SEISMIC RISK OF INTERDEPENDENT LIFELINE SYSTEM USING FUZZY REASONING

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ABSTRACT :

The main objective of this research is the estimation of lifeline's seismic performance taking into account the multiple interdependencies between them. Their functionality is controlled by the vulnerability and the interconnectedness of lifeline elements for a given level of earthquake intensity. A systematic methodology is introduced to evaluate the associated losses of interacting lifeline elements for various strong motion intensities in an interactive relationship using uncertain additive linguistic preference relations. This approach which includes fuzzy reasoning can be directly applied to group decision making problems without loss of information. Group opinions are converted into the form of an "inoperability matrix" composed of elements representing the degree of corresponding impact. Finally, complex fragility curves of interdependent elements are produced using the "inoperability matrix" and the fragility curves of independent lifeline components. In this study the idea of cross impact analysis is employed for the evaluation of system interactions, whereas the impacted probability is formulated on the rigorous basis of probability theory and a systematic approach of risk analysis that is used for risk prevention. Finally, an illustrative numerical example is given to verify the developed approach.

KEYWORDS: seismic risk, interdependency, lifelines, group decision making, linguistic preference

1. INTRODUCTION

In complex urban environment, lifelines are highly intra-dependent and inter-dependent systems, showing a great degree of coupling between sub-components of the same system and with other infrastructures. The inherited complexity makes the assessment of inter-dependent lifeline systems' performance a difficult issue for advanced seismic risk management solutions.

Several types of interdependencies exist, which may seriously affect the seismic risk management (response, recovery and mitigation). Their differences are described by several researchers (Kameda 2000, Rinaldi et al. 2001, Peerenboom et al. 2001, Tang et al. 2004, Yao et al. 2004). The seismic risk (S.R.) of interdependent lifeline systems is described in Eqn.1.1:

$$\{S.R._{interdependent}\}=\{S.R._{independent}\}*\{\text{Interaction function/ matrix}\} \quad (1.1)$$

The scope of the proposed procedure is to evaluate "systemic fragility curves" of interdependent lifelines, as in the case of an earthquake event, malfunction of a system's components can result in cascading effects within the same system and other connected systems. The research work presented herein accounts for the general and functional interaction between different critical infrastructure elements. Several approaches can be used for the estimation of such interactions: economic, fuzzy logic, decision making or composite approaches. The methodology illustrated in this paper (Fig. 1) is a composite approach, as it is based on a combination of decision making and fuzzy linguistic preference relations in order to estimate adequate interdependency indices between different elements of lifeline systems.

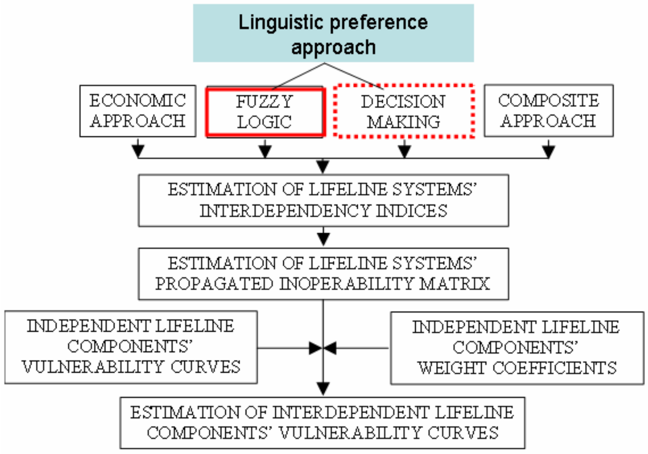

Figure 1 Flowchart of the proposed methodology

The vulnerability of a system of interacting lifeline elements can differ significantly from the fragilities of its components. It depends on the vulnerability of the individual components and the degree of their interdependency. Thus, fragility curves of the interdependent components are estimated based on vulnerability functions of independent elements (e.g. NIBS, 2004) and the "cross impact matrix". The concept of "systemic vulnerability" or "vulnerability of interdependent elements" can be written as a probability of the interdependent event E_N for a three systems' interconnectivity:

$$P(E_N)= P(E_1)+ (1-P(E_1))*P(E_2)*a_{12N} + (1-P(E_1))*P(E_3)*a_{23N} \quad (1.2)$$

where: $P(E_1)$ denotes the probability of event inside system 1 (system 1 independency), $P(E_2)$ denotes the probability of event 2 inside system 2 (system 2 independency) and $P(E_3)$ denotes the probability of event inside system 3 (system 3 independency), a_{12N} denotes a cross impact factor representing the degree of probabilistic contribution (functional dependence) of system 1 and 2 to the lifeline element of node N and a_{23N} denotes a cross impact factor representing the degree of probabilistic contribution of system 2 and 3 to the lifeline element of node N.

The main steps of the proposed methodology involves: (1) the construction of a structural model of interrelationship of all systems under consideration, (2) the quantification of expert opinions using group decision making with uncertain additive linguistic preference relations to illustrate the importance of each lifeline system or element compared to another (3) the conversion of the opinions into the form of a cross impact matrix composed of elements representing degree of corresponding impact and (4) modification of the probability of an event occurrence using the cross impact matrix.

2. GROUP DECISION MAKING WITH UNCERTAIN LINGUISTIC PREFERENCE RELATION METHOD

The group decision making with uncertain linguistic preference relation method (step 2) is used to estimate the "cross impact matrix". In the process of decision making, experts usually need to compare a set of decision alternatives with respect to a single criterion and construct preference relations using exact numerical values (Orlovsky, 1978, Xu 2000, Xu and Da 2003) or linguistic variables (Kacprzyk, 1986, Bondogna et al, 1997, Cordon, 2002). However, many times because of time pressure, lack of knowledge or data and limited expertise with respect to the problem domain, it is more suitable to provide preference values by means of linguistic variables.

Degani and Bortolan (1988) and Delgado et al (1993) developed methods based on fuzzy numbers that support semantics of the linguistic terms. However, both of these methods result in a loss of information and hence a lack of precision (Carlsson and Fuller, 2000). Xu (2004, 2006) developed a method, based on linguistic geometric averaging operator for group decision making with linguistic preference relations that exploits the opinion of every expert. The proposed approach makes use of the method developed by Xu (2006).

2.1. Basic Concepts

Let $S = \{S_\alpha \backslash\ \alpha = -t, \ldots, t\}$ be a finite and totally ordered discrete term set, where t is a non-negative integer. Each term, S_α, represents a possible value for a linguistic variable, and it has the following characteristics:

1) The set is ordered: $S_\alpha > S_\beta$ if $\alpha > \beta$.
2) There is the negation operator: $neg(S_\alpha) = S_{-\alpha}$

To preserve all the given information, we extend the discrete term set S to a continuous term set $\overline{S} = \{S_a / a \in [-q, q]\}$ in which $S_\alpha > S_\beta$ if $\alpha > \beta$ and q(q>t) is a sufficiently large positive integer.

To obtain the optimal decision, Xu (2006) developed a direct approach based on ULA (Uncertain Linguistic Averaging) and ULWA (Uncertain Linguistic Weighted Averaging) operators.

2.2 Description

The following steps are considered:

1) A finite set of alternatives $X = \{x_1, x_2, \ldots, x_n\}$ and a finite set of experts $E = \{e_1, e_2, \ldots, e_m\}$ are considered. The weight vector of the decision makers is $\omega = (\omega_1, \omega_2, \ldots, \omega_m\}^T$, where $\omega_i \geq 0$ and $\sum_{i=1}^{m} \omega_i = 1$. Each expert e_k provides his/ her uncertain additive linguistic preference relation $\widetilde{R}^{(k)} = \left(\widetilde{r}_{ij}^{(k)}\right)_{nxn}$ on X.

For $\widetilde{R} = \left(\widetilde{r}_{ij}\right)_{nxn}$ uncertain additive linguistic preference relation, only the n(n-1)/2 judgments $\widetilde{r}_{ij}$ (i<j) in the upper triangular portion need to be provided by the expert. The n elements $\widetilde{r}_{ij}$(i=1,2,…,n) on the diagonal indicate the preference degrees of the alternatives x_i (i=1,2,…,n) over themselves in an indifference situation. That is, $x_i \sim x_i$ (i=1,2,…,n) and thus they can be denoted by $\widetilde{r}_{ij} = [s_o, s_o]$ (i=1,2,…,n). All the n(n-1)/2 elements $\widetilde{r}_{ij}$ (i>j) in the lower triangular portion of the uncertain additive linguistic preference relation can be determined as followed:

$$\widetilde{r}_{ij} = [r_{ij}^L, r_{ij}^U],\ \widetilde{r}_{ij} \in \widetilde{S}, r_{ij}^L \oplus r_{ji}^U = s_o, r_{ji}^L \oplus r_{ij}^U = s_o \quad \text{for all i,j= 1,2,…, n} \tag{2.1}$$

2) The Uncertain Linguistic Weighted Averaging (ULWA) operator is utilized to aggregate all the uncertain additive linguistic preference relations provided by the experts to obtain the collective uncertain additive linguistic preference relation $\widetilde{R} = \left(\widetilde{r}_{ij}\right)_{nxn}$.

$$\widetilde{r}_{ij} = ULWA_w\left(\widetilde{r}_{ij}^{(1)}, \widetilde{r}_{ij}^{(2)}, \ldots\ldots, \widetilde{r}_{ij}^{(m)}\right) \quad \text{for all i, j = 1, 2, ……, n} \tag{2.2}$$

The ULWA operator is defined as following: Let U L W A : $\tilde{S}_n \rightarrow \tilde{S}$, if

$$ULWA_{\omega}(\tilde{\mu}_1, \tilde{\mu}_2, ..., \tilde{\mu}_n) = \omega_1 \tilde{\mu}_1 \oplus \omega_2 \tilde{\mu}_2 \oplus ..... \oplus \omega_n \tilde{\mu}_n \tag{2.3}$$

where $\omega = (\omega_1, \omega_2, \ldots, \omega_n\}^T$ is the weighting vector of the $\tilde{\mu}_i$ with $\omega_i \in [0,1]$, and $\sum_{i=1}^{n} \omega_i = 1$.

3) The Uncertain Linguistic Averaging (ULA) operator is utilized

$$z_i = ULA(\tilde{r}_{i1}, \tilde{r}_{i2}, ..., \tilde{r}_{in}), \quad \text{for all i = 1, 2, ……, n} \tag{2.4}$$

to aggregate the preference information $\tilde{r}_{ij}$ (j = 1, 2, …, n) in the i[th] line of the $\tilde{R}$, and then get the global preference degree $\tilde{z}_i$ of the i[th] alternative over all the other alternatives.

The ULA operator is defined as following:
Let ULA : $\tilde{S}_n \rightarrow \tilde{S}$, if $ULA(\tilde{\mu}_1, \tilde{\mu}_2, ..., \tilde{\mu}_n) = \frac{1}{n}(\tilde{\mu}_1 \oplus \tilde{\mu}_2 \oplus ..... \oplus \tilde{\mu}_n)$ (2.5)

4) To rank these global preference degrees $\tilde{z}_i$ (i = 1, 2, …, n), first each $\tilde{z}_i$ is compared with all $\tilde{z}_i$ (i = 1, 2, …, n) by using the following rule.

Let $\tilde{\mu} = [s_\alpha, s_b]$ and $\tilde{v} = [s_c, s_d]$ be two uncertain linguistic variables and let $l_{\alpha b} = b - \alpha$ and $l_{cd} = d - c$. Then the degree of possibility of $\tilde{\mu} \geq \tilde{v}$ is defined as:

$$p(\tilde{\mu} \geq \tilde{v}) = \max\left\{1 - \max\left(\frac{d - \alpha}{l_{\alpha b} + l_{cd}}, 0\right), 0\right\} \tag{2.6}$$

For simplicity, let $p_{ij} = p(\tilde{z}_i \geq \tilde{z}_j)$. Then a complementary matrix is developed $P = (p_{ij})_{nxn}$, where $p_{ij} \geq 0$, $p_{ij} + p_{ji} = 1$, $p_{ii} = 1/2$, for all i, j = 1, 2, …, n. All elements in each line of matrix P are summed up to obtain $p_i = \sum_{j=1}^{n} p_{ij}$, i = 1, 2, …, n. The $\tilde{z}_i$ (i = 1, 2, …, n) are then ranked in descending order in accordance with the values of p_i (i = 1, 2, …, n).

3. ILLUSTRATIVE EXAMPLE

A system of four interacting lifeline components (high voltage electric power substation, telecommunication center, M/R station, potable water well) is assumed. Table 1 presents the multiple connections between the four lifeline components (in economical terms). The table inputs represent the cost which is provided by the i[th] lifeline system's product (commodity) and consumed by the j[th] lifeline system in order to operate. For example, electric power system (EPS) generates products that cost 15,000 euros. From these (15,000 euros), 7,500 euros are used by the EPS itself, 2,500, 3,000 and 2,000 euros are supplied to the potable water well (PWW), Natural Gas M/R Station (NGMR) and Telecommunication Centre (TC) accordingly. Naturally, consumption between independent systems can be assumed as zero. The total supply for each component is calculated by the summation of intermediate consumptions.

Table 1 Multiple connections between the four lifeline components in economical terms

	Electric Power Substation (EPS)	Potable Water Well (PWW)	Natural Gas M/R Station (NGMR)	Telecommunication Centre (TC)
EPS	7,500			
PWW	2,500	500		
NGMR	3,000	700	1,800	
TC	2,000	1,300	2,200	500
TOTAL SUPPLY	15,000	5,000	8,000	6,000

Six experts in the field of lifeline earthquake engineering provided their preferences with respect to the importance of interaction between the systems by using the linguistic terms in the set:

$$S = \{S_{-8} = \text{extremely unimportant}, S_{-7} = \text{very strongly to extremely unimportant}, S_{-6} = \text{very strongly unimportant}, S_{-5} = \text{strongly to very strongly unimportant}, S_{-4} = \text{strongly unimportant}, S_{-3} = \text{moderately to strongly unimportant}, S_{-2} = \text{moderately unimportant}, S_{-1} = \text{equally to moderately unimportant}, S_0 = \text{equally important}, S_1 = \text{equally to moderately important}, S_2 = \text{moderately important}, S_3 = \text{moderately to strongly important}, S_4 = \text{strongly important}, S_5 = \text{strongly to very strongly important}, S_6 = \text{very strongly important}, S_7 = \text{very strongly to extremely important}, S_8 = \text{extremely important}) \tag{3.1}$$

Using the above set, six uncertain additive linguistic preference relations $\tilde{R}^{(k)}(k = 1,2,3,4,5,6)$ as listed in Tables 2-7 were produced for each expert respectively.

Table 2 Uncertain additive linguistic preference relation $\tilde{R}^{(1)}$

Expert: 1 (alex)	x_1 (EPS)	x_2 (PWW)	x_3 (NGMR)	x_4 (TC)
x_1 (EPS)	$[S_0,S_0]$	$[S_{-6},S_{-2}]$	$[S_{-8},S_{-4}]$	$[S_{-5},S_{-1}]$
x_2 (PWW)	$[S_2,S_6]$	$[S_0,S_0]$	$[S_{-7},S_{-3}]$	$[S_{-4},S_0]$
x_3 (NGMR)	$[S_4,S_8]$	$[S_3,S_7]$	$[S_0,S_0]$	$[S_{-1},S_3]$
x_4 (TC)	$[S_1,S_5]$	$[S_0,S_4]$	$[S_{-3},S_1]$	$[S_0,S_0]$

Table 3 Uncertain additive linguistic preference relation $\tilde{R}^{(2)}$

Expert: 2 (kakd)	x_1 (EPS)	x_2 (PWW)	x_3 (NGMR)	x_4 (TC)
x_1 (EPS)	$[S_0,S_0]$	$[S_{-6},S_{-2}]$	$[S_{-5},S_{-1}]$	$[S_{-7},S_{-3}]$
x_2 (PWW)	$[S_2,S_6]$	$[S_0,S_0]$	$[S_{-2},S_2]$	$[S_{-2},S_2]$
x_3 (NGMR)	$[S_1,S_5]$	$[S_{-2},S_2]$	$[S_0,S_0]$	$[S_{-3},S_1]$
x_4 (TC)	$[S_3,S_7]$	$[S_{-2},S_2]$	$[S_{-1},S_3]$	$[S_0,S_0]$

Table 4 Uncertain additive linguistic preference relation $\tilde{R}^{(3)}$

Expert: 3 (arg)	x_1 (EPS)	x_2 (PWW)	x_3 (NGMR)	x_4 (TC)
x_1 (EPS)	$[S_0,S_0]$	$[S_{-8},S_{-5}]$	$[S_{-6},S_{-2}]$	$[S_{-7},S_{-3}]$
x_2 (PWW)	$[S_5,S_8]$	$[S_0,S_0]$	$[S_{-3},S_1]$	$[S_{-2},S_2]$
x_3 (NGMR)	$[S_2,S_6]$	$[S_{-1},S_3]$	$[S_0,S_0]$	$[S_{-4},S_0]$
x_4 (TC)	$[S_3,S_7]$	$[S_{-2},S_2]$	$[S_0,S_4]$	$[S_0,S_0]$

Table 5 Uncertain additive linguistic preference relation $\tilde{R}^{(4)}$

Expert: 4 (plia)	x_1 (EPS)	x_2 (PWW)	x_3 (NGMR)	x_4 (TC)
x_1 (EPS)	$[S_0,S_0]$	$[S_{-4},S_0]$	$[S_{-8},S_{-4}]$	$[S_{-8},S_{-6}]$
x_2 (PWW)	$[S_0,S_4]$	$[S_0,S_0]$	$[S_{-6},S_{-2}]$	$[S_{-8},S_{-6}]$
x_3 (NGMR)	$[S_4,S_8]$	$[S_2,S_6]$	$[S_0,S_0]$	$[S_{-6},S_{-2}]$
x_4 (TC)	$[S_6,S_8]$	$[S_6,S_8]$	$[S_2,S_6]$	$[S_0,S_0]$

Table 6 Uncertain additive linguistic preference relation $\widetilde{R}^{(5)}$

Expert: 5 (pit)	x_1 (EPS)	x_2 (PWW)	x_3 (NGMR)	x_4 (TC)
x_1 (EPS)	$[S_0,S_0]$	$[S_{-8},S_{-4}]$	$[S_{-8},S_{-4}]$	$[S_{-4},S_0]$
x_2 (PWW)	$[S_4,S_8]$	$[S_0,S_0]$	$[S_{-8},S_{-5}]$	$[S_{-8},S_{-5}]$
x_3 (NGMR)	$[S_4,S_8]$	$[S_5,S_8]$	$[S_0,S_0]$	$[S_{-3},S_1]$
x_4 (TC)	$[S_0,S_4]$	$[S_5,S_8]$	$[S_{-1},S_3]$	$[S_0,S_0]$

Table 7 Uncertain additive linguistic preference relation $\widetilde{R}^{(6)}$

Expert: 5 (hatz)	x_1 (EPS)	x_2 (PWW)	x_3 (NGMR)	x_4 (TC)
x_1 (EPS)	$[S_0,S_0]$	$[S_{-8},S_{-4}]$	$[S_{-6},S_{-2}]$	$[S_{-2},S_2]$
x_2 (PWW)	$[S_4,S_8]$	$[S_0,S_0]$	$[S_{-6},S_{-2}]$	$[S_{-2},S_2]$
x_3 (NGMR)	$[S_2,S_6]$	$[S_2,S_6]$	$[S_0,S_0]$	$[S_{-2},S_2]$
x_4 (TC)	$[S_{-2},S_2]$	$[S_{-2},S_2]$	$[S_{-2},S_2]$	$[S_0,S_0]$

Following the method described above, a collective uncertain additive linguistic preference relation $\widetilde{R} = \left(\widetilde{r}_{ij}\right)_{4x4}$ is estimated as below:

$$\widetilde{R} = \begin{bmatrix} [s_0, s_0] & [s_{-6.67}, s_{-2.83}] & [s_{-6.83}, s_{-2.83}] & [s_{-5.5}, s_{-1.83}] \\ [s_{2.83}, s_{6.67}] & [s_0, s_0] & [s_{-5.33}, s_{-1.5}] & [s_{-4.33}, s_{-0.83}] \\ [s_{2.83}, s_{6.83}] & [s_{1.5}, s_{5.33}] & [s_0, s_0] & [s_{-3.17}, s_{0.83}] \\ [s_{1.83}, s_{5.5}] & [s_{0.83}, s_{4.33}] & [s_{-0.83}, s_{3.17}] & [s_0, s_0] \end{bmatrix}$$

The opinion of each expert is assumed as equal that is $\omega = (0.167, 0.167, 0.167, 0.167, 0.167, 0.167\}^T$.

Afterwards, the ULA operator $z_i = ULA(\widetilde{r}_{i1}, \widetilde{r}_{i2}, \widetilde{r}_{i3}, \widetilde{r}_{i4})$ is utilized to aggregate the preference information (step 3) in order to get the global preference degree $\widetilde{z}_i$ of the i^th preference over all the other preferences: $\widetilde{z}_1 = [s_{-4.75}, s_{-1.88}]$, $\widetilde{z}_2 = [s_{-1.71}, s_{1.08}]$, $\widetilde{z}_3 = [s_{0.29}, s_{3.25}]$, $\widetilde{z}_4 = [s_{0.46}, s_{3.25}]$.

Finally, we construct the complementary matrix (step 4) that is the "cross impact matrix" of interconnected lifelines of (Eqn.1.2):

$$P = \begin{bmatrix} 0.50 & 0 & 0 & 0 \\ 1.00 & 0.50 & 0.14 & 0.11 \\ 1.00 & 0.86 & 0.50 & 0.49 \\ 1.00 & 0.89 & 0.51 & 0.50 \end{bmatrix}$$

As an example, the cross impact factor between PWW and NGMR is $a_{PWWNGMR} = 0.86$ and between PWW and TC is $a_{PWWTC} = 0.89$.

Fragility curves of interdependent components are estimated applying Eqn.1.2. For example, the estimation of the fragility curve of the electric power substation-EPS as an interdependent element is performed for each damage state i using the fragility curves of the three independent elements of PWW, NGMR and TC and the cross impact factors between the study element and the other three (Eqn. 3.2).

$$P(E_{EPS1})_i = P(E_{EPS0})_i + (1-P(E_{EPS0})_i) * P(E_{PWW0})_i * a_{EPSPWW} + (1-P(E_{EPS0})_i) * P(E_{NGMR0})_i * a_{EPSNGMR} + (1-P(E_{EPS0})_i) * P(E_{TC})_i * a_{EPSTC}, \quad \text{i=minor, moderate, extensive, complete damages} \tag{3.2}$$

Figures 2a – 2d illustrate the comparison between the fragility curves of the independent lifeline component (illustrated with "0" mode) and the fragility curves of interdependent components as calculated from the procedure described previously (illustrated with "1" mode).

If infrastructure i depends on infrastructure j, and j has a high risk of failure, then the likelihood of i being disrupted or failing is correspondingly higher than if i was independent of j. In the case of the three interconnected elements (EPS, PWW and NGMR) of the example, the derived fragility curves are quite different from those referring to independent elements. Only for the telecommunication center, the estimated probability in a specific damage state of the independent element is rather close to the estimated probability in the same damage state of interdependent element.

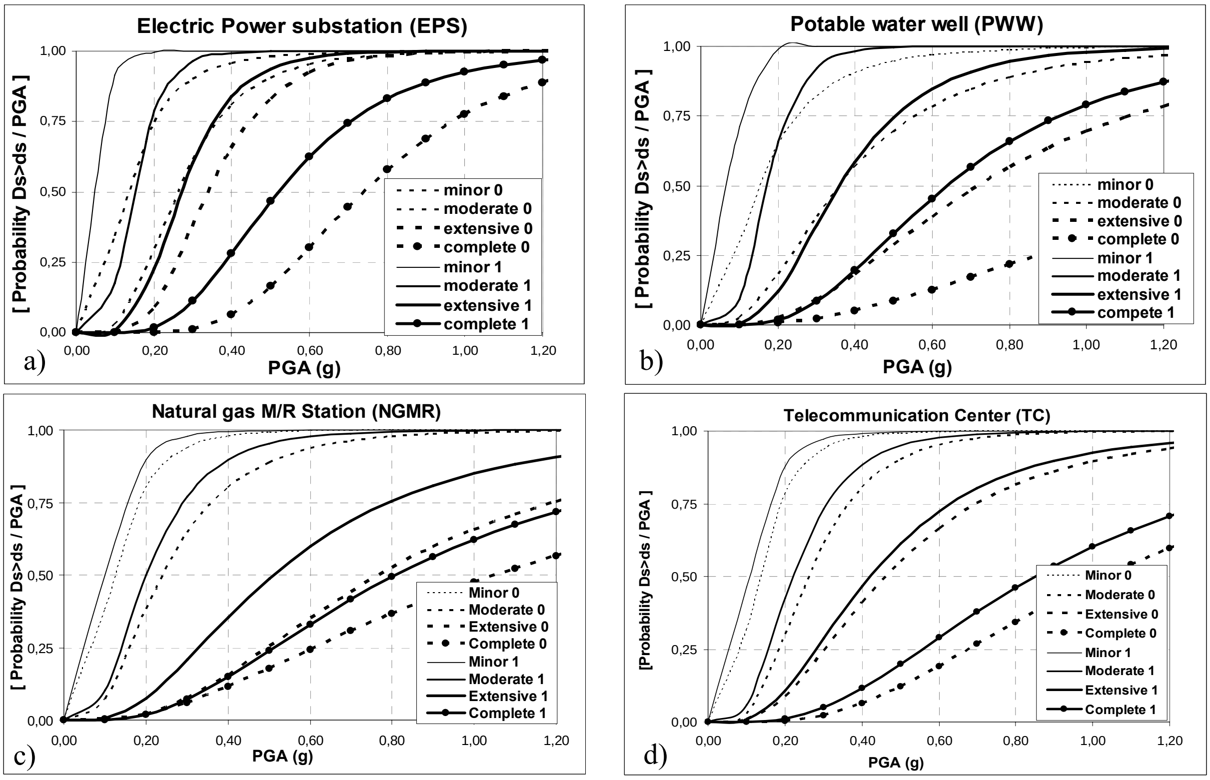

Figure 2 Fragility curves of a) electric power substation (EPS), b) potable water well (PWW), c) natural gas M/R Station (NGMR), and d) telecommunication center (TC) – independent "0"/ interdependent "1" component.

Both in the case of EPS and PWW the fragility curves of the moderate, extensive and complete damage state of the interdependent component is similar with the fragility curve of minor, moderate and extensive damage state of the independent components. For NGMR the fragility curve for the extensive damage state of the independent component is similar with the fragility curve of complete damage state of interdependent component. As a general notice, important differences between independent and interdependent fragility curves exist in the case of moderate, extensive and complete damages above the range of 0.30g respectively. Thus, the prominent effect of the existing interactions between the four elements is evident in the assessment of seismic vulnerability of the interdependent elements.

4. CONCLUSIONS

Infrastructure systems are highly interdependent systems. Capturing and quantifying lifeline interactions are very important aspects within an advanced seismic risk management study of a complex city system. Within this framework, a method is proposed to simulate interdependent lifelines' vulnerability based on an interactive relationship using uncertain additive linguistic preference relations that includes a fuzzy reasoning and can be directly applied to group decision making problems without loss of information.

Furthermore, the notion of propagated inoperability and "systemic vulnerability" is introduced. Fragility curves of the interdependent components are estimated based on the vulnerability functions of independent elements and the "cross impact matrix". Using an illustrative example, the efficiency of the proposed methodology to evaluate the expected seismic performance of complex interacting lifelines (electric power sub-stations, potable water wells, natural gas M/R stations and telecommunication network) is demonstrated. As proved, the inter-dependency of sub-components of different systems increases the seismic vulnerability. Thus, for the same level of seismic excitation, the level of anticipated losses and corresponding loss of functionality are enhanced based on the type and degree of interactions between sub-components and the multiple connections between. The inherent uncertainties on the level of the interdependencies and the way these connections are captured and interpreted are treated by means of fuzzy reasoning. Incorporation of systems' intra-dependencies and generalization of the proposed methodology to address the vulnerability assessment of multiple interacting infrastructure systems consisting of a number of different subcomponents, are the issues where future research will focus on.

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