.

Component repair times are presented in *Appendix A* and *Appendix B*. In *Appendix A,* repair times for structural components are developed for three damage states (i.e. *Low*, *Medium*, and *High*), whereas, in *Appendix B,* for non-structural components, repair times are developed for five damage states (i.e. *Very Low, Low, Medium, High*, and *Very High*).

Once component repair times for each damage state are known, the values can be used to compute total component repair time. This is done by defuzzifying the component repair times using the corresponding membership values, as follows:

$$RT = \sum_{i=1}^{n} rt_{,i} * \mu_{R,i} \tag{9}$$

where RT is the component total repair time, rt_i is the repair time of the component considered, i is the damage state level, $\mu_{R,I}$ represents the damage membership value considered in the analysis.

In this methodology, the repairs sequences presented in REDI™ (Almufti and Willford 2013), which defines the order of repairs (Figure 5.2), is used to quantify the repair time. The repairs sequences depend on the building damage state. That is, if the building damage state is classified as *Medium*, structural components can be repaired simultaneously (in parallel); if the building damage state is classified as *High* or *Very High*, structural repairs are done for one floor at a time (in series). The difference in repair time estimates for a parallel vs. series assumption can be significant. For instance, the parallel scheme estimates may be in the order of months, and the series repair scheme estimates may be in the order of years, depending on the number of floors in the building.

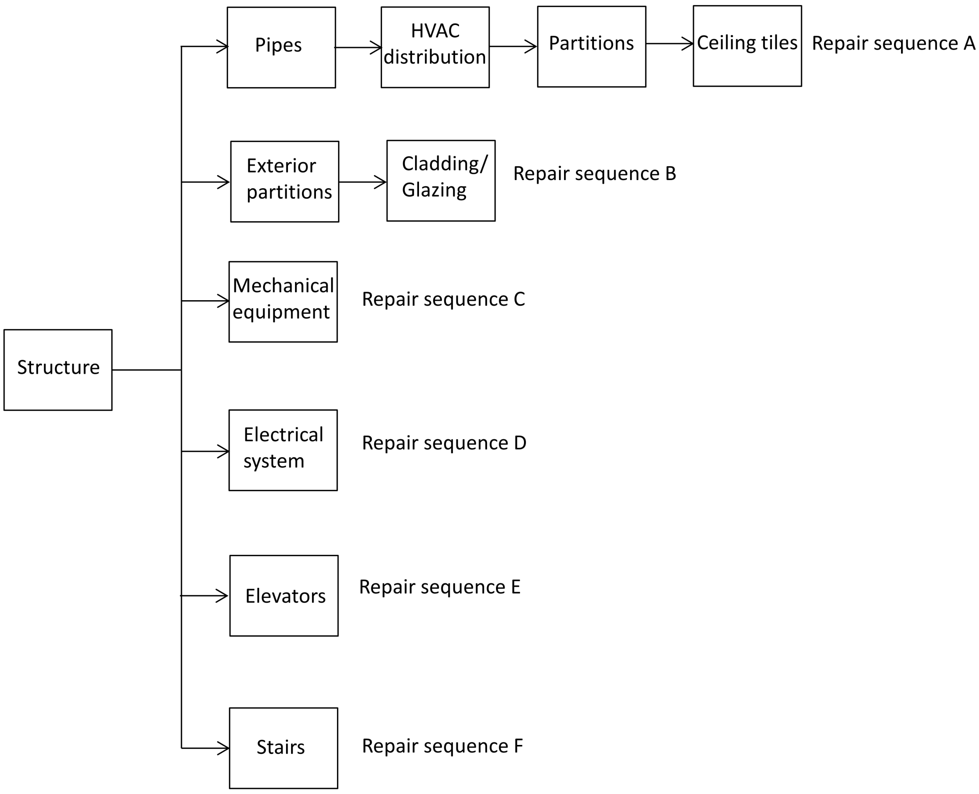

Figure 5.2: Repair sequences from REDi^{TM}

5.1.2 NUMBER OF WORKERS

Repairs can be carried faster or slower, depending on the crew number. Information about the number of workers is obtained from FEMA P-58 and from REDi^{TM}. FEMA P-58 indicates that the maximum number of workers per sq. ft. ranges from 1 worker per 250 sq. ft. to 1 worker per 2000 sq. ft. (FEMA 2012). On the other hand, instead, following the REDI^{TM} instructions, repairs for structural components have a labor allocation limitation for each floor of 1 worker per 500 sq. ft. Such limitation is based on the fact that repairs for structural components happen first separately from no-structural repairs, which happen later. Thus, this means that there is no interfere between structural and no-structural repairs. For non-structural repairs, REDI™ recommends using 1 worker per 1000 sq. ft.

Workers for mechanical equipment, electrical systems, elevator, and stair repairs are allocated on the basis of the average number of damaged units (Table 6). Average crew of workers from RS Means (Alterman et al. 2013) is used to determine the number of workers assigned for each repair sequence component type.

Table 6. Number of workers for repair times

Repair sequence	Component type	Number of workers
/	Structure	1 worker/500 sq.ft.
A	Pipes HVAC distribution Partitions/Cilling	1 worker/1000 sq.ft.
B	Exterior partitions Cladding/Glazings	1 worker/1000 sq.ft.
C	Mechanical equipment	3 workers/d.u.
D	Electrical systems	3 workers/d.u.
E	Elevators	2 workers/d.u.
F	Stairs	2 workers/d.u.

Equation (10) computes the maximum number of workers for structural repairs in a building for a gross area:

$$N_{max} = 2.5x10^{-4} A_{tot} + 10 \qquad (10)$$

where N_{max} is the maximum number of workers on site, and A_{tot} is the total floor area of the building (sq. ft.).

5.2 DOWNTIME DUE TO DELAYS

There are several causes of delay that can increase the time required to achieve a recovery state.

Downtime due to delays is largely based on the building damage. That is, in buildings where the expected damage state is *Low*, less downtime due to delays is likely to occur. Downtime due to delays derived from several irrational components, which were introduced by Comerio (2006) (Figure 5.3).

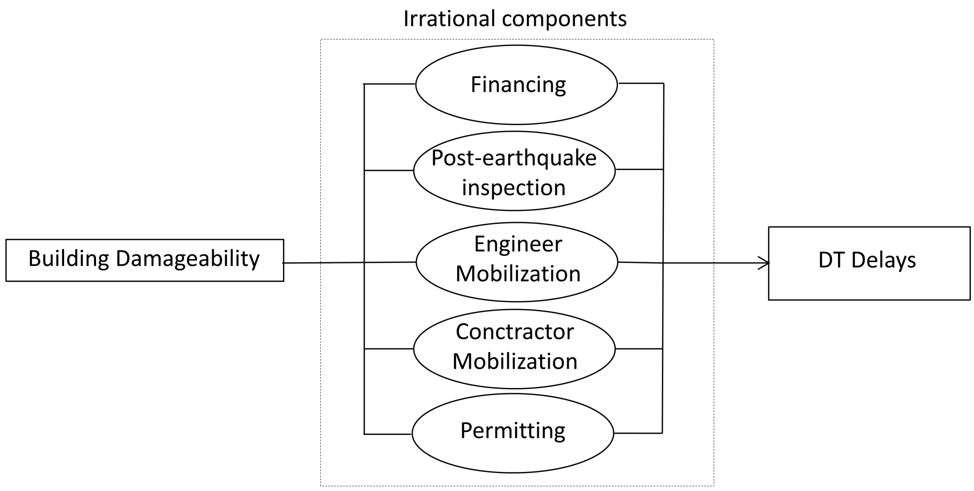

Figure 5.3: Downtime due to *Irrational components*

The irrational components used in the methodology are a selection from the components used by REDI™ and they are:

- Financing
- Post-earthquake inspection
- Engineer mobilization
- Contractor mobilization
- Permitting

In REDi™ guidelines, irrational components are presented in the form of lognormal cumulative distribution functions. These functions are based on data from previous earthquakes that are provided by engineers, contractors, bankers, and cost estimators. The 'best estimate' approximation of the delays that can occur is considered in the methodology. Therefore, results are shown in the form of 50th and 90th percentiles, which are the probabilities of non-exceedance. For instance, the 90th percentile describes a situation in which there is a 90% of probabilities that delays would not exceed a specific amount.

In the following, irrational components are examined.

5.2.1 FINANCING

The time required to obtain financing is considered as a significant delay in the recovery process because an amount of money is required to repair buildings. The degree of delay due to financing depends on the method of financing, which can be:

- Private loans (e.g. bank loans);
- Small Business Administration (SBA), which provides billions of dollars of disaster loans to community after hazard events;
- Insurance;
- Pre-arranged credit line.

Delays due to financing, which are listed in Table 7, depend on the financing method and not on the amount of funds needed. Moreover, if different types of funding are used, the largest delay should be considered.

Delays due to financing need to be considered in case that the building damage membership state is greater than or equal to *High*.

Table 7. Delays due to Financing

Financing method	Delays	
	P50	P90
Pre-arranged credit line	1 week	2 weeks
Insurance	6 weeks	25 weeks
Private loan	15 weeks	36 weeks
SBA-backed loans	48 weeks	100 weeks

5.2.2 POST-EARTHQUAKE INSPECTION

After an earthquake event, official inspectors are often required to inspect the potentially damaged buildings.

Delays due to post-earthquake inspection considered in the methodology have been obtained from REDi^{TM} and depend basically on the building use (Table 8). For instance, if the building is an essential facility, inspectors are expected to arrive earlier due to the importance of the building in the community. In addition, it is possible to sign up for programs such as the *Building Occupancy Resumption Program* (BORP) (Mayes et al. 2011) or other equivalents, which can reduced downtime significantly.

Delays due to post-earthquake inspection are considered for every recovery state if the membership of building damage state is higher than *Medium.* Otherwise they are not included as there would be no structural damage.

Table 8. Delays due to Post-Earthquake inspection

Building type	Delays	
	P50	P90
BORP	1 day	2 days
Essential facility	2 days	4 days
Non-essential facility	5 days	10 days

5.2.3 ENGINEER MOBILIZATION

Delays due to engineer mobilization are mostly the time required for finding engineers plus the time needed to carry out engineering review and/or re-design. It depends on the level of structural damage and the size of the building. Such delays are considered in the analysis if the membership of building damage state is *Mediu*m, *High* and/or *Very High* (Table 9). For instance, if the building damage membership is defined as *Medium*, minor structural repairs should be approved by an engineer and structural calculations are not necessary, or if the building damage membership is classified as *High* the building should be re-design due to the high level of the damage. Thus, the time required for engineer mobilization is the time necessary to realize a new building project.

Table 9. Delays due to Engineer mobilization

Building damage state	Delays	
	P50	P90
Medium	6 weeks	10 weeks
High	12 weeks	20 weeks
Very high	50 weeks	75 weeks

5.2.4 CONTRACTOR MOBILIZATION

The time required for mobilizing a contractor after the earthquake event may cause some delays. Different factors contribute to increase delays due to contractor mobilization such as the lack of availability contractors, materials, and equipment after the earthquake event.

Delays due to contractor mobilization are obtained and adapted from REDi^{TM} for essential and non-essential facility that are less than 20 stories, and for buildings greater or equal to 20 stories (Table 10).

Such delays should be considered if the building damage membership is *High* in re-occupancy state, and if the building damage membership is equal to *Medium* in functional recovery.

Table 10. Delays due to Contractor mobilization

Building type	Building damage state	Delays	
		P50	P90
Essential facility, less than 20 stories	Medium	7 weeks	15 weeks
	High	19 weeks	31 weeks
Non-essential facility, less than 20 stories	Medium	7 weeks	15 weeks
	High	23 weeks	39 weeks
Greater or equale to 20 stories	Medium	7 weeks	15 weeks
	High	40 weeks	61 weeks

5.2.5 PERMITTING

Delays due to permitting consider the time needed for the local building jurisdiction to review and approve the proposed repairs (Table 11). The permit approval is necessary before repairs can start and in general, it is given by the local building jurisdiction.

Delays due to permitting are included in the downtime analysis if the membership of building damage state is *High* for re-occupancy and functional recovery states, and/or *Medium* for full recovery state.

Table 11. Delays due to Permitting

Building damage state	Delays	
	P50	P90
Medium	1 week	3 weeks
High	8 weeks	12 weeks

5.3 DOWNTIME DUE TO UTILITIES DISRUPTION

Utilities are likely to be disrupted after an earthquake event of certain intensity. Since utility service is required for functional and full recovery, delays due to utility disruption need to be considered for these recovery states. In the methodology the utilities studied are based on REDi^{TM} guidelines and they are illustrated in Figure 5.4:

- Electricity
- Natural gas
- Water

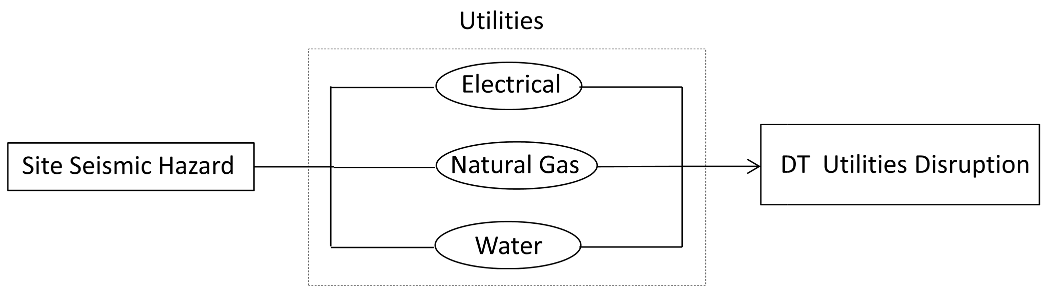

Figure 5.4: Downtime due to *Utilities disruption*

All utility systems are widely distributed geographically, so the systems endure a wide range of seismic intensities and local site effects, and in addition there are several complications that make predictions difficult to achieve, such as the fact that systems are composed of many components, forming a complex network. Due to these limitations, utilities disruption times are defined from data about past earthquakes. As a result of these studies, disruption of utilities should be considered if the membership value of site seismic hazard is greater than or equal to *Medium.* Therefore, utilities disruption is not considered in downtime assessment for the re-occupancy recovery state because this is likely to affect only the buildings functionality.

5.3.1 ELECTRICITY

Electricity systems recover quickly, ranging between 2 and 14 days for a full recovery. They generally perform better than other utility systems because of their high level of redundancy.

In table 12 electricity disruption times are listed for percentiles 50 and 90.

Table 12. Electricity disruption time

Disruption time	
P50	P90
3 days	14 days

5.3.2 NATURAL GAS

Natural gas systems tend to require a longer time for restoration (from 7 to 84 days for full restoration of service). The major cause of disruption for most earthquakes is re-lighting and re-pressurizing the gas services to individual buildings after the gas shut off for safety purpose.

The utility disruption determined by HAZUS is based on the average repair rate of covered distribution pipe, which is an indicator of damage level and also of distribution systems.

In this work, for simplicity, the repair rates are not evaluated and it is determined that disruption time is based on the membership values of the site seismic hazard module. In fact, the site seismic hazard is equivalent to ground deformations. In table 13 natural gas disruption times are presented.

Table 13. Natural gas disruption time

Max. site seismic hazard membership	Disruption time	
	P50	P90
Medium	10 days	36 days

High	42 days	90 days

5.3.3 WATER

Water system disruption time is usually extensive in all earthquakes, ranging from 6 days to 10 weeks for full restoration (Table 14). Eidinger (2012) shows that distribution pipes don’t perform well, in particular the smaller diameter pipes that traverse through liquefaction zones.

The methodology used for determining the water disruption time follows the same criteria of natural gas disruption.

Table 14. Water disruption time

Max. site seismic hazard membership	Disruption time	
	P50	P90
Medium	4 days	8 days
High	21 days	90 days

CHAPTER 6 .

SEISMIC RESILIENCE EVALUATION

This chapter is proposing a development of the methodology in order to evaluate the Seismic Resilience of a given building. A seismic resilience assessment is proposed employing the concepts from fuzzy set theory. The basic resilience parameters, which are Downtime (DT) and Building Damageability (BD), are defined by fuzzy knowledge theory. A simple framework for aggregating the components in a logical way in order to make the system more comprehensive is illustrated. Four steps are used for aggregating the components: creation of linguistic variables, fuzzification, inference, and defuzzification.

6.1 DEFINITION AND MEASURE OF RESILIENCE

Natural and man-disasters have serious impacts upon countries, in terms of number of affected people and in terms of economic damages. Building and communities are often not sufficiently resilient to extreme natural catastrophes, such as earthquakes, tsunamis, hurricanes, etc.; they can't completely prevent every risk but they need to be "*prepared*" and less "*vulnerable*", in order to achieve a high "*resilience*" (Cimellaro 2016). Therefore, building and communities could lead to the reduction of hazardous impacts and enable fast recovery.

The review of existing literature exposes that over the years, many studies are detained on the concept of seismic resilience, also due to an evident progress that has been made in technology. Resilience should measure the ability of a system exposed to hazards to resist extreme events and recover its functionality in a timely and efficient manner (ISDR 2009)-

Resilience (R) can be defined as the capability of the system to sustain the effects ΔQ of extreme event at time t_0 and to recover efficiently the functionality Q_t at time t_f. Based on this definition, Resilience is a function indicating the functionality of a given building and/or system over a period T, as follows:

$$R = \frac{1}{T}\int_{t_0}^{t_0+T} Q(t)\,dt \quad (11)$$

where $Q(t)$ is the functionality function and T is the expected life-time of the system. Moreover, resilience can be defined by a graph, which represents the normalized area below the $Q(t)$ curve (Figure 6.1).

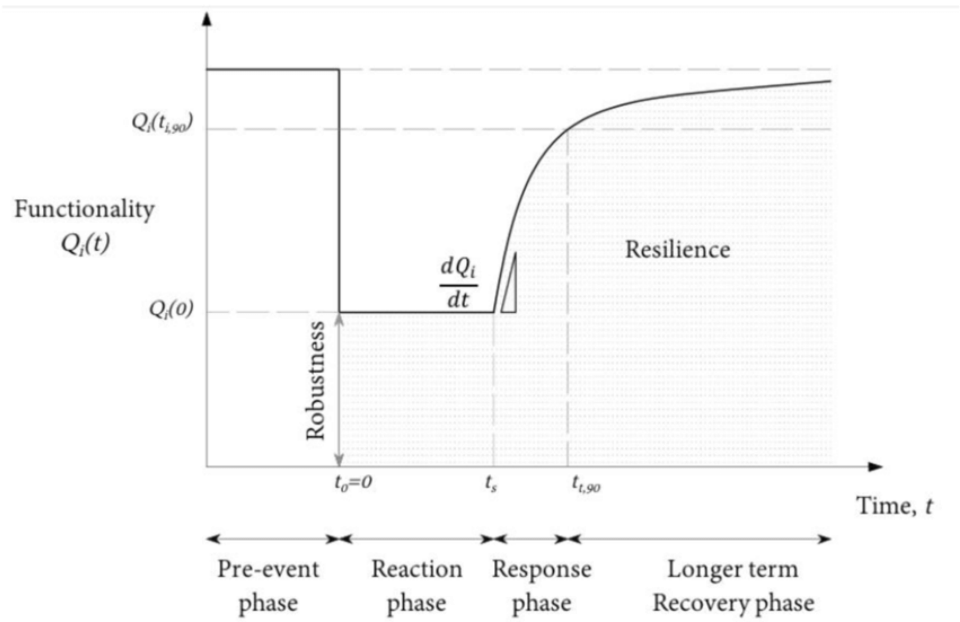

Figure 6.1: Resilience functionality curve

6.2 EVALUATION OF SEISMIC RESILIENCE

Estimation of resilience is performed in different fields, from engineering to economics, and in this context the meaning of seismic resilience can be defined as the ability of engineering and socio-economic systems to rebound after severe events, or disasters, such as earthquakes (Cimellaro et al. 2008).

However, seismic resilience evaluation is traditionally carried out through probabilistic approach, which is not able to treat uncertainties, since resilience concepts is multidimensional and involves complexity and uncertainty. A quantification of the seismic resilience of damaged buildings is based on the assessment of the downtime and on the effects of the deterioration process (the building damage) under uncertainties. To meet this need, a fuzzy logic approach of downtime and building damageability is presented in this thesis. Seismic Resilience of a damaged building is computed through the aggregation of Downtime and Building Damageability into a simple framework, which enables a more systematic analysis of seismic resilience. The framework to estimate seismic resilience of buildings is depicted in Figure 6.2.

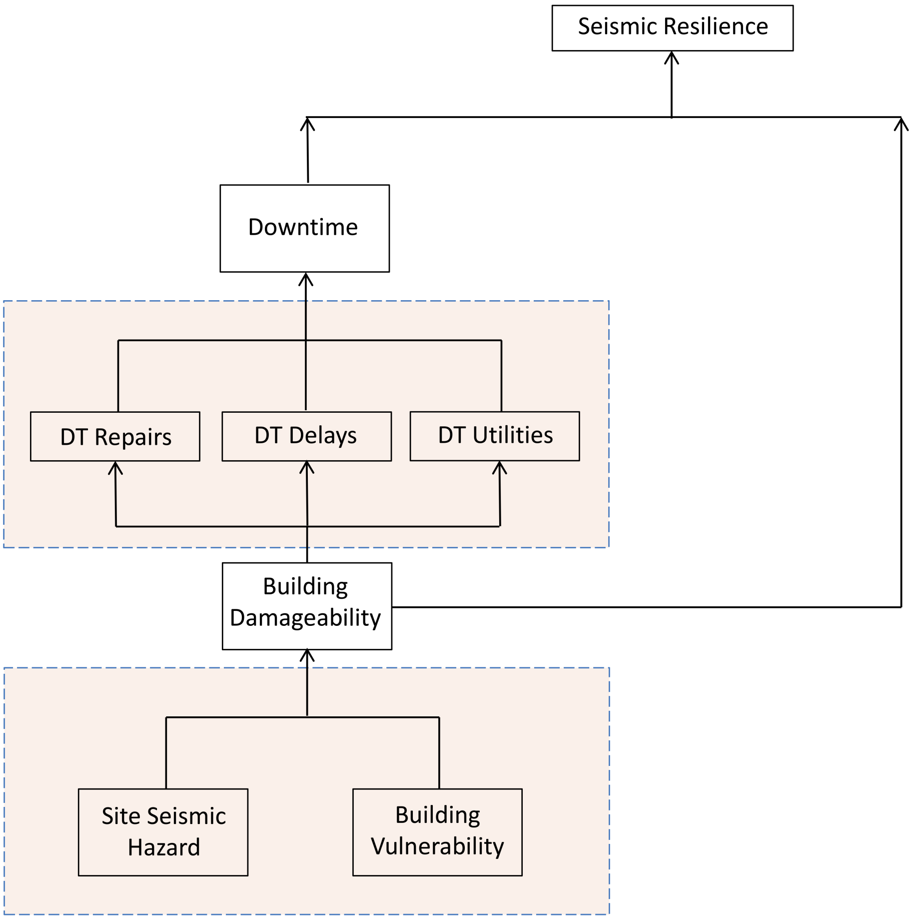

Figure 6.2: The Seismic Resilience framework

The fuzzy logic approach to lifetime assessment of seismic resilience of buildings consists of the following steps:

- Step 1: Creation of linguistic variables

From the previous analysis, the Downtime is computed through the combination between repairs, delays, and utilities disruption that can be determined after calculating the Building Damageability and it is given in terms of days, which correspond to the time required to achieve any recovery state. Thus, it needs to be converted into linguistic terms, as the basic components in the RVS, in order to apply the fuzzy logic.

According to the duration of the time required to repair a damaged building, the Downtime can be classified as *Brief, Average,* and *Long* time.

The transformation values considered in the methodology are 0.2 for *brief* downtime, 0.5 for *average* downtime, and 0.8 for *long* downtime. These values have been adopted from those applied for the basic components in the hierarchical scheme (Figure 4.4).

The building damageability is determined as a membership values by combining the Site Seismic Hazard and Building Vulnerability. As mentioned above, defuzzification is not required for building damageability, as its membership values that are greater than zero are used in the analysis. Therefore, it needs neither to be transformed into qualitative values nor to be fuzzified, but it can be used as a membership in the inference step.

Expert's opinion is used to create these linguistic variables and to define values for membership functions.

- Step 2: Fuzzification

Once the linguistic variables for the Downtime have been set, its fuzzification can be performed.

Fuzzification is the process that converts linguistic variables into fuzzy terms through the fuzzy membership functions and determines the degree of the memberships.

The granulation assigned for the fuzzification consists of five granules (*Very Low, Low, Medium, High, and Very High)* as well as for Building Damageability. The Downtime fuzzification uses triangle fuzzy membership functions, which are an adaptation from Tesfamaraim and Saatcioglu (2008).

The Downtime fuzzy sets are illustrated in Figure 6.3.

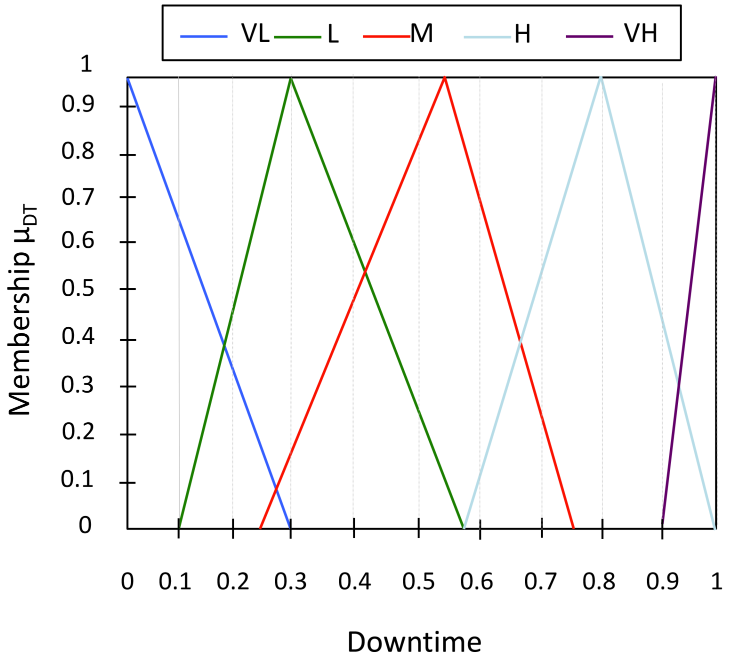

Figure 6.3: Downtime fuzzy sets

- Step 3: Aggregation

The graphical and interpolation method is used for defining the fuzzy base rules. As illustrated before, it consists of a weighting factor assigned to each input, which represents the impact of the input towards the output. Thus, interpolating the weights of the inputs one can then identifies the output.

The fuzzy base rules are listed in Table 15 containing twenty-five rules due to the wide granulation and are aggregated through Mandami's inference system using a simple IF-THEN fuzzy rule. The Downtime is a key aspect of resilience and it is identified as a dynamic process, which increases and returns the functionality of a system. That is why the Downtime has a higher weight than the Building Damageability.

Table 15. Fuzzy rule for Seismic Resilience

Rule	*DT W=2*	*BD W=1*	*R*
1	VL	VL	VL
2	VL	L	VL
3	VL	M	L
4	VL	H	L
5	VL	VH	L
6	L	VL	L
7	L	L	L
8	L	M	L
9	L	H	M
10	L	VH	M
11	M	VL	L
12	M	L	M
13	M	M	M
14	M	H	M
15	M	VH	H
16	H	VL	M
17	H	L	M
18	H	M	H
19	H	H	H
20	H	VH	H
21	VH	VL	H
22	VH	L	H
23	VH	M	H
24	VH	H	VH
25	VH	VH	VH

- Step 4: Defuzzification

Seismic Resilience index (I^R) is evaluated by the defuzzification process. Defuzzification is the opposite process of fuzzification. That is, it converts a fuzzy quantity to a precise crisp result.

Defuzzification process uses the weighted average method introduced above by applying the formulation (6), in which the quality-ordered weights are used. The weights indices are adopted from those introduced by (Tesfamariam and Saatcioglu 2008) in the downtime analysis and they are:

$$\text{For } \mathrm{R}_3 \; q_i = (i = 1,2,3,4) = (0.25, 0.5, 0.75, 1) \quad (12)$$

CHAPTER 7 .

ILLUSTRATIVE EXAMPLE

In this chapter, a case study illustrating the downtime and resilience estimation method is provided. A hypothetical three-story residential building is investigated in the case study. The Northridge earthquake scenario is described in order to individualize the dangerousness of the event, the damages that it caused, and beside to define what the post-earthquake recovery activity has been set. Finally, a simple MATLAB® and Simulink are used to implement the fuzzy system and to analyze the importance and the relationship of different indicators in the analysis. Finally, the chapter performs a sensitivity analysis in order to obtain the indicator degree of importance on the building damageability.

7.1 INTRODUCTION TO THE CASE STUDY

The case study consists of a hypothetical three-story residential building with floor area A= 4800 sq. ft. per floor, structural system SS = C1, and fundamental period T_1 = 0.38s. The 1994 Northridge Earthquake has been selected as the hazard event. From the walk down survey (RVS), information about the analyzed building has been collected and presented in Table 16. In addition, from the response spectrum of the 1994 Northridge Earthquake, the spectral acceleration S_a has been identified as 0.50g. In the following, the downtime and resilience estimation procedure is illustrated in detail.

7.2 THE NORTHRIDGE EARTHQUAKE SCENARIO

The earthquake that hit Northridge on January 17, 1994 is considered as the most damaging earthquake in the history of the United States. The magnitude 6.7 earthquake

Northridge occurred on a fault under the San Ferdinando Valley and extended under the Santa Susana Mountains (Stein 1994). The 1994 Northridge shake map is illustrated in Figure 7.1.

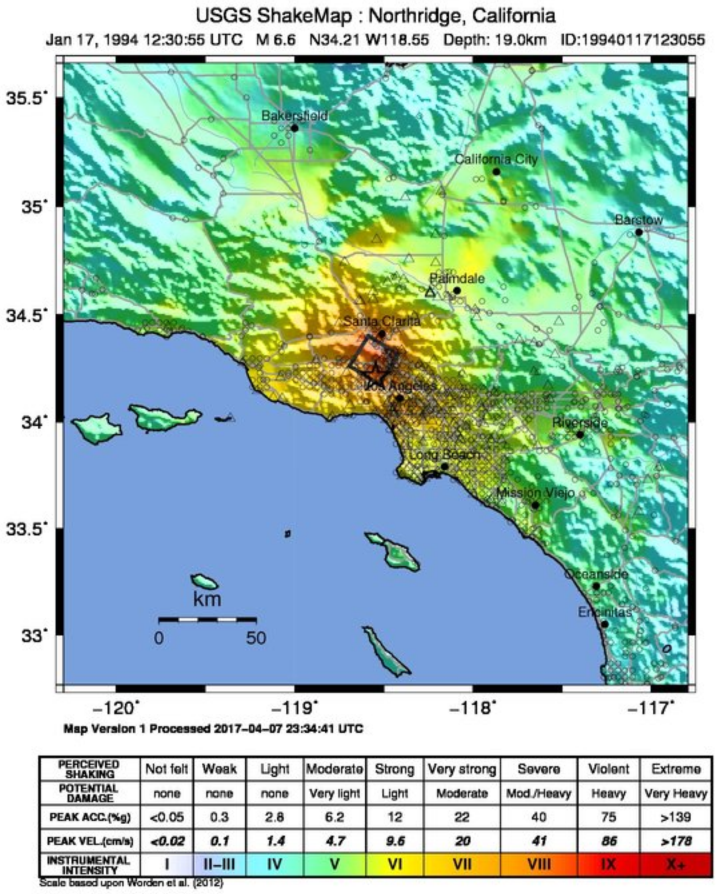

Figure 7.1: The Northrdige earthquake shake map from USGS

Preliminary data on the emergency response and on the social impacts of the Northridge earthquake highlights that structural failure was the underlying cause of facilities directly assigned to the earthquake.

The earthquake caused significant damages to health facilities, in particular non-structural damage to pipes and other utilities. For example, the damage of a rooftop water tank induced the evacuation of a psychiatric hospital, and other facilities were left without water or power (Comerio and Blecher 2010).

Data from the Association of Bay Area Governments (ABAG) and from Assessor for the Northridge-affected areas (Los Angeles city, Los Angeles County and the City of Santa Monaca) estimated the status of residential building damaged by the Northridge earthquake as repaired, demolished or rebuilt. The building evaluation was carried out with a red (unsafe for re-occupancy or entry) and yellow (limited entry) indicator. Such data estimated that 3127 residential buildings were repaired, 126 were demolished, and 378 were rebuilt.

Later around three weeks from the seismic event, FEMA received applications for assistance through the Disaster Housing Program, the Small Business Administration (SBA), which provide housing assistance and, if it is necessary, funds for temporary housing.

The Northridge earthquake illustrates that the post-disaster recovery activity started almost immediately after the hazard event. The high-priority activities included: providing water to areas where that utility was damaged; developing an alternative transportation system to reduce congestion; and making plans to deal with the school-system disruption (Tierney et al. 1995).

Real data for damaged structural and non-structural components are not available, unfortunately. Thus, in the illustrative case study, unreal information on damaged components has been used.

7.3 DAMAGE ESTIMATION

7.3.1 STEP 1: TRANSFORMATION

The first step is to transform the basic risk items into a comparable number, which are mainly based on expert knowledge. In particular, the transformation values for VI, PI and, CQ are calibrated for the 1994 Northridge Earthquake damage database (Tesfamariam and Saatcioglu 2008). The transformation values are listed in Table 16.

Table 16. Basic risk items and trasformation

Basik risk item	Field observation	Transfomation
Structural system (SS)	C1	0.70
Vertical irregularity (VI)	Yes	0.80
Plan irregularity (PI)	Yes	0.80
Contruction quality (CQ)	Poor	0.99
Year of construction (YC)	1960	-0,01*YC+20,25

7.3.2 STEP 2: FUZZIFICATION

Fuzzification is the conversion of input values into corresponding membership with respect of their granulation. That is, after selecting a transformation value for each parameter (Table 16), one can enter into corresponding fuzzy sets graph and obtain the degree of membership for each parameter. The results are presented in Table 17.

Table 17. Fuzzification process

Basic risk items	Fuzzification
Vertical irregularity	$(\mu_L^{VI}, \mu_M^{VI}, \mu_H^{VI}) = (0, 0.40, 0.60)$
Plan irregularity	$(\mu_L^{VI}, \mu_M^{VI}, \mu_H^{VI}) = (0, 0.40, 0.60)$
Construction quality	$(\mu_L^{CQ}, \mu_M^{CQ}, \mu_H^{CQ}) = (0, 0.01, 0.99)$
Year of construction	$(\mu_L^{YQ}, \mu_M^{YQ}, \mu_H^{YQ}) = (0, 0.60, 0.40)$
Structural system	$(\mu_L^{SS}, \mu_M^{SS}, \mu_H^{SS}) = (0, 0.50, 0.50)$
Site seismic hazard	$(\mu_{VL}^{SSH}, \mu_L^{SSH}, \mu_M^{SSH}, \mu_H^{SSH}, \mu_{VH}^{SSH}) = (0, 0.50, 0.50, 0, 0)$

7.3.3 STEP 3: INFERENCE

Mamdani's inference system is performed through the hierarchical scheme (Figure 4.4). It is implemented using a bottom up approach, starting with R_1 and R_2 till

R_5. An example of inference for the Increase-in-Demand index (I^{ID}) is given in this section. The inference of other indices is done in a similar fashion.

As mentioned before, the *Increase in demand* index (I^{ID}) is the combination of vertical and plan irregularities. Using the fuzzy rule base, I^{ID} is computed to be:

$$ID = \begin{array}{l} \mu_L^{ID} = max(min(0,0),min(0,0.40)) = 0 \\ \mu_M^{ID} = max(min(0,0.60),min(0.40,0),min(0.40,0.40),min(0.40,0.60),min(0.60,0)) = 0.4 \\ \mu_H^{ID} = max(min(0.60,0.40),min(0.60,0.60)) = 0.60 \end{array} \quad (13)$$

7.3.4 STEP 4: DEFUZZIFICATION

Defuzzification is the inverse process of fuzzification, which converts fuzzy output into a crisp number.

Using the previously introduced quality-ordered weights factors, q_i *(i=1,2,3) = [0.25, 0.5, 1]*, the I^{ID} is defuzzified as follows:

$$ID = \sum_{i=1}^{n} q_i \cdot \mu_i = 0.25 \times 0 + 0.5 \times 0.4 + 1 \times 0.6 = 0.80 \quad (14)$$

Defuzzification of other indexes is given in Table 18.

Table 18. Defuzzification process

Index	Inference/Aggregation	Defuzzification
I^{DR}	(R2)= YC + CQ	0.77
I^{SD}	(R3)= I^{ID} + I^{DR}	0.63
I^{BV}	(R4)= I^{SD} + I^{SS}	0.54

For the Building Damageability index (I^{BD}), defuzzification is not performed because the membership values are used in the subsequent analysis (i.e., components repair time evaluation), as we mentioned before.

The membership of I^{BD} is given through inferencing the *Site seismic hazard* index (I^{SSH}) and the *Building vulnerability* index (I^{BV}) as:

$$(\mu_{VL}^{BD}, \mu_{L}^{BD}, \mu_{M}^{BD}, \mu_{H}^{BD}, \mu_{VH}^{BD}) = (0, \mathbf{0.35}, \mathbf{0.65}, 0, 0)$$

Since the memberships that are greater than zero are associated with μ_L^{BD} (0.35) and μ_M^{BD} (0.65), the downtime analysis for I^{BD} = *Low* and I^{BD} = *Medium* is carried out. According to the membership degrees results, the downtime is quantified for re-occupancy recovery state.

7.4 DOWNTIME DUE TO REPAIRS

In this example, the main interest is in calculating the 'best-estimate' repair times, so the median values (50th percentile, 50% probability of non-exceedance) are used. PACT provides the necessary repair time for each type of damaged component in terms of 'worker-days'. The process for obtaining this information is presented in Table 19 and Table 20, where repair times for building components related to *Low* and *Medium* damage state, organized by repair sequence, are summarized.

Once component repair times are known, they are defuzzified with the corresponding membership degrees of the building damage state (in the case study 0.35 and 0.65), using Eq. (9).

Table 19. Component repair times and worker days for *Low* damage

Floor	Repair	Component type	Worker-days per unit or area	EA or SF	Total worker-days	Defuzzification
Floor 1	Structural repairs	Concrete beam	22.758	2 units	45.5	15.93
		Link beams < 16"	17.358	1 units	17.358	6.08
	Repair sequence A	Interior partitions	5	215.3sq.ft	1076.4	376.74
		Ceiling	17	30sq.ft	510	178.50
	Repair sequence B	Exterior partitions	32	20sq.ft	640	224
	Repair sequence D	Transformer < 100 kVA	1.818	1 unit	1.818	0.64
		Low voltage switchgear	2.226	1 unit	2.226	0.78
	Repair sequence F	Stairs	13.965	4 units	55.86	19.55
Floor 2	Structural repairs	Concrete beam	22.758	1 unit	22.758	7.97
		Link beams < 16"	17.358	1 unit	17.358	6.08
	Repair sequence A	Interior partitions	5	220sq.ft	1100	385
		Ceiling	17	10sq.ft	170	59.5
	Repair sequence B	Exterior partitions	32	5sq.ft	160	56
	Repair sequence D	Transformer < 100 kVA	1.818	1 unit	1.818	0.64
		Low voltage switchgear	2.226	1 unit	2.226	0.78
	Repair sequence F	Stairs	13.965	4 units	55.86	19.55
Floor 3	Structural repairs	Concrete beam	22.758	3 units	68.27	23.89
	Repair sequence A	Interior partitions	5	190sq.ft	950	332.5
		Ceiling	17	15sq.ft	255	89.25
	Repair sequence D	Transformer < 100 kVA	1.818	1 unit	1.818	0.64
		Low voltage switchgear	2.226	1 unit	2.226	0.78
	Repair sequence F	Stairs	13.965	4 units	55.86	19.55
Roof	Repair sequence C	Chiller	11.088	1 unit	11.088	3.88

Table 20. Component repari times and worker days for *Medium* damage

Floor	Repair	Component type	Worker-days per unit or area	EA or SF	Total worker-days	Defuzzification
Floor 1	Structural repairs	Concrete beam	22.758	2 units	45.5	29.58
		Link beams < 16"	17.358	1 unit	17.358	11.28
	Repair sequence A	Interior partitions	5	215.3sq.ft	1076.4	699.66
		Ceiling	17	30sq.ft	510	331.50
	Repair sequence B	Exterior partitions	32	20sq.ft	640	416
	Repair sequence D	Transformer < 100 kVA	1.818	1 unit	1.818	1.18
		Low voltage switchgear	2.226	1 unit	2.226	1.45
	Repair sequence F	Stairs	13.965	4 units	55.86	36.31
Floor 2	Structural repairs	Concrete beam	22.758	1 unit	22.758	14.79
		Link beams < 16"	17.358	1 unit	17.358	11.28
	Repair sequence A	Interior partitions	5	220sq.ft	1100	715
		Ceiling	17	10sq.ft	170	110.5
	Repair sequence B	Exterior partitions	32	5sq.ft	160	104
	Repair sequence D	Transformer < 100 kVA	1.818	1 unit	1.818	1.18
		Low voltage switchgear	2.226	1 unit	2.226	1.45
	Repair sequence F	Stairs	13.965	4 units	55.86	36.31
Floor 3	Structural repairs	Concrete beam	22.758	3 units	68.27	44.38
	Repair sequence A	Interior partitions	5	190sq.ft	950	617.5
		Ceiling	17	15sq.ft	255	165.75
	Repair sequence D	Transformer < 100 kVA	1.818	1 unit	1.818	1.18
		Low voltage switchgear	2.226	1 unit	2.226	1.45
	Repair sequence F	Stairs	13.965	4 units	55.86	36.31
Roof	Repair sequence C	Chiller	11.088	1 unit	11.088	7.21

7.4.1 STRUCTURAL REPAIRS

Low and *Medium* building damage states implies that the structural components can be repaired in parallel. Considering that the floor area is the same at all floors, the number of workers allocated to each floor is:

$$n.of\ workers=(4800sq.ft)(1worker/(500sq.ft))=10\,workers \quad (15)$$

Equation (10) shows that the maximum number of workers that are allowed to perform structural repairs at any time is 22 workers. Thus, the number of workers computed in Eq. (15) is considered acceptable because it is less than the maximum number allowed. Summing the number of defuzzified 'worker-days' related to structural components at floor 1, floor 2 and floor 3 and dividing by the number of workers defined using Eq. (15), one can obtain the days required for structural repairs. The results are 2.2, 1.4, and 2.4 days, respectively for the *Low* damage analysis. Instead, the results are 4, 2.6, and 4.4 day, respectively for *Medium* damage analysis. Thus, all the floors can be repaired in parallel in around 2.4 days (*Low* damage) and 4.4 days (*Medium* damage).

7.4.2 NON-STRUCTURAL REPAIRS

Non-structural repairs can begin after all structural repairs are complete. Repair sequences considered in the case study are Repair Sequence A, B, C, D, and F and they are summarized in Table 21, in which the number of workers per floor and the corresponding maximum number of workers allowed are presented.

Table 21. Number of workers for non-structural repairs

Repair Sequence	Number of workers per floor	Max number of worker per component type
Repair Sequence A	#workers = (4800sq.ft) (1worker/1000sq.ft) = 5 workers	15
Repair Sequence B	#workers = (4800sq.ft) (1worker/1000sq.ft) = 5 workers	15
Repair Sequence C	#workers = (1 damaged unit) (3 workers/damaged unit) = 3 workers	9
Repair Sequence D	#workers = (1 damaged unit) (3 workers/damaged unit) = 2 workers	9
Repair Sequence F	#workers = (4 damaged unit) (2 workers/damaged unit) = 8 workers	6

Repair sequence F has a larger number of workers per floor than the maximum allowed per Repair sequence. Thus, the number of workers is limited to 6 workers for Repair Sequence F. The repair time for each repair sequence is calculated by summing their respective worker-days and dividing by the number of workers assigned to that repair sequence (Table 22 and Table 23).

Table 22. Repair time for each Repair Sequence for *Low* damage

Floor 1	Repair sequence A	RT = (555.34 worker days) /5 workes = 111.05 days
	Repair sequence B	RT = (224 worker days) /5 workes = 45 days
	Repair sequence D	RT = (1.42 worker days) /2 workes = 0.71 day
	Repair sequence F	RT = (19.55 worker days) /6 workes = 2.76 days
Floor 2	Repair sequence A	RT = (444.5 worker days) /5 workes = 88.9 days
	Repair sequence B	RT = (56 worker days) /5 workes = 11.2 days
	Repair sequence D	RT = (1.42 worker days) /2 workes = 0.71 day
	Repair sequence F	RT = (19.55 worker days) /6 workes = 2.76 days
Floor 3	Repair sequence A	RT = (421.75 worker days) /5 workes = 84.4 days
	Repair sequence D	RT = (1.42 worker days) /2 workes =0.71 day

	Repair sequence F	RT = (19.55 worker days) /6 workes = 2.76 days
Roof	Repair sequence C	RT = (3.88 worker days) /3 workes = 1.3 days

Table 23. Repair time for each Repair Sequence for *Medium* damage

Floor 1	Repair sequence A	RT = (1031.16 worker days) /5 workes = 206.23 days
	Repair sequence B	RT = (416 worker days) /5 workes = 83.2 days
	Repair sequence D	RT = (2.63 worker days) /2 workes = 1.31 day
	Repair sequence F	RT = (36.31 worker days) /6 workes = 6.05 days
Floor 2	Repair sequence A	RT = (825.5 worker days) /5 workes = 165.1 days
	Repair sequence B	RT = (104 worker days) /5 workes = 20.8 days
	Repair sequence D	RT = (2.63 worker days) /2 workes = 1.31 day
	Repair sequence F	RT = (36.31 worker days) /6 workes = 6.05 days
Floor 3	Repair sequence A	RT = (783.25 worker days) /5 workes = 156.65 days
	Repair sequence D	RT = (2.64 worker days) /2 workes =1.31 day
	Repair sequence F	RT = (36.31 worker days) /6 workes = 6.05 days
Roof	Repair sequence C	RT = (7.21 worker days) /3 workes = 2.40 days

7.5 DOWNTIME DUE TO DELAYS

The downtime analysis due to delays is carried out only for the *Medium* damage. That is, delays can increase the downtime if the building damage is greater than *Low*, otherwise irrational components don't influence the result. Delays considered are: post-earthquake inspection and engineer mobilization (Table 24)

Table 24. Delays

Post-earthquake	Engineer mobilization

inspection			
Building type	Delays P50	Max buil. damage	Delays P50
BORP	1 days	Medium	6 weeks

Delays due to post-earthquake hazard inspection depend basically on building use. Owners can sign up for a Building Occupancy Resumption Program (BORP) (Mayes et al. 2011) or equivalents. In this case, delay is reduced due the presence of prearrangement and there is no necessity of official city-inspectors. Repair of minor structural damage would likely require an engineer to stamp and approve the proposed repair strategy, but not necessary perform any structural calculations. This may take some time for the engineer to review the damage.

7.6 DOWNTIME DUE TO UTILITIES DISRUPTION

Utilities disruption is not considered in downtime assessment for re-occupancy recovery state because this only affects building functionality.

7.7 TOTAL REPAIR TIME

As mentioned before, in the re-occupancy recovery state downtime calculation is carried out through the sum of DT repairs and DT delays, as follows:

$$\begin{aligned} &DT(damage{=}Low){=}DTrepairs{+}DTdelays = 284.3 + 0 = 284.3\ days \\ &DT(damage{=}Medium){=}DTrepairs{+}DTdelays = 527.98 + 43 = 571\ days \end{aligned} \tag{16}$$

Once the downtimes for each damage state have been calculated, the final results can be weighted with the damage membership values defined above, as follows:

$$DT = \sum_{i=1}^{n} DT_i * \mu_i = (284.3 * 0.35) + (571 * 0.65) = 470.6\ days \tag{17}$$

Equation (17) shows that the final downtime of the residential building is around 470.6 days.

Repair schedules help to identify the repairs that control the total repair time (Figure 7.2, Figure 7.3). In the figures, the x-axis represents the days needed to complete repairs, while the y-axis is the floor at which repairs are conducted. DT repairs is obtained assuming that repair sequence A controls the overall repair duration, as shown in the repair schedule. The other repair sequences can be organized in different ways with no impact on downtime (Almufti and Willford 2013).

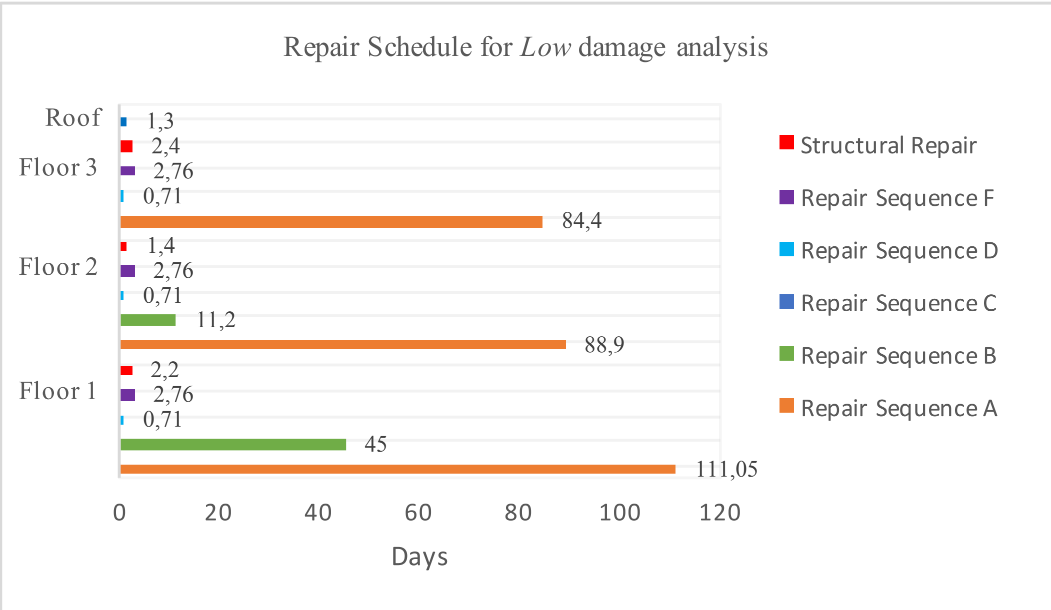

Figure 7.2: Repair schedule for *Low* damage analysis

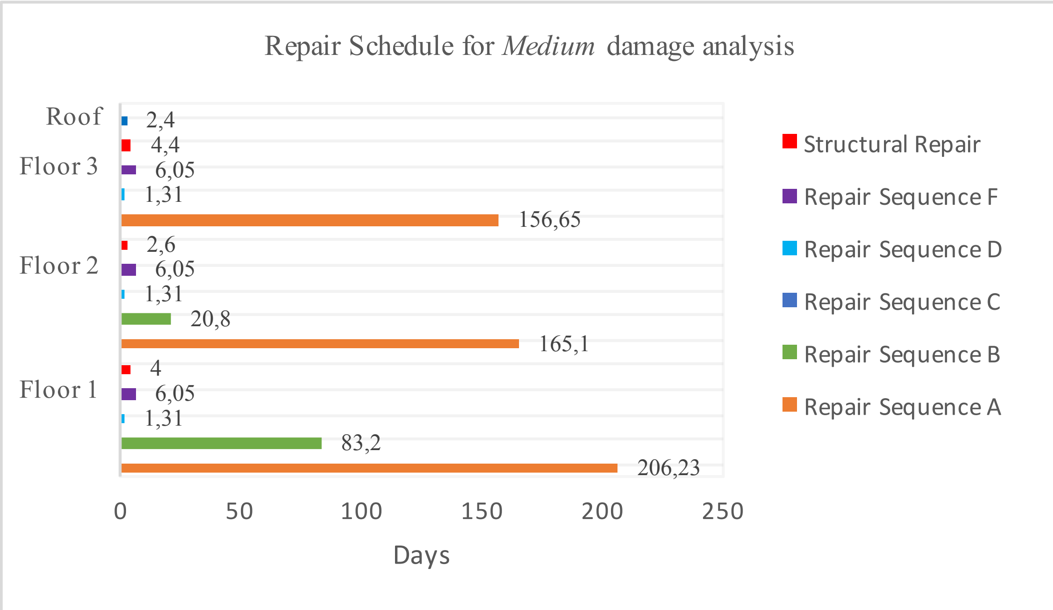

Figure 7.3: Repair schedule for *Medium* damage analysis

7.8 SEISMIC RESILIENCE ESTIMATION

7.8.1 STEP 1: TRANSFORMATION

The first step is to transform the Downtime into a comparable number, which is mainly based on expert knowledge.

The downtime resulted from the previous analysis is about 471 days, thus it can be classified as *Average* total repair time. Its transformation value is 0.5.

7.8.2 STEP 2: FUZZIFICATION

The second step is to fuzzify the transformed value using its corresponding graph (Figure 6.3) in order to obtain the membership values with the respect of the assigned granularity.

The membership function of downtime is the following:

$$(\mu_{VL}^{DT}, \mu_L^{DT}, \mu_M^{DT}, \mu_H^{DT}, \mu_{VH}^{DT}) = (0, 0.25, 1, 0, 0)$$

The building damageability membership function, which has been obtain from inferencing the site seismic hazard and the building vulnerability, is given:

$$(\mu_{VL}^{BD}, \mu_L^{BD}, \mu_M^{BD}, \mu_H^{BD}, \mu_{VH}^{BD}) = (0, 0.35, 0.65, 0, 0)$$

7.8.3 STEP 3: INFERENCE

Mandami's inference system is performed through the scheme illustrated in Figure 6.2, in which the seismic resilience index (I^R) is the combination of the Downtime and the Building Damageability. Using the fuzzy rule base listed in Table 15, the I^R is computed to be:

$$I^R = (\mu_{VL}^{R}, \mu_L^{R}, \mu_M^{R}, \mu_H^{R}, \mu_{VH}^{R}) = (0, 0.20, 0.65, 0, 0)$$

7.8.4 STEP 4: DEFUZZIFICATION

The resilience index I^R can be defuzzified using the quality-ordered weights factors $q_{VL} = 0$, $q_L = 0.25$, $q_M = 0.5$, $q_H = 0.75$, and $q_{VH} = 1$, as follows:

$$I^R = \sum_{i=1}^{n} q_i * \mu_i = 0*0 + 0.25*0.20 + 0.5*0.65 + 0.75*0 + 1*0 = 0.38 \quad (18)$$

Note that weights factors using in resilience defuzzification are adapted to those used by (Tesfamariam and Saatcioglu 2008).

7.9 MATLAB IMPLEMENTATION

To build the fuzzy logic system applied in the case study, it is interesting the use of Matlab Fuzzy Logic Toolbox and Simulink® software. Simulators are common in many fields of engineering, such as electronic and network communication.

The system is built using the Graphical User Interface (GUI) tools provided by the Fuzzy Logic Toolbox, as it is easier than the command line. The graphical interface consists of five primary GUI tools that are dynamically linked for building, editing, and observing fuzzy inference systems: Fuzzy Inference System Editor (FIS), Membership Function Editor, Rule Editor, Rule Viewer, and Surface Viewer. The Membership Function Editor defines the shapes of the membership functions associated with each variable; the Rule Editor is used for editing the fuzzy rules of the system; the Rule Viewer displays the fuzzy inference diagram and it can show how a single membership function shape influences the results. Finally, the Surface Viewer takes into account the dependency of the output on the inputs – that is, it can generate and plot an output surface map for the fuzzy system. The system is defined through the Fuzzy Logic Controller (FLC), which analyzes and simulates complex system behaviors using simple logic rules in a Fuzzy Inference System. The advantage of FLC is the simplicity to design and build a complex system without knowing the mathematical model of the system.

Mamdani Fuzzy Logic controller is designed in Matlab through the Fuzzy Inference System, which consists of two inputs and one output (Figure 7.4). FLC uses the triangular membership functions, which have been illustrated above. Moreover, the fuzzy rules carried out through the graphical interpolation method are edited in the Rule Editor. Finally, Table 25 shows the methods used in fuzzification and defuzzification process, which is the default setup in Matlab.

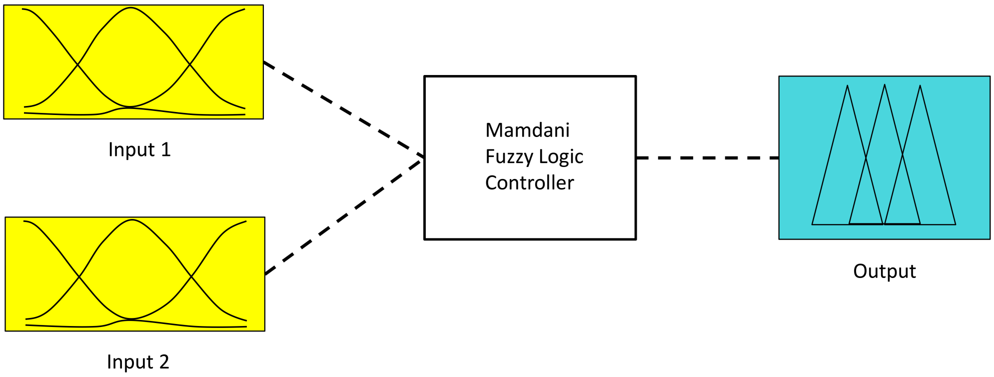

Figure 7.4: Mamdani Fuzzy Logic Controller (FLC)

Table 25. Mamdani Fuzzy Logic Controller

And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

Simulink® is a block diagram environment for multi domain simulation. It is integrated with MATLAB® and simulates a fuzzy inference system with the use of a graphical editor in easier and faster way (Sivanandam et al. 2007). Furthermore, Simulink® system is the most popular simulator tool for designing systems since it can be converted into different program languages. Simulink® represents a system as a collection of blocks, which are used for modeling, simulating or testing some systems. Figure 7.5 shows the simple case study model, in which the blocks used are listed below:

- Sources: provide an input;
- Fuzzy Logic Controller: evaluates the Fuzzy Inference System (FIS) for a given set of inputs and generates the corresponding output;
- Bus creator: creates a signal from its inputs;

* Display: provides a numeric output.

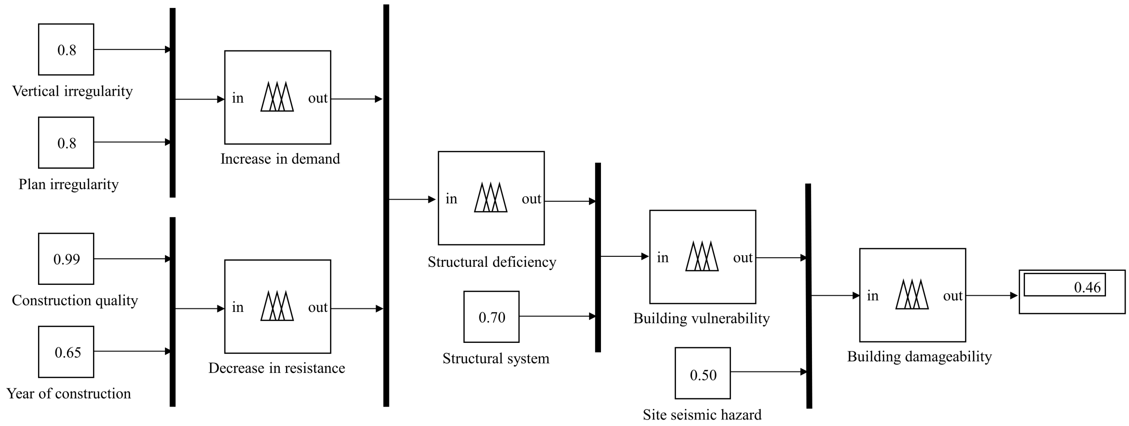

Figure 7.5: Simulink model

After modeling each level of the system and ensuring that the combination between each block is correct, the Simulink model is then run through the Run tool in order to obtain the building damageability index.

The I^{BD} index (0.46) evaluated through the Simulink® implementation must be fuzzified in order to obtain the building damage membership through the corresponding graph shows in Figure 6.3.

7.10 SENSITIVITY ANALYSIS

All parameters in the methodology have not the same level of importance. It is clear that their importance is not equally weight in the downtime and resilience evaluation.

This section aims to realize a sensitivity analysis on the parameters that are combined in the hierarchical scheme through the Simulink framework (Figure 7.5), in which the Building Damageability is the output. In particular, the components that are analyzed are: Vertical Irregularity (VI), Plan irregularity (PI), Construction Quality (CQ), Year of Construction (YC), Structural System (SS), and Site Seismic Hazard (SSH). The reason is that the basic components are the direct inputs of the network and they are not resulted from the Fuzzy Inference System (FIS). Two main possible scenarios are analyzed:

1. The presence of irregularities;
2. The absence of irregularities;

Parameters can be fixed and changed within the two main scenarios through the simulations of the framework in Simulink®.

It can be observed that, as expected, for a building with poor Construction Quality and YC= 1960 (moderate code), with the presence of both irregularities, the building damageability increases. Instead, the absence of irregularities makes the building damage decreased. Moreover, the Vertical Irregularity (VI) shows a slightly higher impact than the Plan Irregularity (PI), whose only presence shows no difference from the presence of only VI. One interesting point is the impact of VI and PI towards the Increase in Demand output in the Rule Viewer of the Fuzzy Logic Toolbox. Figure 7.6, Figure 7.7 show that if VI shifts towards high values, the Increase in Demand output increases, instead the presence of only PI has no impact on the output, which seems to be constant.

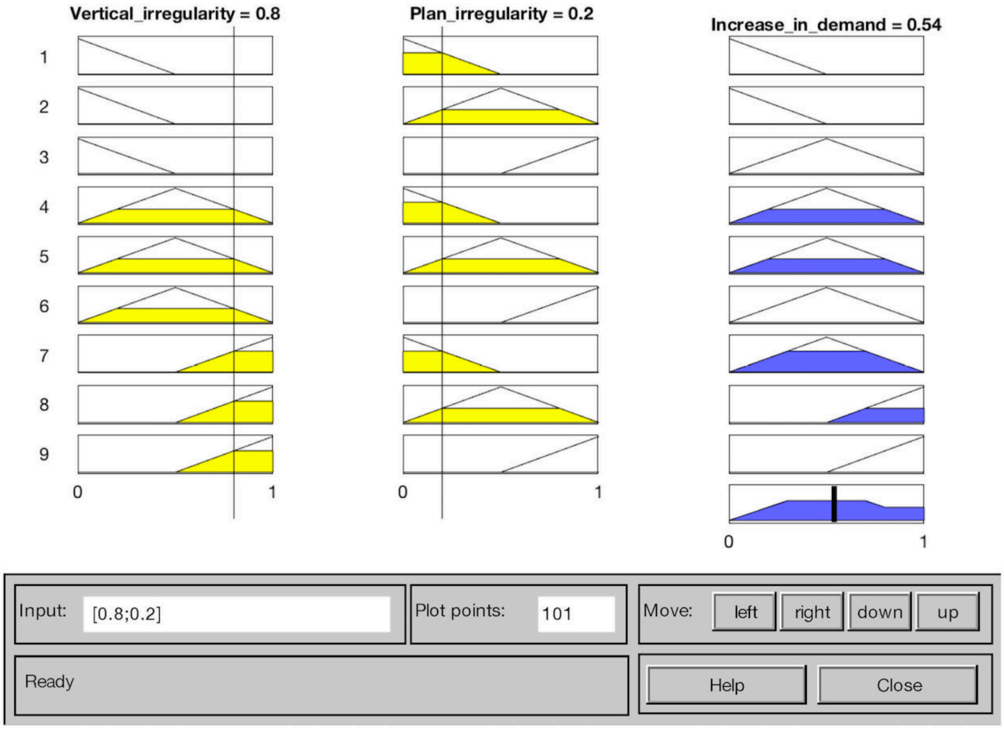

Figure 7.6: Presence of only Vertical Irregularity

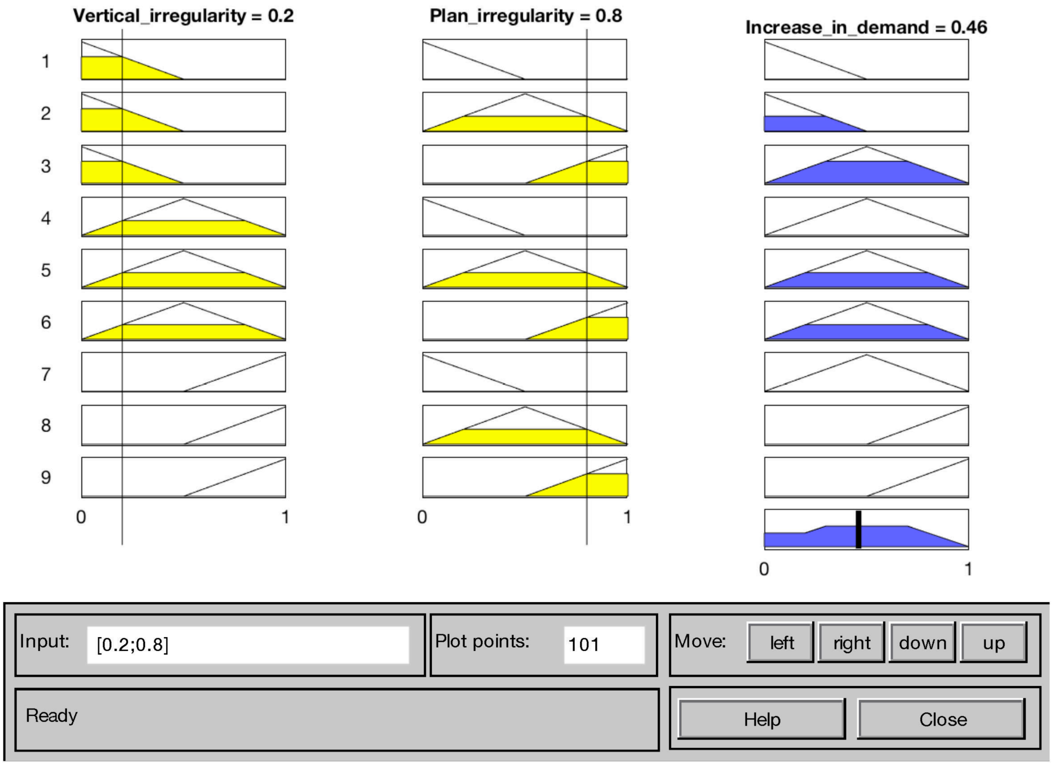

Figure 7.7: Presence of only Plan Irregularity

For a building with poor Construction Quality, YC=1940 (low code), and the presence of irregularities, the Building Damageability rises highly (BD= 0.70) that it can be considered as the worst possible scenario. Quite the opposite, a building with a good Construction Quality, YC= 1980 (high quality), and the absence of irregularities shows a lower damage level of about 0.35 (the best scenario). However, Construction Quality dominates the building damageability value compared to Year of Construction in both scenarios. The building type has a lower impact towards the building damageability. However, it is simulated in scenario 1 (presence of irregularities) and in scenario 2 (no irregularities). Results show that shear walls work better than other building types; that is, a shear walls building type is affected by lower damages.

Finally, as it is expected, an increase in Site Seismic Hazard makes the building damageability value higher, especially in the worst scenario.

An illustrative example of the worst and best scenarios is shown in Figure 7.8, where it is evident the difference between the two damage values in two scenarios.

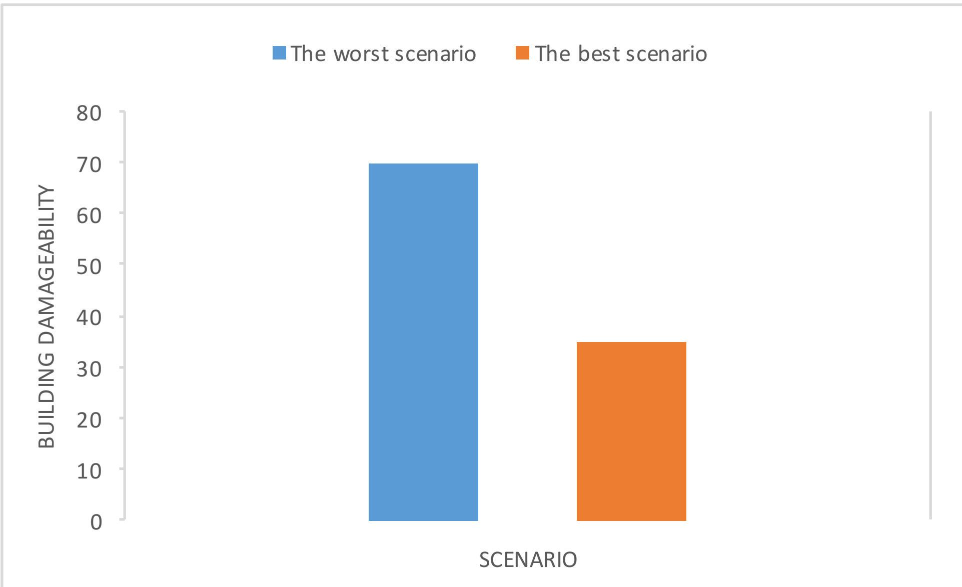

Figure 7.8: Building damage in function of the worst and best scenario

CHAPTER 8 .

CONCLUSION

8.1 CONTRIBUTIONS

The current research has presented a new methodology for quantifying the Downtime and, consequently the Resilience of residential buildings following earthquake events for the decision-making process preparedness. In the downtime and resilience evaluation, the decision-making framework it is a highly uncertain process since it requires complex analysis of parameters that have contributed to different types of uncertainties. It includes building irregularities (topography), construction quality and the relationship between the building damage and the seismic hazards.

In order to have a simple method for predicting the Downtime and the Resilience for building structures after earthquakes in cases with high-uncertainties, the thesis proposes and builds a new methodology for three recovery states (e.g. re-occupancy, functional and full recovery), in which the Fuzzy logic is applied to overcome the aforementioned uncertainties. Compared to the traditional probabilistic methodologies, the advantage of the use of the Fuzzy in the downtime and resilience process is that: it is simpler and faster for quick assessment and decision-making; it deals with imprecise and fuzzy data, which includes linguistic parameters; it can provide a downtime and resilience evaluation of buildings under different hazards.

The methodology can be divided in five main areas: quantification of Building Damage, evaluation of repairs (rational components), delays (irrational components), and utilities disruption, and measure of Resilience parameter. The structural and non-structural components included in the downtime evaluation were selected and modified from PACT (FEMA 2012), and they are referred to three (structural components) and five (non-structural components) damage states. Delays before construction, such as

Financing and Engineer mobilization contribute significantly to the total repair time after a disastrous event. That is, irrational components increase the total downtime. Thus, the Downtime is variable in each recovery state because of different parameters are analyzed.

A repair schedule, showed in the case study section, is used to estimate the component repair times of the damaged building. It is evident that non-structural components conditioned the results, as they control the overall repair time.

The implementation of the building damage system in MATLAB Fuzzy Logic Toolbox and Simulink, describe in chapter 7, was necessary to realize a sensitivity analysis of the system.

8.2 LIMITATIONS OF RESEARCH

The goal of the presented research has been to develop a new methodology for downtime and resilience analysis. In pursuit of this goal, different implications were taken, that although acceptable for this work, may be improved upon in future. These limitations are described:

- Some simplifications were taken in the building structure selection. In the methodology only three building structural types are considered: moment resisting frames, moment resisting frames with masonry walls, and shear walls;

- Existing data base for component repair times and delays used in the methodology, is limited to the U.S.A;

- The methodology is limited to damaged buildings. However, it is known that communities are also composed by infrastructures;

- A simplified damaged analysis approach is used in the work. The analysis focuses on repair times, delays and utilities disruption. However, secondary effects caused by an earthquake, such as fires and hazard spills, could damage a building with no significant structural and no-structural damages;

- The illustrative case study considers unrealistic data regarding buildings that are damaged by earthquakes, because of concrete information and details on damages are not always available.

8.3 FUTURE DIRECTIONS

- The methodology can be extended in order to cover more structural types, such as light wood-frame system (structures with shear walls that are made of timber frames to which a wood-based panel) or mixed structures made of timber framing and masonry;

- Expanding the library of component, delays, and utilities repair times in order to apply the methodology in other countries, for instance in Italy where recent earthquake events have caused hazardous damages;

- A holistic methodology would be able to consider and include all the parameters regarding not only buildings but also infrastructures into communities to quantify community's downtime and resilience;

- Developing the methodology accounting secondary effects with realistic models. The work can be used for emergency planning, such as evacuation plans and identifying buildings in higher risk.

- Using different membership shapes in the methodology, such as Gaussian, trapezoidal, and generalized bell, in order to compare the results and analyze the effects of different types of membership functions on Fuzzy Logic.

CHAPTER 9 .

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APPENDIX A.

STRUCTURAL COMPONENTS REPAIR TIME

Component repair times for structural components are selected and modified from PACT (FEMA 2012). All structural components are presented for three damage states: *Low, Medium,* and *High.* Each component repair time is defined for percentile 50th and 90th. Information that is not available is marked with a dash (/).