A methodology to estimate the downtime of building structures using Fuzzy Logic

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ABSTRACT

Recent natural and man-made disasters (e.g. earthquake, tsunami or floods) have induced increased attention in quantification of their impact on residential buildings, which are designed to withstand damage through their elastic and plastic deformations. The damage can make the buildings to be unsafe, and consequently unoccupied for a period of time, called the *downtime*. This paper develops a new methodology to predict the downtime of buildings before the earthquake events through the use of Fuzzy logic in order to assess information of building specifications and irregularities. Generally, the downtime can be divided into three main components: downtime due to the actual damage (DT1); downtime due to irrational delays (DT2); and downtime caused by utilities disruption (DT3). DT1 is evaluated by relating the repair time to building's components and the number of workers required for the repair. A Rapid Visual Screening (RVS) survey form has been designed to acquire information about the potentially damaged building and it is implemented using a hierarchical scheme. DT2 and DT3 are evaluated using the REDi^{TM} Guidelines. DT2 depends on the irrational components, while DT3 is based on the site seismic hazard and on the infrastructure system vulnerability. The methodology aims to identify the downtime of the building by combining the three components at three recovery states: re-occupancy; functional recovery; and full recovery.

1 INTRODUCTION

The engineering community has recently made a lot of progress in developing new methodologies to identify the effects of natural and man-made disasters to buildings and infrastructures. However, there is still a large uncertainty in determining such effects. In engineering, the concept of resilience has several definitions. (Bruneau et al. 2003) defined seismic resilience as "the ability of both physical and social system to withstand earthquake-generated forces and demands and to cope with earthquake impacts through situation assessment, rapid response, and effective recovery strategies." (Cimellaro et al. 2010) claimed that resilience depends on physical and social factors and focused on the concept of functionality recovery. Recently, different organizations such as the United States Resiliency Council (USRC) (USRC 2015) have shown that one of the main recommendations and need from the earthquake community is the introduction of a resilience rating system. The 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. Structural Engineers Association of Northern California (SEAONC) developed the Rating System for the Expected Performance of Buildings (Mayes et al. 2011) with the objective of communicating seismic risk to non-engineers. A quantitative method to evaluate resilience at the state level was introduced by (Kammouh et al. 2017a, Kammouh et al. 2017b). In their approach, 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), which is a work developed by the United Nations (UN). Generally, the most challenging component in the seismic resilience evaluation is the *downtime*, which is "*the time necessary to plan, finance, and complete repair facilities damaged by earthquakes or other disasters and is composed by rational and irrational components*" (Comerio 2006). The "rational" components are easily quantifiable, such as construction costs and the time needed to repair damaged facilities. Instead, the "irrational" components consider the time needed to mobilize for repairs (financing, regulatory and economic uncertainty).

The Federal Emergency Management Agency (FEMA) have performed several studies focusing on implementing earthquake loss estimation techniques, which have resulted in the development of a loss estimation software "HAZUS" (Kircher et al. 2006). The downtime in HAZUS is derived from the structural and nonstructural damage probabilities. (Porter et al. 2001) introduced a new methodology called *Assembly-Based Vulnerability* (ABV), which is a framework for evaluating the seismic vulnerability and performance of buildings on a building-specific basis. Moreover, FEMA recently released the *Performance Assessment Calculation Tool* (PACT) (FEMA 2012a, FEMA 2012b), which is an electronic tool for performing probabilistic computation and accumulation of losses for individual buildings. It perform a methodology to assess the seismic performance of individual buildings accounting for uncertainty in the building response.

The methodologies described above mainly consider probabilistic type uncertainty. Moreover, the decision making framework is complex and it involves ignorance, imprecision, vagueness, and subjective judgment (Tesfamariam et al. 2010). Therefore, it is crucial to have a simple method for quantifying the downtime for building structures. A new methodology to predict downtime for three recovery states (e.g. re-occupancy, functional and full recovery) of building structures is proposed. The methodology allows a fast and economical estimation of parameters that involve uncertainties using the Fuzzy Logic hierarchical scheme (Tesfamariam and Saatcioglu 2010) in which information of damaged building is combined. Such information is obtained from a Rapid Visual Screening, which is a questionnaire carried out by a screener to identify the design and the components of the damaged buildings. Moreover, the use of a fuzzy inference system applied into a hierarchical scheme allows the estimation of building damageability, which is the main parameter to quantify downtime.

2 FUZZY LOGIC

(Zadeh 1965) introduced the concept of fuzzy set and the theory behind it that systems with high complexity cannot be analysed using classical mathematical methods because they are not expressive to characterize the relationships between input and output. While in the classical 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) (Tesfamariam and Saatcioglu 2008). The fuzzy logic consists of three main steps (Figure 1): 1) Fuzzification; 2) Fuzzy inference system; and 3) Defuzzification.

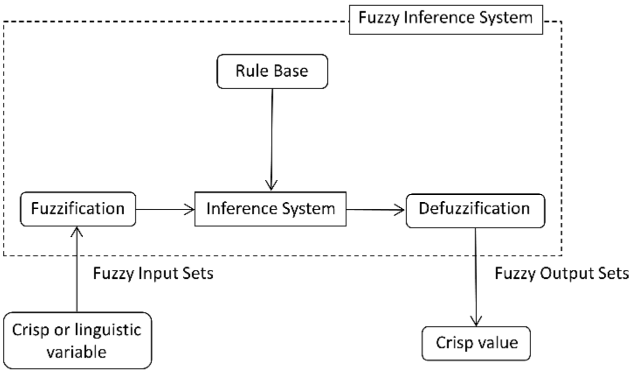

Figure 1. The Fuzzy Inference System (FIS)

2.1.1 *Fuzzification*

Every basic input parameters have a range of values that can be clustered into linguistic quantifiers, for instance, very low (VL), medium low (ML), medium (M), medium high (MH) and very high (VH). Linguistic values are assigned following a process 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 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 shapes of membership functions but the most common types are the triangular, trapezoidal, and Gaussian shapes. The type of the membership function is related to the user experience (Mendel 1995).

2.1.2 *Fuzzy Rules*

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_1 and x_2, the i^{th} rule has the following formulation:

$$R_i: IF\ x_i\ is\ A_{i1}\ AND\ x_2\ is\ A_{i2}\ THEN\ y\ is\ B_i (1)$$

where x_1 and x_2 are the inputs linguistic variables (antecedent), A_1 and A_2 are input sets, y is the output linguistic variable (consequent), B_i is the output fuzzy set. The fuzzy rules are assigned using a proposed weighting method in order to systematize the process. A weighting factor W, 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 2 signifies a higher impact of the input towards the output). The output is then identified by considering the weights of the inputs. For example, consider the following fuzzy rule base: 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*. The output y is *medium* because x_2 has more weight than x_1. The Fuzzy rules assigned to each parameter are listed in Table 1, Table 2, Table 3, Table 4, and Table 5.

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

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

Table 3. 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

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

Table 5. Fuzzy rule for Structural Deficiency

Rule	*ID W=1*	*DR W=2*	*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

2.1.3 Fuzzy Inference System (FIS)

The results of the rules are combined to obtain a final output through a process called *inference*. 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 behaviour 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).

2.1.4 Defuzzification

Defuzzification is the inverse of the fuzzification process. It is performed according to the membership function of the output variable. The purpose of the defuzzifier component of a fuzzy logic system (FLS) is to defuzzify the fuzzy output and obtain a final crisp output. Many different techniques to perform defuzzification are available in the literature, such as: center of the area, center of gravity, bisector of area, etc.

3 METHODOLOGY TO QUANTIFY THE DOWNTIME

The Downtime assessment can be performed following five steps, which are:

1. Performance of a Rapid Visual Screening (RVS) of the potentially damaged buildings;
2. Creation of a hierarchical scheme, in which information obtained from the RVS is used as input;
3. Translation of the RVS results into numerical data through the use of Fuzzy system. The numerical data is used to define the Building Damageability membership (BD) following the defined hierarchical scheme;
4. Evaluation of the repairs (rational components), delays (irrational components), and utilities disruption considering the damage memberships that are greater than zero;
5. Defuzzification of the downtimes obtained from the analysis to quantify the total repair time.

In the following, each step will be expounded.

The evaluation of the downtime can be handled through a comprehensive hierarchical structure (Figure 2), 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 buildings based on a survey form performed by an expert. A Fuzzy system is implemented in the procedure to translate the RVS results from linguistic terms into numerical data. Building information from the RVS is incorporated through a hierarchical structure, which follows a logical order for combining specific contributors (e.g. site seismic hazard and building vulnerability modules) to estimate the building damage (Tesfamariam and Saatcioglu 2010). 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. Thus, 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*. 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.

Downtime due to *delays* is based on irrational components. The irrational components considered in the methodology are a selection from the components introduced in REDI^{TM}: post-earthquake inspection, engineering mobilization, financing, contractor's mobilization, and permitting. (Comerio 2006).

Downtime due to *utilities* depends on the 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 downtime can be estimated. A downtime value is computed for each damage membership as follows:

$$DT = \sum_{i=1}^{n} DT_i * \mu_i \tag{2}$$

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.

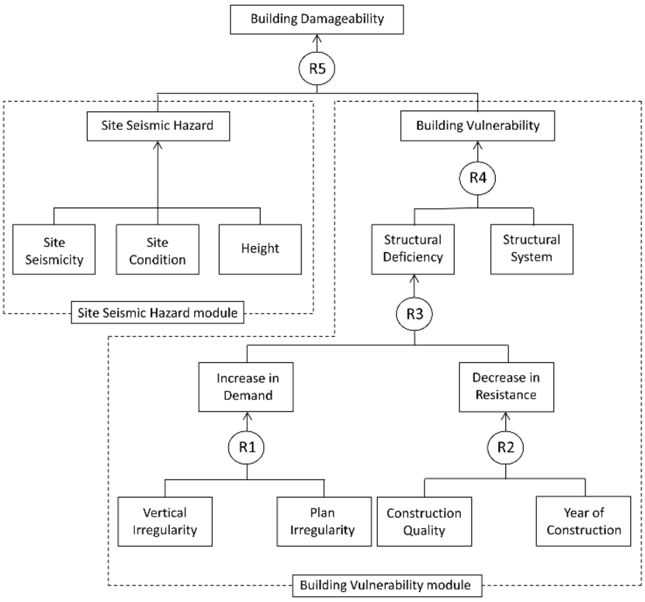

Figure 2. The building damageability hierarchical scheme, adapted from Tesfamariam and Saatcioglu (2008)

4 DAMAGE ESTIMATION

The building damage is estimated through a hierarchical scheme that includes all variables contributing to the building damage (Figure 2). The proposed hierarchical scheme for the building damageability is an adaptation from (Tesfamariam and Saatcioglu 2008), in which aggregation of the variables is done through the fuzzy model described before, and the granularity assigned to the fuzzification is associated with the level of damage state. Furthermore, a heuristic model to assign membership values starting from linguistic information is employed in this paper. The membership functions considered in the methodology are those introduced by (Tesfamariam and Saatcioglu 2008), which are based on triangular fuzzy numbers (TFNs). The weighting method introduced before is used to define the fuzzy rules and to connect the inputs and the outputs of the system. Finally, at each level of the hierarchical scheme, the weighted average method is used for the defuzzification to obtain an index I, as follows:

$$I = \sum_{i=1}^{n} q_i * \mu_{R,i} \tag{3}$$

where q_i is the quality-ordered weights, $\mu_{R,i}$ is the degree of membership, i is the tuple fuzzy set. The 1991 Northridge Earthquake damage observations are used to calibrate the quality-ordered weights in the methodology (Tesfamariam and Saatcioglu 2008).

The defuzzification process is not required for the Building Damageability. 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. Following the proposed hierarchical scheme, the Building Damageability index (I^{BD}) is evaluated by combining Site Seismic Hazard (SSH) and Building Vulnerability (BV). Building Vulnerability index (I^{BV}) is obtained through the integration of the two components: Structural Deficiency (SD) and Structural System (SS). On the other hand, the Site Seismic Hazard index (I^{SH}) is obtained by combining the earthquake source conditions, source-to-site transmission path properties, and site conditions. I^{SH} is expressed in terms of building response acceleration, which can be obtained as a function of the building fundamental period (T).

Structural Deficiency can be divided into two categories (Saatcioglu et al. 2001): factors that increase the seismic demand (Increase in Demand) and factors contributing to a reduction in ductility and energy absorption (Decrease in Resistance). Parameters that contribute to the decrease in resistance are Construction Quality (CQ) and Year of Construction (YC). 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. Parameters that contribute to the increase in seismic demand are Vertical Irregularity (VI) and Plan Irregularities (PI).

Three popular reinforced concrete building types are identified for the evaluation of the Structural System component (SS): moment resisting frames (C1), moment resisting frames with infill masonry walls (C2) and shear wall (C3). The granulation assigned to each parameter is shown in Figure 3.

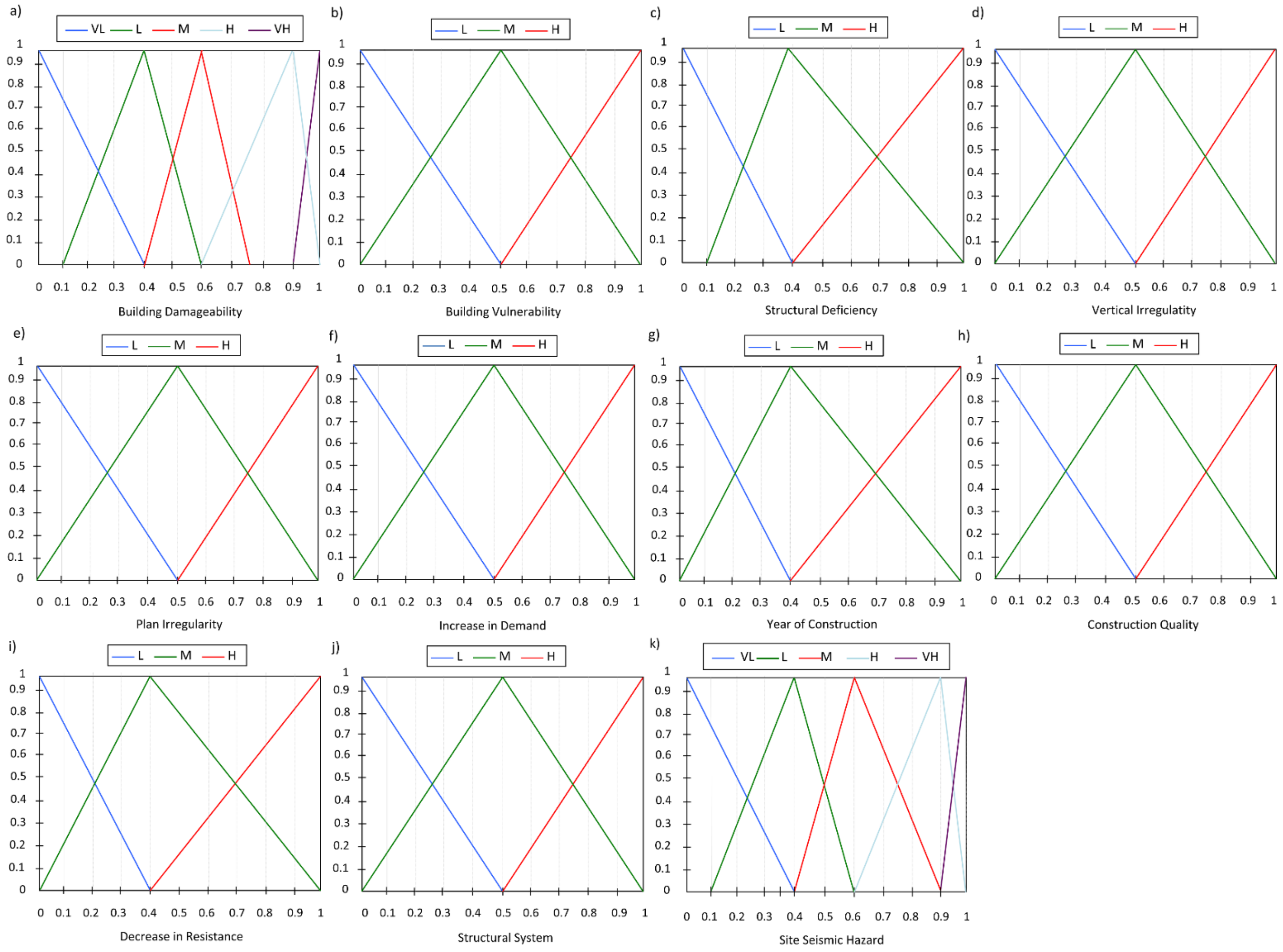

Figure 3. Membership functions and granulation for: a) building damageability; b) building vulnerability; c) structural deficiency; d) vertical irregularity; e) plan irregularity; f) increase in demand; g) year of construction; h) construction quality; i) decrease in resistance; j) structural system; k) site seismic hazard

5 DOWNTIME DUE TO REPAIRS

In general, the Downtime (*DT*) is the combination of the time required for *repairs* (*DT repairs*, rational components), *delays* (*DT delays*, irrational components), and the time of *utilities* disruption, as follows:

$$DT=max((DT\,repairs+DT\,delays);DT\,utilities) \quad (4)$$

The combination of the three components depends on the chosen recovery state (i.e. re-occupancy recovery, functional recovery, and full recovery) (Bonowitz 2010). For example, in the re-occupancy recovery state, consideration of *utilities* disruption is not required, thus the downtime is the result of the time required for *repairs* and *delays* only.

Downtime due to repairs considers rational parameters: the state of the damaged components and the number of workers assigned.

5.1 *State of Components*

Component repair times are obtained from PACT, an electronic calculation tool released by (FEMA 2012a), which provides the repair times from consequence functions that indicate the distribution of losses as a function of damage state. The distribution (and dispersion) of the potential repair time is derived from data representing the 10th, 50th, and 90th percentile estimates of labor effort. In this work, only data representing the 50th and 90th percentile has been used as the 10th percentile is not desirable for downtime assessment. Once component repair times for each damage state are known, the values can be used to compute the total component repair time by defuzzifying the component repair times using the corresponding membership values, as follows:

$$RT\colon \sum_{i=1}^{n} rt_i * \mu_{R,i} \qquad (5)$$

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 4), is used to quantify the repair time and depends 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.

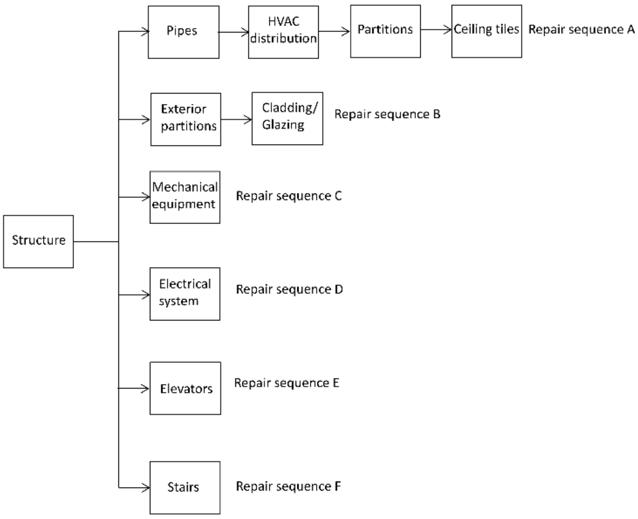

Figure 4. Repair sequence from REDi™

5.2 Number of workers

Repairs can be carried faster or slower, depending on the crew number,. 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 2012b). Following the REDI™ instructions, repairs for structural components have a labor allocation limitation of 1 worker per 500 sq. ft per floor. For non-structural repairs, REDI™ recommends using 1 worker per 1000 sq. ft.

Equation (6) computes the maximum number of workers for structural repairs in a building for a gross area:

$$N_{\max} = 2.5x10^{-4} A_{tot} + 10 \qquad (6)$$

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

6 DOWNTIME DUE TO DELAYS

Downtime due to delays is derived from irrational components introduced by (Comerio 2006) (Figure 2). The irrational components used in the methodology are a selection from the components presented in REDI™: Financing, Post-earthquake inspection, Engineer mobilization, Contractor mobilization, and Permitting.

Downtime due to delays is largely based on the building damage. For instance, in buildings where the expected damage state is *Low*, less downtime due to delays is likely to occur. In the following, irrational components are examined.

6.1 Financing

The degree of delay due to financing depends on the financing method: private loans, Small Business Administration (SBA), insurance, or pre-arranged credit line. Delays due to financing need to be considered in case the building damage state is greater than or equal to *High*.

6.2 Post-earthquake inspection

Delays due to post-earthquake inspection depend basically on the building use. 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 reduce downtime significantly. Delays due to post-earthquake inspection are considered for every recovery state if the building damage state is higher than *Medium*. Otherwise they are not included as there would be no structural damage.

6.3 Engineer mobilization

Delay due to engineer mobilization is mostly the time required for finding engineers plus the time needed to carry out engineering review and/or re-design. Such delay is considered in the analysis if the building damage state is *Medium* or *High.*

6.4 Contractor mobilization

Delays due to contractor mobilization are obtained from FEMA. Their consideration depends on the building damage state in each recovery state: *High* in re-occupancy, *Medium* in functional recovery, and *Low* in full recovery state.

6.5 Permitting

Delays due to permitting consider the time needed for the local building jurisdiction to review and approve the proposed repairs. It is necessary to include delays due to permitting if the building damage state is *High* and/or *Medium.*

7 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 those recovery states.

Utilities disruption times are defined from data about past earthquakes (Kammouh and Cimellaro 2017). Generally, the disruption of utilities should be considered only in *functional* and *full recovery* states when the maximum membership value of the site seismic hazard is greater than or equal to *Medium* (O'Rourke and Ayala 1993, O'Rourke and Deyoe 2004, Eidinger and Davis 2012).

In this work, we consider three utility systems:

7.1 Electricity

In general, electricity systems recover quickly, ranging between 2 and 14 days for a full recovery, and they perform better than other utility systems because of their high level of redundancy.

7.2 Natural gas

Natural gas systems tend to require a longer time for restoration (from 7 to 84 days for full restoration of service). That's because the gas services need to be re-lighted and re-pressurized after the gas shuts off for safety purpose.

7.3 Water

Water system disruption time is usually extensive in all earthquakes, ranging from 6 days to 10 weeks for full restoration. The methodology used for determining the water disruption time follows the same criteria of natural gas disruption.

8 CONCLUSION

This paper introduces a new methodology for quantifying the downtime of residential buildings against earthquake events. Downtime is defined as the timespan between a disaster event and recovery. In the methodology, downtime is divided into three main components: downtime due to repairs, downtime due to delays, and downtime due to utilities disruption. To overcome the complexity of other existing methodologies of downtime analysis that are based on probabilistic formulations, the fuzzy logic is used. Unlike the traditional probabilistic methodologies, the advantage of the proposed Fuzzy method is that it is simpler and faster for the assessment and decision-making; it accepts 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 into five main modules: quantification of building damage, evaluation of repairs (rational components), delays (irrational components) and utilities disruption, and quantification of the Downtime parameter.

Further research work will be oriented towards extending the methodology to cover more building structural types, to expand the library of building components, delay, and utilities repair times in order to apply the methodology in other countries.

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