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DOWNTIME ESTIMATION FOR RESILIENCE ASSESSMENT ACCOUNTING EXTERNAL FACTORS

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Abstract. *Downtime –as the time necessary to restore a system's functionality- is the critical parameter of the recovery process after an abrupt event. This quantity is usually underestimated to the repair time, while the recovery process also includes the "recovery initiation delay". The paper tries to use a model to estimate the time needed to start the building repair after the hazard occurrence. Among several factors affecting downtime, those external to the building play a key role in determining this duration. Such factors are strongly dependent on community relationships. External factors - including transportation access, building inspection, utility disruption, financing, etc. - from Loma Prieta earthquake are compiled and analyzed in order to investigate the relative effect of community dependent factors on building recovery initiation delay. A sensitivity analysis is done, as different factors do not have the same influence on recovery path.*

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1 INTRODUCTION

"Estimation of downtime losses is and will remain perhaps the biggest challenge of seismic performance assessment and risk management." [1]. Downtime estimation cannot be restricted to repair time, as the repair process never starts immediately after the hazard occurrence. The time needed to prepare for the repair process is not negligible. This period is mostly affected by community-dependent factors and the economic, environmental, socio-political and technical considerations.

The objective of this paper is to review and postulate factors affecting downtime with a particular focus on those external to the building. Relevant literature on loss and downtime estimation are reviewed, from which a list of external factors affecting downtime is collected. A model is used in order to quantify the delay caused by these factors and identify the critical activities. The method must incorporate uncertainties, as the pre-repair activities duration does not remain constant for different buildings. The output is time required to start the building repair and is presented via probability distributions. The method is applied on a numerical example: Loma Prieta earthquake. Different scenarios are assumed to analyze the input (pre-repair activities duration) sensitivity on output (overall delay caused by externalities). Results illustrate the importance of managing and controlling the external factors, which is extremely related to the community role and relationships.

2 BACK GROUND

An early loss model by Czarnecki (1973) [2] formulated a methodology to relate repair costs to shaking intensity where repair costs were specific to the individual building. The earliest model incorporating external factors in downtime estimation is the risk assessment software package Hazus-MH built on GIS (Geographic Information System) technology, released by FEMA in 2004 [3]. "Total downtime of the community may be associated with a bridge, road, or utility that can be damaged by a hazard." The repair time is equal to the estimated construction time, whereas the extensive damage state also includes the time for activities such as finance, design, and permits [4]. Such activities have been acknowledged by Comerio [5] as "irrational" components, which include four issues dominating the preconstruction period: (1) the need to secure financing, (2) the ability to relocate building functions, (3) the availability of labor, and (4) economic and regulatory uncertainties. According to Comerio, total downtime is the aggregation of rational and irrational components. The Resilience-based Earthquake Design Initiative for the Next Generation of Buildings [6] framework combined the downtime due to delays, repairs, and utility disruption. Downtime due to delays and utility disruption occur simultaneously after the earthquake occurrence, and downtime due to repairs follows the downtime due to delays. The time needed to complete all three sources of downtime represents the total downtime to achieve the recovery state under consideration. Delays are caused by factors which include completion of post-earthquake building inspection, securing financing for repairs, mobilizing engineering services, re-designing damaged components, obtaining permits, mobilizing a contractor and necessary equipment, and the contractor ordering and receiving the required components including 'long-lead time' items. Burton [7] discussed these factors within the concept of "lead time" through the recovery path which is the time required for building inspection and/or evaluation, finance planning, architectural/engineering consultations, a competitive bidding process, and mobilizing for construction. In addition to these contributors to lead time, factors outside of a building's footprint that has been defined as externalities, such as utility services, building access, shortage of the materials and skilled labor needed to conduct repairs or the adverse economic effect, were acknowledged.

However, most methodologies do not fully consider all factors affecting downtime, even though the majority of these studies acknowledge the importance of the various factors. These activities are mostly related to the community; they have a sequence and the relative importance of them must be investigated. As an example, a building must be inspected for the probable damage before the engineering and redesigning services is mobilized and, following these steps, necessary components and materials can be ordered and received. Availability of these components itself, depends on the transportation access. All these dependencies create a network of activities, leading to the overall recovery path. There are different methods - such as critical path method (CPM), and Program evaluation and review technique (PERT) - to apply this sequence and find out the relative importance of the external factors.

3 METHODOLOGY

Critical path method identifies the time required to complete the activities in a project, and the order of the steps. It determines the “critical” activities (on the longest path) and prioritize activities for the effective management of them. Having the required information -including the duration and dependencies of all activities to complete the project- a chart can be produced to illustrate the project schedule. According to the chart, the longest path to complete the project and the earliest and latest time for each activity to start and finish -without making the project longer- is determined. The activities in the longest path are critical and the others can be delayed as long as their “total float” without impeding the project [8].

Initially, the overall project will be divided into separate operations, which are necessary for total project completion; and sequential relationship of the activities is determined. The time estimate of each activity is the second phase. Earliest possible start, earliest possible finish, latest possible start, and latest possible finish must be calculated in this phase and according to the chart created by means of this information, free and total float is extracted. Float is the amount of time that a task can be delayed without causing a delay to the subsequent tasks - called free float- and the project completion date -called total float- [9].

For downtime estimation - with focus on external factors - this method can be applied in order to understand the critical factors and different ways to reduce downtime. Furthermore, it helps find out the least costly ways to speed up the recovery process. However, the duration of repair activities are not usually determined with certainty; especially for the activities related to community scale. In contrast with CPM, PERT (program evaluation and review technique) is a method with the same approach which “incorporates uncertainty by making it possible to schedule a project while not knowing precisely the durations of all the activities” [10].

PERT distribution uses the most likely value, and it is designed to generate a distribution that closely resembles realistic probability distribution. PERT distribution creates a smooth curve that fits well to the normal or lognormal distributions. It requires minimum value (a), maximum value (b), and the most likely value or mode (m). In the PERT distribution, the expected value μ and the standard deviation σ are calculated according to equations 1 and 2 [11].

$$\mu = \frac{a+b+\lambda m}{\lambda+2} \tag{1}$$

$$\sigma = \frac{b-a}{6} \tag{2}$$

Where a is an optimistic time to perform the activity, m is the most likely time to perform the activity (mode), b is a pessimistic time to perform the activity, and λ is an additional scale parameter, which determines the height of the distribution; the default value for this parameter is 4. According to these parameters, the activities can come in a variety of shapes (figure 1).

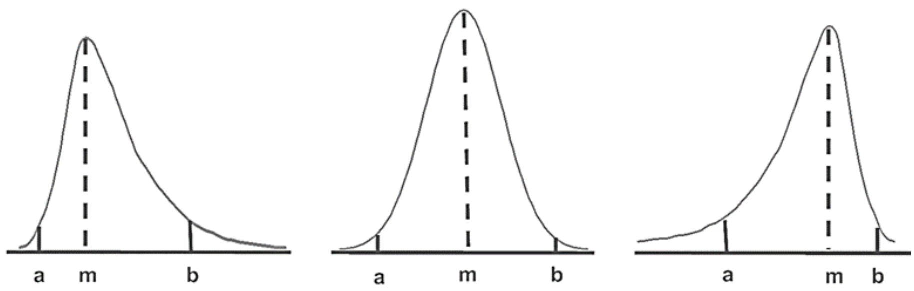

Figure 1: Expected shapes of distribution of the activity duration

A critical path can be determined using the mean completion time for each activity (for the activities without uncertainty, the precise duration can be utilized). Each project may have one or more critical paths. A critical path is the sequence of project network activities, which add up to the longest overall duration. According to the central limit theorem (CLT), "given certain conditions, the arithmetic mean of a sufficiently large number of iterates of independent random variables -each with a well-defined (finite) expected value and finite variance- will be approximately normally distributed, regardless of the underlying distribution" [12]. Thus, the overall duration of the project can be normally distributed.

The project mean completion time is determined only by the completion time of the activities on the critical path. Based on the activities probability distribution, the overall project completion time is normally distributed. The mean time (ɱ) of the overall project is equal to the sum of the mean times of the activities on the critical path. Additionally, the overall variance of the project is the sum of the variances (σ2) of critical activities. Using these values, Probability of project completion within any given period is calculated. The probability of a project completion within X days- with known ɱ and σ- can be calculated using the normal probability table (Z table) according to equation 3.

$$Z = \frac{X - \mu}{\sigma} \tag{3}$$

"A standard normal table, also called the unit normal table or Z table, is a mathematical table for the values of Φ, which are the values of the cumulative distribution function of the normal distribution. It is used to find the probability that a statistic is observed below, above, or between values on the standard normal distribution, and by extension, any normal distribution" [13].

4 NUMERICAL EXAMPLE

Applying numerical examples is an essential step in analyzing the external factors and identifying the critical ones. Studying the data from previous disasters would highlight the effect of different parameters such as hazard type, hazard intensity, the community role, etc. on external factors. It would also help the decision makers in getting prepared for future disasters by understanding the critical factors and parameters. In this study, the model is implemented on Loma Prieta earthquake, occurred in northern California in 1989.

The first step in applying the method, is compiling data about different external factors. For each activity, we need to estimate an optimistic duration, a pessimistic duration and a mode to calculate expected duration for PERT model. According to the type of data needed, in some cases estimation of the mode is more critical than the maximum and minimum value. Mode is the value that is repeated more than any others in a set of data, and Because of insufficient data, we assumed no skewness for the beta distribution of the activities. In this case, the mode is considered in the middle of optimistic and pessimistic duration.

4.1 Loma Prieta earthquake 1989

The Loma Prieta earthquake affected the San Francisco area on October 17, 1989, causing the loss of 63 lives. A magnitude 6.9 earthquake severely shook the San Francisco and Monterey Bay regions. Loma Prieta was clearly a major earthquake for the San Francisco Bay Area. Initial government estimates formulated a few weeks after the event indicated that over 22,000 residential structures, 1,567 businesses, and 137 public buildings in the area of impact were destroyed or sustained significant damage [14].

Table 1 presents the information about external factor for Loma Prieta earthquake. This information is gathered from different reports and sources, which is presented in the "basics" column in the table. For three of the activities (colored in grey) including "Engineering mobilization and review/re-design", "Ordering/receiving initial components" and "Mobilizing contractor and workforce", as the result of insufficient data, tenuous assumptions are considered. In order to have logical bounds, the assumptions are adopted from lognormal cumulative distribution of impeding factors of Resilience-based Earthquake Design Initiative rating system [6]. By implementing different scenarios, we could analyze the impact of different assumptions on the output of the method. This would lead us to a stochastic sensitivity analysis.

Activity	Code	Optimistic time (a)	Mode (m)	Pessimistic time (b)	Expected duration (M)	Predecessors	Basics/ References
Transportation	A	0	15	30	15	-	(Tierney 1991), (Webber 1992), (SPUR 2010), (Benuska 1990), (Yashinsky 1998), (Giacomini & Witt 1998)+Assumption
Building inspection	B	1	72	143	72	A	(Tubbesing & Mileti 1994), (Martin 2013)+Assumption
Engineering mobilization and review/re-design	C	14	42	70	42	B	Assumption (C1)
	C	175	350	525	350	B	Assumption (C2)
Obtaining permits	D	3	184	365	184	C	(California Seismic Safety Commission 1991)+Assumption
Ordering/receiving initial components	E	1	16	31	16	C, J	Assumption (E1)
	E	30	45	60	45	C, J	Assumption (E2)
Mobilizing contractor and workforce	F	21	49	77	49	J	Assumption (F1)
	F	77	175	273	175	J	Assumption (F2)
Electricity	G	0	1	2	1	-	(Tierney 1994) +Assumption
Water	H	0	7	14	7	G	

Gas/oil	I	10	20	30	20	-	
Financing	J	0	225	450	225	-	(California Seismic Safety Commission 1991)+Assumption

Table 1: PERT parameters for activities due to external factors in Loma Prieta earthquake

According to table 1, several scenarios are presented based on damage state, activity dependencies and type of financing. Following comes the analysis of different situations.

4.1.1. High damage intensity:

In this case, “engineering mobilization and re-designing (activity C)” takes the longest duration (assumption 2) and -regardless of the other variables-, critical path will always remain the same: A-B-C-D. The project completion mean time –time needed before starting the repair process- is equal to 621 days. Building inspection as one of the long lasting activities in the critical path can significantly reduce the total downtime. Programs such as BORP [25] can ensure downtime reduction. Calculation shows that the implication of BORP (in which the optimistic and pessimistic duration equals 1 and 3 days) can reduce the total duration up to 70 days.

4.1.2. Low damage intensity:

For less intense damage states, lower values are considered for estimating the duration of “engineering mobilization and re-designing” (activity C). The project completion mean time is less than the high damage intensity situation and is equal to 400 days. In this case, the expected duration of “mobilizing contractor and workforce” (activity F) can affect the critical path; If it takes a long duration (assumption 2) the critical path is likely to be changed into J-F.

Furthermore, since “Financing” (activity J) turns into a critical activity, it becomes viable to be crashed. This will happen if the independent financing or an earthquake insurance exists. A BORP like economic agreement -which ensures financing within a specific period after the earthquake- would be helpful. As an example, if the mode is reduced to two weeks, not only the total duration will be reduce up to 87 days, but also the critical path will be changed to A-B-C-D. Diagram of Loma Prieta earthquake activities for the situation number 1 and 2 is presented in Figure 2.

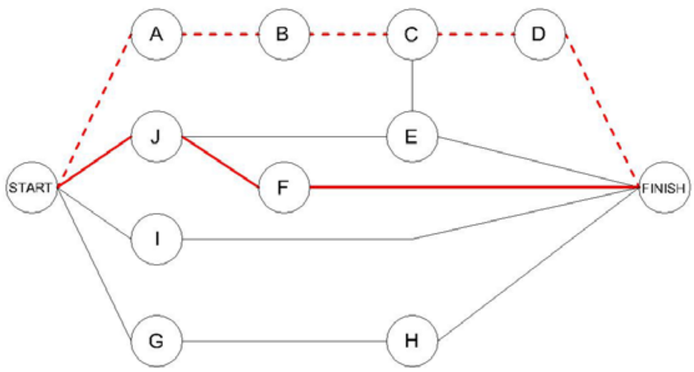

Figure 2: Critical path diagram of Loma Prieta earthquake for situation number “1” (critical path presented in red dashed line) and “2” (critical path presented in red line).

4.1.3. Necessary pre-payment for mobilizing engineer and re-designing:

The study shows the importance of activity dependencies, which vary according to the regulations and community relationships. These changes must be applied in different ways, such as modifications of the project sequence logic. As an example, if a prepayment is necessary for engineering and redesigning process (activity C), financing will be a predecessor for this activity and the diagram will be modified as below (Figure 3). This changes the critical path into J-C-D. This path will remain critical regardless of any changes in all other assumptions and even if both activity C and F take their longest duration, critical path will not change. The project completion mean time is more than the previous situations and is equal to 759. This duration can be reduced up to 138 days if a BORP like economic agreement is adopted. This would also change the critical path to A-B-C-D.

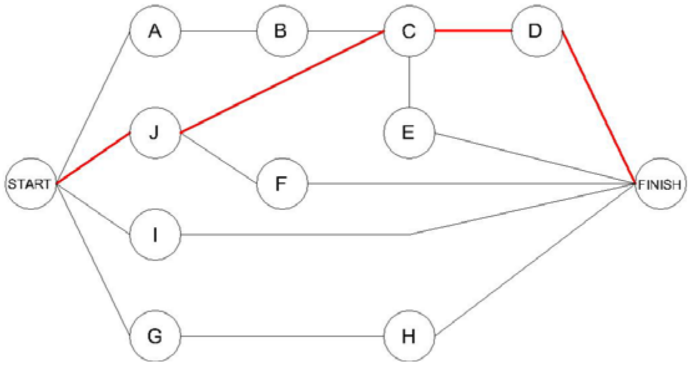

Figure 3: Critical path diagram of Loma Prieta earthquake for situation number “3”.Red lines indicate the critical path

5 FINAL CONCLUSIONS

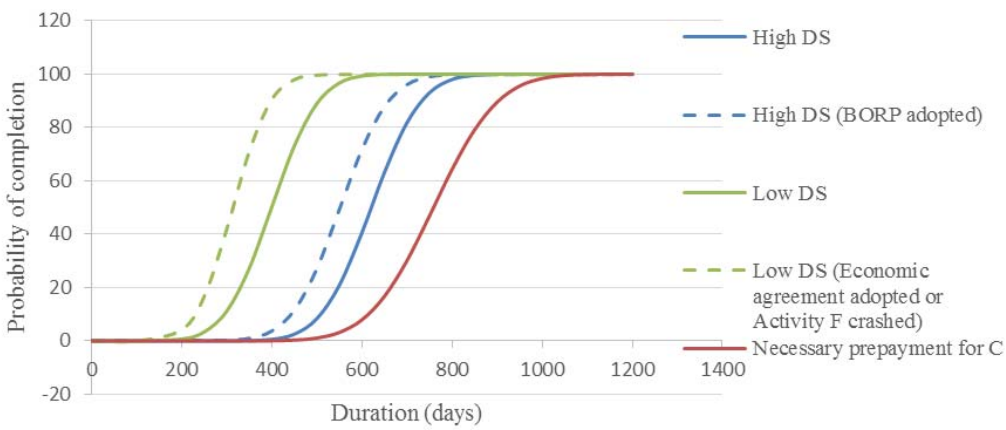

Figure 4: Probability distribution of the project completion for Loma Prieta Earthquake

Several fragility curves are presented for the Loma Prieta assumed situations (Figure 4) in order to summarize the results obtained from PERT analysis. The curves show the probability distribution of the project completion for different cases considered. Each curve is drawn according to the chance that a project can be finished on or before a specific time.

The blue lines refer to high damage states (situation 1), and the green lines present the low damage states (situation 2). This analysis demonstrates that the damage state not only increases the repair duration, but also affects the pre-repair period significantly. A-B-C-D is the most likely path to be critical. Crashing each of these activities –which are dependent on community relationships- leads to a significant reduction in total downtime.

The effect of community preparedness programs are represented by dashed lines in figure 4. Adopting programs like BORP –by reducing the time required for inspection (Blue dashed line) - or granting easy permits are two examples of crashing attempts. “Mobilizing contractor and workforce” (activity F) is the other important activity which can change the critical path to J-F if it takes a long duration. Considering this activity in a post-hazard agreement is also effective (green dashed line).

The red line presents the third situation in which a pre-payment for “mobilizing engineer and re-designing” is necessary. The project is likely to be finished later than any other cases. By crashing activity J (Financing), in the best situation the project would be the same as the previous cases as the critical path changes. This demonstrates that financing is relatively the most important factor among those external to the building. “Financing” could exist in the critical path under certain situations, which are affected by the activity dependencies and community relationships. In this case, BORP like economic agreements, independent financing or hazard insurance programs could reduce the downtime significantly.

Among critical activities, the duration of “Mobilizing engineers and re-designing” depends on the damage state more than the others. Nevertheless, adopting a post-hazard engineering agreement before the occurrence of the abrupt event could attenuate the effect of this activity on downtime. “Ordering and receiving initial components” (Activity E) do not exist in the critical path either in its first or second assumption or even if the largest value for activity “C” and “F” are not assumed. This happens because of the large value of its total float, which is the result of long expected durations considered for critical activities.

The study demonstrates the considerable effect of external factors on downtime in the pre-repair phase. Considering and improving such factors leads us to systems that are more resilient. Applying a numerical example on the proposed method shows that the community relationships - such as government role, economic situation, existence of preparedness programs, etc. - play a key role in determining these factors and their correlations.

In addition, community preparedness programs -such as BORP agreement- would definitely ensure the downtime reduction. However, this program is only limited to “inspection” of the buildings. Assuming such programs in this study for different activities illustrated their significant effect on reducing downtime quantity.

Above all, the most influential activities, which are more likely to be in critical path -such as financing, inspection, transportation access, etc. -, are determined by doing the sensitivity analysis. Besides, utilities backup must be considered as an essential factor to guarantee the habitability of the buildings. However, it never turns into a critical activity and so it does not impede the repair process.

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