A Time-Dependent Seismic Resilience Analysis Approach for Networked Lifelines

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ABSTRACT: This paper presents an integrated resilience-based modeling approach for assessing the resilience of coupled networked lifeline systems considering as input-spaces their capacity, fragility, and response actions, including those informed by engineering and community-based policy. We develop a time-dependent resilience concept for systems under seismic hazards, which rests upon a flow-based core for assessing performance while considering interdependencies among them. This approach relies on robust mathematical optimization techniques for studying distributed systems and their ability to allocate limited resources in time during the recovery process. The proposed approach not only outperforms typical connectivity based assessments with a better physical approximation of lifelines, but also is proven practical computationally as it enables sensitivity assessments to redundancy, robustness, and resourcefulness in the context of interdependent lifelines geared towards improving resilience. For lifeline benchmark models we found that provisioning a minimum size of restoration can increase time-dependent resilience as much as 25% for relatively fragile systems.

1. INTRODUCTION

Networked lifeline systems, or simply lifelines thereafter, are critical distributed systems for modern societies. They are necessary for guaranteeing communities' stability and wellbeing. However, they are becoming more interdependent due to an aggregation of socio-economical and technical reasons such as population growth and efficient exchange of services in normal operation.

It has been shown that interdependencies increase lifelines susceptibility to cascading failures (Buldyrev et al. 2010; Dueñas-Osorio et al. 2007), thus neglecting them underestimates the overall consequences from disruptions across and among systems. Therefore, a great portion of past and current research has focused on developing methods and tools to predict the response of interconnected systems to external disruptions. Moreover, interdependencies in the context of critical infrastructures is a relatively new area of research and quantification efforts are still in its infancy (Chan and Dueñas-osorio 2014; Dueñas-Osorio and Kwasinski 2012; Paredes et al. 2014). Furthermore, resilient communities are able to persist against natural and man-made disasters. In this context, dimensions of community resilience have been proposed (Bruneau et al. 2003), and among the technical ones stand resourcefulness, robustness and redundancy. This work links interdependencies across lifelines with their resilience properties.

When measuring technical resilience, the 'classic' metric considers the difference between the areas below the performance (P) and target performance (TP) curves within a control time required for full system restoration t_f (Bruneau et al. 2003). However, this metric does not convey enough information about the ability of a system to recover to normal operation, and its development for lifelines is less mature than for structural systems. In order to overcome ambiguity and limitations of the classic metric (e.g. account for multiple hazards and their multiple occurrence, as well as custom restoration strategies for lifelines) the concept of time-dependent infrastructure resilience has been introduced (Ouyang and Dueñas-Osorio 2012). Considering a time horizon T (which could also be a lifetime), a time-dependent resilience $R(T)$ metric can be computed as:

$$R(T) = \frac{\int_0^T P(t)dt}{\int_0^T TP(t)dt} \quad (1)$$

Despite these efforts, there is neither general consensus on a standard metric for measuring resilience (Miller-Hooks et al. 2012), nor a standard definition of resilience. However, there is a growing interest towards modeling and studying the resilience of lifelines computationally (e.g. Cimellaro et al. 2010), so as to accelerate research and gain insights on the impacts of lifelines resilience on the community (Chang and Rose 2012). The paper is structured as follows: Section 2 describes the framework to analyze resilience of infrastructures systems subject to earthquakes considering interdependencies. Section 3 presents the design of experiments and artificial systems considered to perform sensitivity analyses on parameters influencing $R(T)$ and its uncertainty. Section 4 discusses the results from sensitivity analyses and identify performance trends for practical application. Section 5, provides relevant conclusions and an outline for future research.

2. TIME-DEPENDENT RESILIENCE ASSESSMENT

This section describes an approach for assessing the resilience of interdependent distributed systems within a time horizon in the context of seismic hazards. This approach is consistent with the three-stages of resilience by Ouyang et al. (2012), which are disaster prevention, damage propagation process, and the recovery process. Nevertheless, we consider flows among interdependent networks (Lee II et al. 2007), so as to more realistically assess the service level of networked lifelines and decide their restoration strategies.

Although the notion of resilience encompasses various dimensions (Bruneau et al. 2003), this paper is mostly concerned with the technical dimensions of resilience. In this context, we assess lifeline's resilience underlining their capacity to recover services. The backbone of the proposed approach has three major modules: local fragility assessment, systemic fragility assessment considering interdependencies, and a time-dependent resilience analysis.

2.1. Assessment of Local-Level Fragilities

Component failure probabilities are fully described by means of fragility curves. Often, empirical or analytical fragility curves are not available due to lack of data or their computational cost (Lin et al. 2012), therefore an standardized method for multihazard risk analyses (HAZUS 2003) is frequently used as source of fragilities for main elements of utility systems (e.g. substations, generation plants and transmission lines of the power network) in the United States.

The proposed approach allows considering multiple hazards due to its consistency with the three-stages of resilience framework, however, in a first attempt to illustrate in-depth explorations of resilience dimensions in networked lifelines, we consider the seismic hazard only. Ground motion models (Jayaram and Baker 2009) are used to generate seismic Intensity Measures (IM) for each component location. These methods ensure risk-consistent studies of infrastructure networks accounting for the distribution of IM and enable estimating performance loss exceedance curves.

2.2. Vulnerability Assessment of Interdependent Systems

In this study we adopt a network flows approach acknowledging physical interdependencies among infrastructure systems. Most of the studies have considered connectivity or accessibility to assess the performance of the system (e.g. Poljanšek et al. 2012), those considering flows limit their scope to vulnerability assessments of systems (e.g. Ouyang et al. 2009) or have not considered interdependencies yet (e.g. Miller-Hooks et al. 2012); recent studies considering flows, however, have been focusing in the restoration process only (e.g. González et al. 2014) or when focusing on both resilience and vulnerability (Franchin and Cavalieri 2014) do not consider availability of resources for establishing recovery strategies.

Although connectivity or reachability is a necessary requirement for the function of lifelines, it is not sufficient because it neglects the capacity of generating and transporting their respective commodities. For this reason, we analyze the functionality of lifelines after a given event considering their residual generation capacity and its optimal flow and resource allocation across the capacitated networks to supply demanded services as much as possible. We can solve this problem using a Mixed Integer Linear Programming (MILP) formulation as a building block to assess the performance of the systems after a seismic event. The formulation used is in the next subsection (fixing the value of parameter v_k to 0 to assess level of performance only).

2.3. Resilience analysis

We adopt a time-dependent resilience metric (Ouyang et al. 2012) to conduct analyses of resilience and its dimensions within an arbitrary time period (e.g. life cycle). Also, we adopt two assumptions in terms of prioritizing recovery actions. First, the restoration strategies will aim to reduce shortfalls or percentage of impacted costumers which, besides restoring essential facilities, is what utility managers do in practice after a significant shock (Branningan 2014). Second, restoration ends when a target level of performance is achieved and, although any target level can be adopted, we will assume for simplicity the original performance level; also, restoration may end prematurely if time T has been exceeded. What-if analyses within this framework support actions increasing lifelines resilience, informing retrofits, and appropriately sizing restoration resources (e.g. spare parts and personnel). This resilience assessment helps reducing uncertainty in potential losses estimates for seismic scenarios across distributed systems, and, if used to support mitigation measures, reduces the potential losses themselves.

In order to make this assessment more attractive to stakeholders, we adopt an optimization supported decision making approach. These techniques establish restoration sequences assessing the recovery capacity of lifelines and improve current assessments in practice, mainly based on empirical judgment (Branningan 2014). For simplicity, we will consider the case of lifelines getting back to normal operation via repairing and rebuilding them to their original state. Nevertheless, it should be noted that the right aim towards restoring infrastructures is to exploit the opportunity of reconstruction to build them more resilient (e.g. considering relocation, reconfiguration, and retrofitting). For this purpose, we adopt an iterative approach (González et al. 2015) that has proven computationally efficient for finding restoration sequences. Although in practice available resources for restoration comprise many aspects (e.g. workforce and spare-part availability), we will capture this phenomena in the form of simultaneous repairs and reconstruction jobs tied to resources v. Also, for illustrative purposes we will assume that recovery jobs have fixed duration Δt_j. The used MILP formulation is described next.

Let $G(N, A)$ be a graph, where N is the set of all infrastructures nodes and A is the set of all infrastructure arcs. Moreover, let K be the set of all infrastructure networks (e.g. power and potable water networks). Similarly, let L be the set of commodities that can flow across and among infrastructures (e.g. electricity and water). Furthermore, let the subgraph $G_{k\bar{k}}(N_{k\bar{k}}, A_{k\bar{k}})$ be an infrastructure $k \in K$ when $k = \bar{k}$, with set of nodes $N_{kk} \in N$ and set of arcs $A_{kk} \in A$, or the interface between infrastructures $k \in K$ and $\bar{k} \in K$ when $k \neq \bar{k}$, with interface nodes $N_{k\tilde{k}} \in N$ and arcs $A_{k\tilde{k}} \in A$ from infrastructure $k \in K$ to infrastructure $\bar{k} \in K: \{\bar{k} = \tilde{k}, k \neq \tilde{k}\}$. Each infrastructure $k \in K$ has an associated subset $L_k \epsilon L$ denoting the commodities $l \in L_k$ that can flow across nodes N_{kk} and arcs A_{kk}, and that can also flow in the interface nodes $N_{k\tilde{k}}$ and arcs $A_{k\tilde{k}}$, $\forall \tilde{k} \in K: k \neq \tilde{k}$.

Each infrastructure $k \in K$ and node $i \in N_{kk}$ has an associated demand or supply $b_{ikl\bar{k}}$ of commodity $l \in L_{\bar{k}}$ associated to infrastructure $\bar{k} \in K$. When $b_{ikl\bar{k}} < 0$, i is a supply node of commodity $l \in L_{\bar{k}}$; if $b_{ikl\bar{k}} = 0$, i is a transshipment node of commodity $l \in L_{\bar{k}}$. More specifically, when $k = \bar{k}$, b_{iklk} is a service supply or demand of commodity $l \in L_k$; conversely, when $k \neq \bar{k}$, $b_{ikl\tilde{k}}$ is an interdependent demand of commodity $l \in L_{\tilde{k}}$ that node $i \in N_{kk}$ requires for operation. Each node $i \in N_{kk}$ has a reconstruction cost denoted by q_{ik}. Likewise, each arc $(i,j) \in A_{kk}$ of infrastructure $k \in K$ has an associated cost of reconstruction f_{ijk}, capacity u_{ijk}, and unit flow cost c_{ijkl} per unit flow of commodity $l \in L_k$. Moreover, M^{-}_{ikl} is the unit cost of commodity $l \in L_k$ that has not been supplied to node $i \in N_{kk}$. Furthermore, the parameters $y0_{ijk\bar{k}}$ and $w0_{ik}$ take the value of 1 if the arc $(i,j) \in A_{kk}$ and node $i \in N_{kk}$ respectively are not destroyed, and 0 otherwise. Also, each infrastructure $k \in K$counts with a limited amount of resources (e.g. workforce, spare parts availability and budget), thus limiting the number of nodes and/or arcs v_k per infrastructure that can be reconstructed.

The flow of commodities $l \in L_k$ through arc $(i,j) \in A_{k\bar{k}}$ is represented by the continuous variable $x_{ijk\bar{k}l}$. Furthermore, the binary variables $y_{ijk\bar{k}}$ and w_{ik} take the value of 1 if arc $(i,j) \in A_{k\bar{k}}$ and node $i \in N_{kk}$ are functional, and 0 otherwise. Also, the continuous variables $\delta^{-}_{ikl\bar{k}}$ and $\delta^{+}_{ikl\bar{k}}$ represent respectively the deficit and surplus of commodities $l \in L_{\bar{k}}$ at node $i \in N_{kk}$ in infrastructure $k \in K$. In addition, binary variables yr_{ijkk} and wr_{ik} take the value of 1 if the arc $(i,j) \in A_{kk}$ and node $i \in N_{kk}$ respectively are to be repaired, and 0 otherwise.

The problem of assessing the performance level and deciding restoration actions is formulated according to the next formulation.

minimize

$$\sum_{k\in K}\left(\sum_{\bar{k}\in K}\left(\sum_{l\in L_k}\left(\sum_{(i,j)\in A_{k\bar{k}}} c_{ijk\bar{k}l}x_{ijk\bar{k}l}\right)\right) + \sum_{l\in L_k}\left(\sum_{i\in N_{kk}} M^{-}_{ikl}\delta^{-}_{iklk}\right) + \sum_{i\in N_{kk}} wr_{ik}\, q_{ik} + \sum_{(i,j)\in A_{kk}} f_{ijk}yr_{ijkk}\right) \tag{2}$$

subject to

$$\sum_{j:(i,j)\in A_{k\bar{k}}} x_{ijk\bar{k}l} - \sum_{j:(j,i)\in A_{k\bar{k}}} x_{jik\bar{k}l} = b_{ikl\bar{k}} - \delta^{-}_{ikl\bar{k}} + \delta^{+}_{ikl\bar{k}} \quad \forall k,\bar{k}\in K, \forall i\in N_{k\bar{k}}, \forall l\in L_{\bar{k}}, \tag{3}$$

$$\sum_{l\in L_{\bar{k}}} x_{ijk\bar{k}l} \leq y_{ijk\bar{k}}u_{ijk\bar{k}l} \quad \forall k,\bar{k}\in K, \forall (i,j)\in A_{k\bar{k}} \tag{4}$$

$$\sum_{l\in L_{\bar{k}}} x_{ijk\bar{k}l} \leq w_{ik}u_{ijk\bar{k}l}, \quad \forall k,\bar{k}\in K, \forall (i,j)\in A_{k\bar{k}}, \tag{5}$$

$$\sum_{l\in L_{\bar{k}}} x_{ijk\bar{k}l} \leq w_{j\bar{k}}u_{ijk\bar{k}l}, \quad \forall k,\bar{k}\in K, \forall (i,j)\in A_{k\bar{k}}, \tag{6}$$

$$w_{ik}b_{ikl\tilde{k}} \leq b_{ikl\tilde{k}} - \delta^{-}_{ikl\tilde{k}}, \quad \forall k,\tilde{k}\in K: k\neq \bar{k}, \quad \forall i\in N_{k\bar{k}}: b_{ikl\tilde{k}} < 0,\ \forall l \in L_{\tilde{k}} \tag{7}$$

$$w_{ik} \leq w0_{ik} + wr_{ik}, \forall k\in K, \forall i\in N_{kk} \tag{8}$$

$$y_{ijk\bar{k}} \leq \left(y0_{ijk\bar{k}} + yr_{ijk\bar{k}}\right), \quad \forall k,\bar{k}\in K, \forall (i,j)\in A_{k\bar{k}}, \tag{9}$$

$$\sum_{i\in N_{kk}} wr_{ik}\, q_{ik} + \sum_{(i,j)\in A_{kk}} f_{ijk}yr_{ijkk} \leq v_k, \quad \forall k\in K, \forall i\in N_{kk}, \forall (i,j)\in A_{kk} \tag{10}$$

The objective function (2) minimizes the deficit of supplying services (i.e. maximizes performance) while reducing operation and reconstruction costs. Constraint (3) ensures conservation of flows considering supply/demands deficits. Constraint (4) limits the capacity of arcs considering their functional state. Constraints (5) and (6) guarantee that arcs whose end-nodes are failed cannot be used for operation. Constraint (7) restricts the operation of nodes whose interdependent demands are not satisfied. Constraint (8) and (9) prevent damaged nodes and arcs to be used unless repaired. Constraint (10) limits the amount of nodes and/or arcs that can be reconstructed per infrastructure.

As resources become available, the previous MILP formulation decides which components should be repaired for all lifelines. Therefore, a time dependent performance curve can be constructed on the basis of performance measurements with relative distance Δt_j in the time axis.

3. COMPUTATIONAL EXPERIMENT DESIGN SETUP

Computational experiments are conducted to explore the input variable space effects on resilience and their interaction. We will study the next *dimensions* (Bruneau et al. 2003) of technical resilience: redundancy, in the form of alternating paths to transport and deliver services; robustness, in the form of reliability of local components; and resources, in the form of number of components (v_k) that can be repaired in a period of time Δt_j. We will also consider short and long term management effects via the ratio $\Delta t_j/T$, which captures the relative time scale between restoration logistics and a time horizon of interest for decision making.

For carrying out this sensitivity analysis we use artificial systems whose topology is adjustable, which enables measuring input effects on resilience without confounding factors of real heterogeneous network topologies. A procedure to generate randomized ideal *capacitated networks* is described in the next subsection.

3.1. Topology

In this study we consider the grid network model and its two extremal topologies, namely the Greedy Triangulation (GT) and the Minimum Spanning Tree (MST) constructions (Buhl et al. 2006). These models exemplify highly redundant and minimally connected planar networks respectively. Also, we consider a variant of the GT model, the pseudo-Greedy Triangulation (p-GT). The former may contain connections between nodes that are relatively far apart respect every other pairs, which generally is not the case in real networks due to the cost of building such lengthily connections. The p-GT model disregard connections between nodes that are farther away than the third neighbors. Furthermore, we consider lifeline components' spatially distributed following a two dimensional regular lattice layout. Also, networks will be embedded in a square of length 1 and the total (100%) population served is uniformly distributed in a square of length 1,111 sharing the same center.

3.2. Interdependencies

Interdependencies among infrastructures are typically studied using the interdependence strength I_{str} (Poljanšek et al. 2012), which captures the probability of propagation of component failures among systems. Nevertheless, because in the framework of this paper we can formulate actual flows among systems (Lee II et al. 2007), we will consider interdependence as physical flow exchanges among systems.

For simplicity, we consider two networks (i.e. power and water) with grid topology. Also, to assess the effect of interdependencies we consider two cases reflecting high and low availability of back-up systems. First, a percentage (10%) of water network nodes require incoming power flows. Second, a high percentage (90%) of water network nodes require incoming power flows. Lastly, for the purpose of modelling, interconnections are established based in geographical proximity.

3.3. Operational properties

Since the purpose of this experimental setup is to illustrate the practical use and computational suitability of flow-based resilience sensitivity analyses, we first generate ideal "capacitated networks" under the next set of assumptions. First, the population and associated demands are uniformly distributed across space. Second, the generation resources are heterogeneous across space, yet, sufficient to supply the population before a shock. Lastly, there is a limited number of nominal edge capacities that can be used to design the networks.

Enabling flow analyses requires operational properties from power and water networks. The summary steps for generating capacitated networks is as follows:

1. Randomly extract groups of nodes from the total population and assign a respective functional responsibility (i.e. generation, distribution, and transshipment). We adopt the proportions for a case study in the Shelby County, TN (Adachi and Ellingwood 2008).
2. Assign demands to distribution nodes using a nearest neighbor criteria.
3. Assign generation capacities using a random number generator following a power-law distribution to capture the spatial heterogeneity of available resources.
4. As reference for design, compute the minimum cost flow of networked systems assuming quadratic costs for all edges and maximum nominal capacity to distribute the flows across the network. Then, compute a histogram of the flows for each system and extract the highest values from the 33rd, 67th and 100th percentiles respectively.
5. Assume the previous values as nominal capacities in which the construction cost of each arc is directly proportional to its capacity, and design the network assuming arc capacities as discrete variables (Osiadacz and Gorecki 1995).

The previous steps yield ideal networks, yet, these systems feature real lifelines characteristics remaining tractable for interpreting sensitivity analysis of infrastructures' resilience dimensions.

4. SIMULATION RESULTS FOR IDEALIZED LIFELINES

This section analyzes the simulation results of networks subjected to seismic hazards, with realistic fragilities, and pursuing measures of resilience for the two cases. *Independent networks*, using extremal topological constructions and *Interdependent networks*, using grid topologies and different levels of interdependence.

4.1. Independent networks

Figure 1 shows the effects of enhancing resilience dimensions for the same water network realization. It is interesting to note the effect of $\Delta t_j/T$ on $R(T)$. When t_f and T are about the same order, resources seem to impact resilience the most, whereas when T grows larger, both resources and robustness seem to be equally important. It should be noted that in this study the enhancement of robustness was not optimized, and therefore the rate of increase in resilience towards this direction is rather low when comparing the increase of the same rate in the resources direction that has been optimized (Eq. 2). When analyzing the effect of redundancy in Figure 1, it interacts with system robustness and resources in a similar fashion as evidenced by the translation of the response surface in the expected *t-d* resilience axis. This is consistent with the fact that as redundancies increase, from the MST to the p-GT model, increasing robustness and resources allows for more components surviving the event and more possibilities of reconfiguring the system when improving performance.

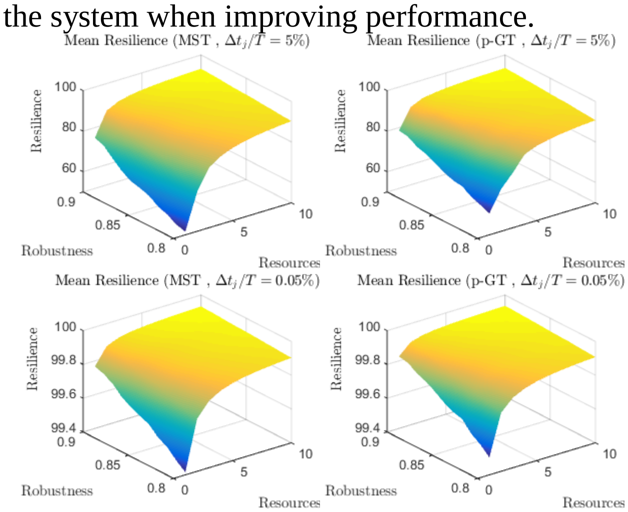

Figure 1. Estimated t-d Resilience as a function robustness and resources for the MST and p-GT water network models and different $\Delta t_j/T$ values.

4.2. Interdependent networks

In this subsection, we discuss results for the cases of low and high interdependence between the power and water networks.

Figure 2 shows the degradation of estimated performance $\bar{P}(t)$ for both systems when interdependencies are present. In the first case, both systems can be restored at similar rates due to the low coupling, although the power system seems to recover slightly faster in the first stages due to physical interdependence; however, at advanced stages, the water system recovers faster. Even if the advantage of the water system is not significant and within the uncertainty levels of this study (1000 iterations), the cause of this advantage are the proportions of generation and distribution nodes for both networks, as the water systems presents a greater number of generating nodes that can favor its recovery after overcoming physical interdependence during later stages. Also, as expected, the second case shows how increasing interdependencies impacts the performance of the water system. It is interesting to note that increasing interdependence does not cause uncertainty to increase using the restoration algorithm in Section 2. We have confirmed this for intermediate levels of interdependence.

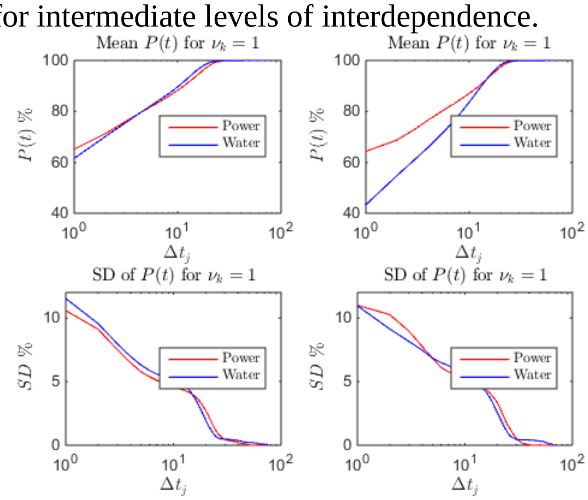

Figure 2. Performance curves for the two interdependence levels studied. Low coupling (left) high coupling (right).

5. CONCLUSIONS

An approach for studying input sensitivity on the potential performance loss of utility systems due to seismic hazards considering aftermath response actions is introduced in this study. The time-dependent resilience analysis supports non-linear network flow effects on resilience when considering different time horizons. Insights on how resources should be prioritized include favoring resourcefulness enhancement of the system for increasing short-term resilience, whereas for long-term resilience enhancing robustness, redundancy and resourcefulness are equally important.

Also, the formulation used in this paper supports integrating interdependencies in the decision making-process, which shows it helps managing uncertainty in networked lifelines when coupling is either low or high.

Future research could expand this approach to the multihazard context, integrating it into the life-cycle assessment of lifelines using optimization based resilience enhancements for robustness and redundancies, to account for the potential evolution in resilience of the system (from deployment to refurbishing to decommissioning). Lastly, systematic explorations with new parameters capturing interdependence are encouraged, here we used the percentage of nodes requiring inputs from an external system.

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