Paper N° 1783

Registration Code: S-I1463143724

Seismic Resilience of Integrated Critical Infrastructure Network System

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Abstract

In order to examine the seismic resilience of the integrated electric power supply, transportation and community system, an Agent-Based Modeling (ABM) framework is developed and presented in this paper. Three agents, the community Administrator, the Operator of Electric Power Supply System (EPSS) and the Operator of Transportation System (TS), are defined and considered. Their individual behavior as well as the interaction patterns are defined using a set of agent attributes. The recovery trajectories of the power demand from the community, the power supply capacity of EPSS, and the functionality of TS can, therefore, be modeled using a compositional supply/demand approach. The seismic resilience of an example EPSS-TS-Community system is examined using the proposed ABM framework. Parametric studies are conducted to investigate the impact of different earthquake scenarios and different agents′ behavioral attributes on the system resilience. The interdependency between the two infrastructure systems is found to significantly affect the recovery path for the integrated EPSS-TS-Community system.

Keywords: Seismic Hazard; Interdependency; Electric Power Supply System; Transportation System; Resilience

1. Introduction

The modern Critical Infrastructures (CIs) are becoming more integrated and interdependent through sharing of resources and information [1]. While such interdependency affords more efficient operation of the CIs, it simultaneously renders them more vulnerable to disruptive events such as natural hazards, terrorist attacks, and random operational errors [2]. The resulting local damage can cascade through one or more CIs and lead to the severe global failure of the system of CIs [3, 4]. According to the field observations from the recent catastrophic earthquake disasters around the world, the damaged CIs are usually struggling to recover from the initial damage they have sustained [5]. Moreover, the sluggish recovery of one CI usually hampers the restoration of many other CIs, as well as the rescue and evacuation of people in the affected areas [6, 7]. In this paper, a framework to quantify the seismic resilience of an integrated CI system is proposed. Specifically, the Electric Power Supply System (EPSS), the Transportation System (TS), and the corresponding inhabited Community they serve, are considered. The Agent-Based Modeling (ABM) method is employed in this framework to model the recovery of the intertwined EPSS and TS after an earthquake. The three individual agents, the operators of EPSS and TS, and the community Administrator, are defined by attributes that model their behaviors during the post-earthquake recovery process. More importantly, the rules for the interaction among these agents are specified.

The developed framework is exemplified using a case study CI system. The recovery trajectory of the system is computed under different seismic scenarios. The impact of the interdependence between EPSS and TS on the systemic resilience behavior is highlighted. The influence of different agent behavior characteristics on the resilience behavior of the system, is also considered and discussed.

2. The Agent-Based Modelling Framework

Modern CI-Community system is a complex and interconnected socio-technical network. Its recovery and resilience behavior following extreme natural events is dynamic and contingent on many influential actors [8, 9].

In a typical earthquake, the components of all the CIs and the elements of the built environment of the corresponding community would be damaged to some degree. After (some) information about the damage state of a CI has been collected, the recovery process starts as the repair teams of each CIs are sent to repair the damaged facilities. Typically, CIs act independently, following their own repair prioritization plans. However, owing to the interdependence among different CIs, the recovery process of single CI would affect, and in turn, be influenced by the restoration of the other CIs, as well as by the recovery of the affected community.

A compositional supply/demand for modeling the post-earthquake recovery process of the CI-Community system and measuring its resilience [10, 11] is extended in this study to analyze the interdependencies occurring during the post-disaster recovery process. To achieve this goal, the recovery paths of the CIs are modeled using an Agent-Based Modeling paradigm to account for the different strategies and capabilities of the entities involved in the recovery process [12]. It was assumed that the post-disaster recovery priorities of the CIs are governed by their business needs and repair costs and effort, not necessarily by the recovery requirements of the community. Therefore, the recovery process may need to be overseen and coordinated externally. A community administrator, typically an emergency management coordination entity, assumes such a role.

Without loss of generality, only the EPSS and TS CIs are incorporated in the model presented in this paper. Therefore, three principal players, the **EPSS Operator**, the **TS Operator** and the community **Administrator** are modeled using separate agents. The **EPSS Operator** and **TS Operator** agents follow predefined recovery plans based on independently-derived repair priority schemes constrained by their own resources. Crucially, a successful implementation of the EPSS recovery plan depends on the availability of roads: EPSS repair crews can only go to the substations by driving along the instantaneously available roads and bridges, which are simultaneously undergoing a repair process. Therefore, most efficient path for the EPSS repair crews along the available roads is computed using the state of the TS in each new time step. Finally, it is likely that the repair priorities for the Community and the CIs will differ during the post-disaster recovery process. The **Administrator** agent is, therefore, defined to coordinate the CI recovery campaign and optimize the outcome with respect to predefined community priories. The behavior of the agents is defined using random variables called attributes and pre-defined repair plans as follows:

- **EPSS and TS Operators** are agents whose behaviors is described by three attributes: *Speed*, *Efficiency* and *Enforcement Power*. The *Speed* attribute quantifies the average travelling velocity of the repair team between different repair locations; the *Efficiency* describes restoration rate expressed as the percentage of component functionality restoration per day; and the *Enforcement Power* defines the degree with which the agent can stick to its own repair plan. Each CI agent has a repair plan, specifying a sequence of component repairs, developed to satisfy a set of CI performance objectives.
- **Administrator** is an agent whose behavior is defined by one attributes, *Enforcement Power*, quantifying its ability to enforce its own repair plan and override the CI agent repair plans at a decision point during the recovery process. The **Administrator** agent also has a mandate to achieve a set of Community performance objectives during the post-disaster recovery process.

In a CI-Community system post-earthquake recovery simulation, the **EPSS Operator** agent was set to start the repair of the damaged EPSS components one and half days after the earthquake, providing some time for life-saving emergency actions, acquisition of the damaged state of the EPSS, and repair crew and equipment mobilization. The EPSS components were ordered by their damage grade, from least to most seriously damaged. Such repair sequence enables quick recovery of the last damaged portions of the EPSS system, provides more options for power dispatch management early on, and maximizes the amount of supplied power, thus potentially maximizing the profit of the EPSS.

Without loss of generality, only one EPSS repair crew was used in this simulation. Thus, at the beginning of the post-disaster recovery process simulation, this EPSS crew is sent from the repair center to restore the least damaged EPSS component first. The crew calculates the time needed to reach the EPSS component location, starting from the EPSS repair center, taking into account the current state of the TS functionality to compute the shortest path between the origin and the destination, and the **EPSS Operator** *Speed* attribute. Once at the EPSS component site, the crew repairs the EPSS component to fully restore its functionality. The required repair time is calculated based on the component damage state and the **EPSS Operator** *Efficiency* attribute. Once this repair is completed, the **EPSS Operator** agent is at a decision point. It selects the next EPSS component on its current repair priority list, and repeats the process starting from its current location and taking into account the current state of the TS.

Similarly, the **TS Operator** agent was set to start the repair of the damaged TS components two days after the earthquake. Again, a single TS repair crew, initially located at the TS repair center, was used in this simulation. The nearest damaged TS component, reachable using the available road network from the current location of the TS repair crew, is repaired first regardless of its calculated damage probability. Such repair strategy is adopted assuming that the deployment of heavy equipment and materials to repair a damaged TS component is impeded by the state of the very road network that is being repaired. It is assumed that the TS repair crew does not depend on the electric power provided by the EPSS.

The **Administrator** agent monitors the Community recovery process using a set of resilience measures [10, 11]. The community recovery performance objectives are formulated in terms of surpassing threshold values of selected community resilience measures at certain intervals after the earthquake. In this simulation, the **Administrator** agent determines if the rate of community recovery is satisfactory or not by comparing a community resilience measure to a threshold value at one point in time after the earthquake, called the *Resilience Check Time*. In each simulation, if the rate of recovery is not satisfactory at this time, the value *Enforcement Power* attribute of the **Administrator** is increased. This renders it more likely that the **Administrator** will intervene and force **EPSS Operator** and **TS Operator** (if their randomly generated *Enforcement Power* attribute values are both smaller than that of the **Administrator**) to perform a one-time adjustment their attributes and repair schedules. In such a situation, the *Speed* and the *Efficiency* attributes of the **EPSS Operator** and the **TS Operator** are incremented (to speed up the recovery process), and the repair schedules are updated to prioritize the recovery of the community at the expense of the costs and profit of the CI system operators.

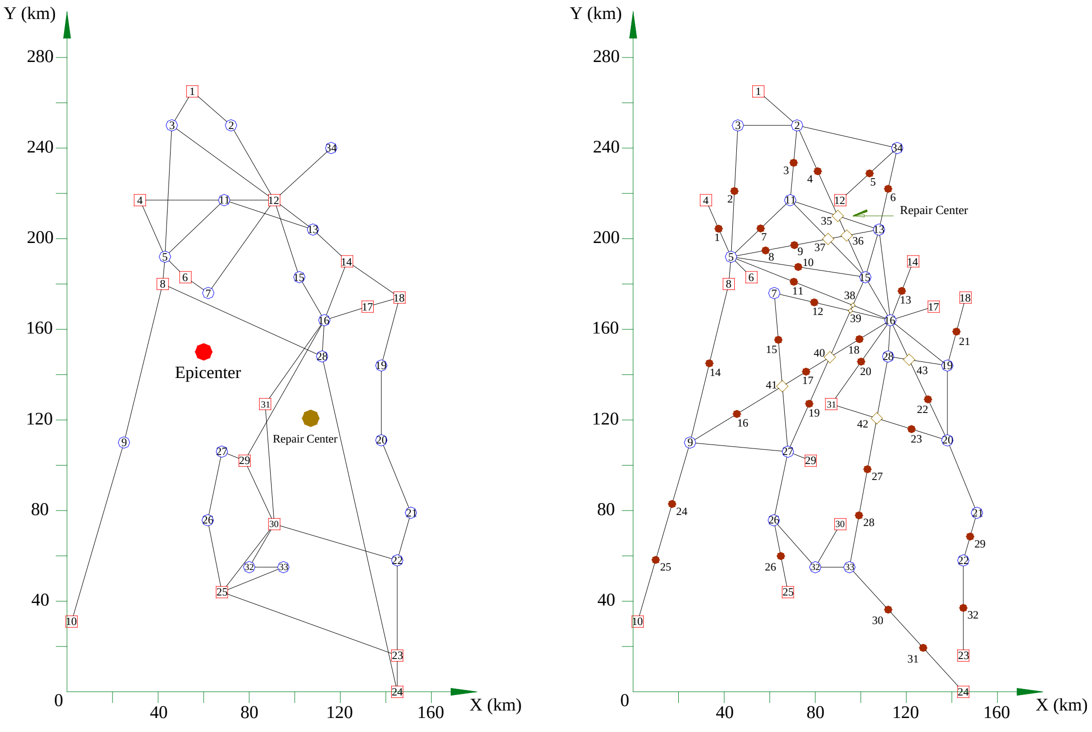
3. Case Study

This case study is developed building on the case study used in [11]. Namely, the EPSS was extracted from the IEEE 118-node Benchmark System [13]. As illustrated in Fig. 1 (a), the EPSS has 15 generation substations (red squares) and 19 distribution substations (blue circles). The generation substations produce electric energy and transit high-voltage power, while the distribution substations transform the high-voltage power into low-voltage power and transit high-voltage power. In this case study, the configurations of the generation and distribution substations were assumed to be the same.

The Community consist of electric power consumers, grouped into residential communities, industrial zones, and emergency and important facility locations (such as hospitals and schools) according to the structural and functional characteristics of the built environment. These inhabited communities were assumed to be located near the EPSS distribution substations. Their pre-earthquake demand was proportioned according to the assumed capacity of the EPSS distribution substations.

The road network of the TS was designed to serve the Community, and thus has a configuration similar to that of the EPSS (Fig. 1(b)). It has 32 bridges shown by red dots. The individual roads were modeled only as links between the TS nodes. The EPSS repair center was located near node 42 while the TS repair center was located near node 35, as shown in Fig. 1(a) and Fig. 1(b).

The size of the case study region was modified by reducing the length scale of the IEEE 118 Benchmark System 5 times to simulate the effect of moderate earthquakes in dense population settings [11]. The seismic hazard environment was modeled by fixing the locating the earthquake hypocenter close to the geographic center of the case study region (Fig. 1(a)). Given that an earthquake of magnitude M occurs, the intensity of shaking at each EPSS, TS and Community component site was computed using the ground motion attenuation relations for a rock site [14].



(a) EPSS

(b) TS

Fig. 1 –Topology of the EPSS and TS

3.1 Community Resilience Simulation

The resilience of the EPSS-TS-Community system is modeled using the compositional supply/demand framework [10, 11]. The state of the electric power supply and demand is modeled through the earthquake damage Absorption and Recovery phases. The Absorption phase is a relatively short period immediately following the earthquake when the EPSS-TS-Community systems is accumulating damage (direct and cascading) and finding a new equilibrium at a substantially lower functionality level.

Damage to the EPSS components and the Community built environment components is computed using seismic vulnerability functions, expressing the probability that each component will retain a certain portion of its functionality conditioned on the intensity of the earthquake ground motion at its location [10]. The decrease of power supplied by the EPSS and the decrease of the power consumed by the Community was assessed in proportion to the loss of component functionality using a model of EPSS operation, a so-called power dispatch model.

In this study, only the bridges of the TS were considered to be vulnerable to earthquakes. Earthquake-induced damage to the bridges was classified into three damage states (DS1: no damage; DS2: slight to moderate damage; and DS3: extensive damage or collapse) using the fragility function developed by the probabilistic seismic demand analysis on the concrete overpass bridges [15]. Bridges in damages states DS2 and DS3 were considered to be closed to all traffic immediately after the earthquake.

After the Absorption phase, the EPSS-TS-Community system enters a considerably longer Recovery phase. Resumption of function of the EPSS was modeled by the developed ABM while the Community components was done using recovery functions, expressing the conditional probability that each component will recover its full functionality after a given period of time in the Recovery phase, conditioned on the damage state it was in at the end of the Absorption phase [10, 11]. The ability of the EPSS to deliver power was computed at each decision point considering the current state of the EPSS components (improved by the repairs) and a seismic contingency power dispatch model to balance the EPSS and prioritize the supply to communities that have the largest post-earthquake demand. The ability of the Community to consume electric power is determined at each decision point considering the current state of the Community built environment components (improved by the repairs).

Recovery of the traffic function of the damaged bridges was modeled as follows. For bridges in DS2, rate of function recovery was assumed to be given by the *Efficiency* attribute of the **TS Operator** agent. However, the recovery process of the significantly more damaged bridges in DS3 was modeled using recovery functions to take into account that the repair or, perhaps, rebuilding of such bridges may take a considerably longer time. The parameters of the recovery functions for TS bridges in DS3, which were assumed to follow lognormal distributions, are shown in Table 1. Note that two recovery functions are used to express different probability distributions of time to full restoration of bridge traffic in cases when the **Administrator** agent does not and does intervene in the post-earthquake recovery process.

Table 1 – Parameters for the recovery function of severely damaged bridges (DS3)

Administrator	Mean (Days)	Std. (Days)
Does not intervene	150	90
Intervenes	90	60

3.2 Agent Parameters

The attributes of the **EPSS and TS Operators** and **Administrator** agents are random variables. The probability distribution function types and the value bounds of these attributes are listed in Table 2. The specific values of the agent attributes are determined once, at the beginning of each post-earthquake recovery simulation.

For example, the *Speed* attribute of the **EPSS Operator** has a uniform probability distribution and takes values between 8 and 10 km/h. Note that at every decision point, the **EPSS Operator** computes the shortest path for the repair crew to travel from the current to the next repair location using the current traffic function state of the TS. This is the point where the EPSS and TS interact. Similarly, the *Speed* attribute of the **TS Operator** is randomly set to between 7 and 8 km/h and the next repair location is computed as the nearest one given the current function state of the TS.

A constant repair rate is specified using the *Efficiency* attribute in terms of the portion of functionality of a component repaired per day. In this simulation, duration of repair the EPSS supply substations to full functionality is computed using such constant repair rate. However, the time to restore EPSS distribution substations to full functionality is (a randomly determined) constant, and depends on the magnitude of the earthquake. The repair rates and durations assumed here refer to the assumption that the EPSS and the TS have a single repair crew each. While additional simulations need to be conducted with multiple repair crews, the obtained results are still general enough if the obtained recovery durations are taken relative to each other.

Finally, the *Enforcement Power* attribute bounds for the three agents are specified relative to each other. These attributes are used to determine if the **Administrator** intervenes if the recovery process valuated at the *Resilience Check Time* does not meet the Community performance objectives. This is the point where the Community and the EPSS and TS interact.

Table 2 – Attributes of the **EPSS Operator**, **TS Operator** and **Administrator** agents

	Distribution	Lower Limit	Upper Limit
EPSS Operator			
Speed (km/h)	Uniform	8 km/h	10 km/h
Efficiency (per day)	Uniform	20%	30%
Recovery Threshold (day)	Uniform	M-4.5	M-4
Enforcement Power	Uniform	0.4	0.5
Administrator			
Enforcement Power	Uniform	0.3	0.4
TS Operator			
Speed (km/h)	Uniform	7 km/h	8 km/h
Efficiency (per day)	Uniform	40%	50%
Enforcement Power	Uniform	0.35	0.45

* M is the earthquake magnitude.

** Speed attributes for both the EPSS and TS Operator agents are reduced by length scale of 5.

3.3 Community Recovery Performance Check

Resilience of the EPSS-TS-Community system is quantified by monitoring the difference between the electric power delivered by the EPSS and the electric power consumed by the Community at each decision point during a post-earthquake recovery process simulation. Among possible measures of system resilience, an instantaneous measure, the percentage of people in the Community without power (PPwoP) at a point in time during the Recovery process, is used to monitor the post-earthquake recovery process.

The values of the *Enforcement Power* attributes (Table 2) are initially set to allow the EPSS and TS to affect repairs according to their own priorities and capabilities. However, the Community performs a *Resilience Check* by comparing the PPwoP three days after the earthquake to a pre-defined threshold. If the attained PPwoP value is larger than an acceptable threshold, the recovery process is deemed to be unsatisfactory, and the Administrator agent may intervene to speed it up. If the rate of recovery is not satisfactory, the current value

Enforcement Power attribute of the Administrator is increased by 0.1. Compared to the *Enforcement Power* attribute values of the EPSS Operator and TS Operator, this makes it more likely that the Administrator will intervene (if their randomly generated *Enforcement Power* attribute values are both smaller than that of the Administrator) and force EPSS Operator and TS Operator to perform a one-time adjustment their attributes and repair schedules. The **EPSS Operator** repair schedule is changed (inverted) such that the most severely damaged EPSS components are repaired first, its *Speed* attribute is increased by 10% and its *Efficiency* attribute was doubled. The **TS Operator** repair schedule is not changed, but its *Speed* attribute is increased by 10% and its *Efficiency* attribute is doubled. In addition, the estimated repair time for bridges in DS3 is shortened (Table 1).

4. EPSS-TS-Community System Behavior

The post-earthquake damage absorption and recovery process of the case study EPSS-TS-Community system was investigated by conducting simulations in a Monte Carlo setting. Each time, the post-earthquake recovery process was extended for a period of 360 days for 1000 runs under each different scenarios.

Two cases were investigated separately. First, the simulations were conducted without the **Administrator** agent, in order to observe the behavior of the system where Community performance objectives are neglected and the only interaction is between EPSS and TS impacting the travel time of the EPSS repair crew. Second, the simulations were conducted with the **Administrator** agent, allowing the Community to interact with the EPSS and TS that serve it and assert its post-earthquake recovery performance objectives. The effects of agent attribute values and earthquake magnitude were investigated in each case. In each analysis, the presented values are the median values derived from the 1,000 Monte Carlo simulations.

4.1 The case without the Administrator agent

The medians of the EPSS electric power generation capacity for four earthquake magnitude levels M equal to 6, 6.5, 7, and 7.5 are shown in Fig. 2. Two scenarios are considered: the "baseline" scenario, computed assuming that the TS is not vulnerable, and the "intertwined" scenario, where damage to the TS is considered in the simulations. The difference is significant. The "intertwined" system takes much longer to recover (52, 73, 78 and 83 days, respectively) than the "baseline" system (17, 21, 23 and 26 days, respectively). This result indicates that post-earthquake recovery simulations without considering the interaction among the community CI systems may produce not conservative estimates of the community recovery times, more so for more intense earthquakes.

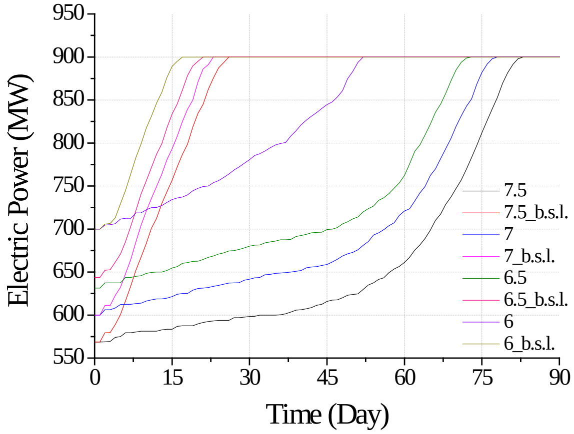


Fig. 2 – Median generation capacity curves in the "baseline" and "intertwined" scenarios

The reason for a significant prolongation of the post-earthquake recovery in the "intertwined" scenario is the idling of the EPSS repair crew while it was waiting for the TS repair crew to complete the various bridge repairs. In more intense earthquake simulations (M>6), there is a change in the rate of generation capacity increase about 50 days after the earthquake, when the bridges critical for EPSS repair were repaired and open for traffic. Conversely, given the assumed agent parameters, the **TS Operator** seems to be the bottleneck for recovery after strong earthquakes. Simulations at lower intensities (M<6.5) indicate that TS damage and recovery affects the EPSS recovery to a lesser extent.

The evolution of functionality loss of the EPSS in the M=7.5 “intertwined” scenario, tracked as the gap between the deliverable and demanded power, is shown in Fig. 3. Before the earthquake, the EPSS supplies 900 MW of electric power (Fig. 2) and covers the 733 MW of community demand (Fig. 3). Immediately after the earthquake, the median demanded power decreased to 660 MW as the earthquake damage was absorbed in the community. Meanwhile, the median power generation capacity dropped to 568.5 MW (Fig. 2). Further, due to failure of transformers and losses of transit capacity, the median ability for EPSS to deliver power decreased to 531 MW. Thus, the EPSS was not able to satisfy the demand anymore. The shaded area in the figure refers to the period of functionality loss and is termed “lack of resilience”. Similar to Fig. 2, the deliverable power remains almost unchanged over the first week and then start to increase. The gap between the delivered and demanded power reduced since then, and disappeared on the 64th day after the earthquake. However, it took 165 days for the community power demand to be restored to the pre-disaster level. The supply delivered by the EPSS was able to follow this increase in demand without problems.

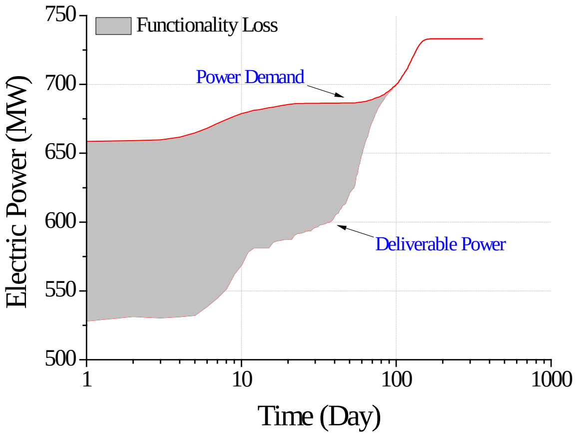


Fig. 3 – Median of the delivered power and power demand for a M=7.5 earthquake “intertwined” scenario

The evolving functionality of TS under in the “intertwined” scenarios is shown in Fig. 4 for the four earthquake intensities. The number of operational bridges (DS1) was 7, 8, 9 and 12 for magnitude 7.5, 7, 6.5 and 6 earthquakes. The earthquakes in DS3 delay the recovery process, evident in the change of slope of the functionality curves. The duration to full TS recovery (all bridge repaired) was quite similar for the four earthquake magnitudes (77 days for M=7.5 and 75 days for M=6).

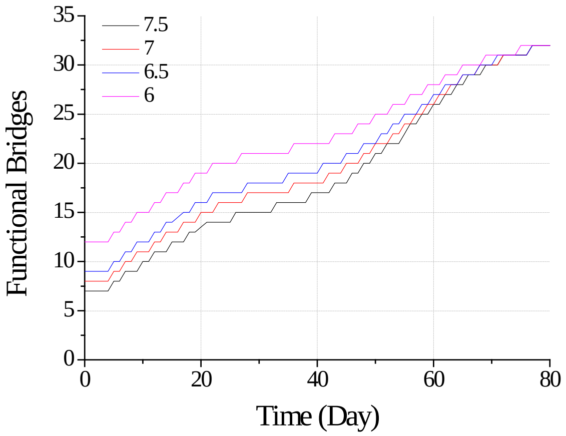
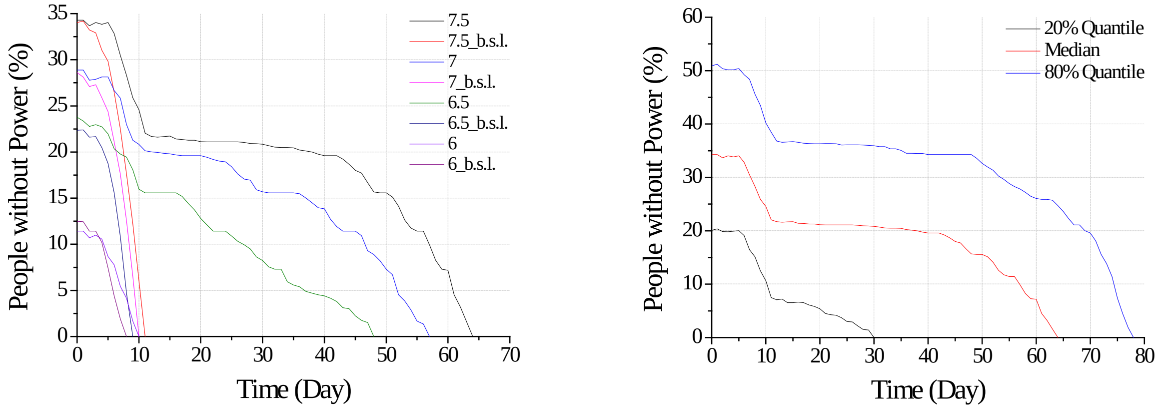


Fig. 4 – Median of the TS function recovery of TS in four “intertwined” earthquake scenarios

Fig. 5 illustrates the evolution of the median values of the PPwoP system resilience measure. The “baseline” and the “intertwined” scenarios are compared in Fig. 5 (a), indicated significant difference. For more intense earthquakes (M=7.5, 7, 6.5) it took 64, 57 and 48 days to provide power to the entire population in the “intertwined” scenario and only 11, 10 and 9 days in the “baseline” scenario, indicating a very significant role the TS plays in the recovery of the EPSS. However, for the M=6 earthquake, it only took 10 and 8 days, respectively, to supply the entire population, principally because that the initial functionality loss at this earthquake intensity was much smaller than in the stronger earthquakes, while the damage to the community built environment (i.e. demand) was still significant. Therefore, the EPSS can cover the power demand much sooner, even through it still took more than 50 days for the “intertwined” EPSS-TS to fully restore the power generation capacity (Fig. 2).

In Fig. 5 (b), the evolution of randomness associated with the PPwoP system resilience measure for the M=7.5 earthquake and the “intertwined” scenario, was plotted. Note that the median PPwoP remained virtually constant (at about 20%) from day 10 until day 40 after the earthquake. This can be very demanding for the population. The 20% and 80% quantile curves indicate that the randomness is large, and that it affects the PPwoP measure equally across the entire time period of observation.



(a) Comparison of different scenarios

(b) Randomness in the M=7.5 “intertwined” scenario

Fig. 5 – Evolution of the PPwoP system resilience measure

4.2 The case with the Administrator agent

The effects of the interaction between the Community and the EPSS and TS are shown by comparing the simulations conducted with and without the **Administrator** agent. Four scenarios are investigated. Namely, in simulations with the **Administrator,** at the *Resilience Check Time*, set at 3 days after the earthquake, the attained PPwoP value is compared to 10% (most demanding), 20% and 30% (least demanding) thresholds to determine if the post-earthquake recovery process is satisfactory or not form the community standpoint. If in a simulation the attained PPwoP exceeded the threshold, *Enforcement Power* attribute of Administrator agent was increased by 0.1 and compared to the *Enforcement Power* attributes of the **EPSS** and **TS Operator** agents. Note that the agent attributes were generated randomly at the beginning of the simulation. The **Administrator** won if its *Enforcement Power* was larger than the *Enforcement Power* of both the **EPSS Operator** and **TS Operator**. In this case, the repair plan of the **EPSS Operator** was inverted and the attributes of the CI agents updated to increase the rate of recovery, as specified in Section 3.

Figure 6 presents the median of the generation capacity of intertwined EPSS-TS-Community system after earthquakes of magnitude M=7.5 for the three threshold values of PPwoP=10%, 20% and 30%. For comparison, the case without the activation threshold, i.e. without the **Administrator** agent, is also plotted. The effect of intervention to speed up the post-earthquake recovery process is significant, particularly in the case of the 10% PPwoP threshold, when it took 62 instead of 83 days (Fig. 2) for the EPSS to fully recover the power generation capacity. The effect of the interference from the **Administrator** is also evident at higher PPwoP decision thresholds, but was not as strong.

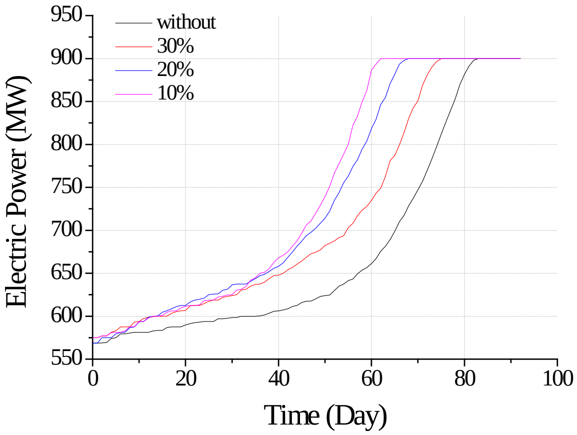


Fig. 6 – Median of recovery of the power generation capacity for three PPwoP threshold values for the M=7.5 earthquake

The effect is similar for TS, but not as strong. As shown in Fig. 7, the recovery is shortened by only 5 days for the PPwoP threshold value of 10%.

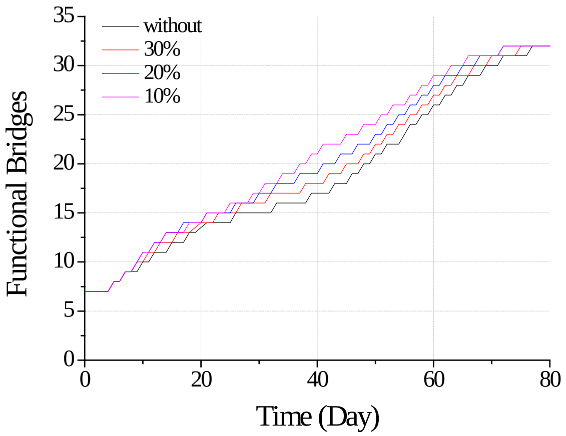


Fig. 7 – Median of recovery of the TS for three PPwoP threshold values for the M=7.5 earthquake

The data on the rate of PPwoP reduction shown in Fig. 8 indicates that the intervention of the **Administrator** to speed up the recovery process can be very effective. The resulting PPwoP evolution trajectories are significantly different compared to the case without intervention. Most important, the long horizontal "plateau" shown in Fig. 5 did not appear anymore, indicating that the **Administrator** fulfilled its task. Also important is that the difference between the 10% and the 20% PPwoP threshold values is not large, while the 30% PPwoP case is only slightly worse. Thus, to meaningfully affect post-earthquake recovery, the Community recovery performance objective should be set such that the Community can intervene and speed-up the recovery process. If the PPwoP reseilence measure is used, a threshold value between 10% and 20% three days after the earthquake could be adopted.

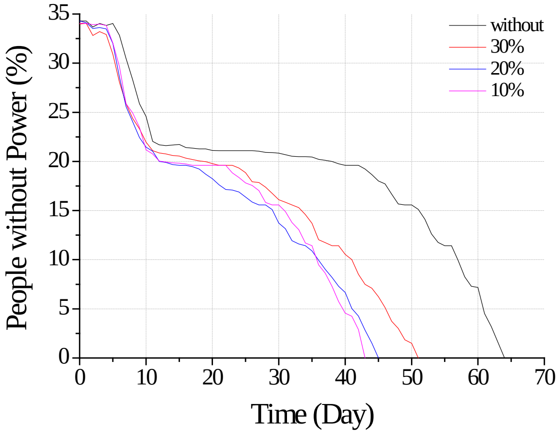


Fig. 8 – The evolution of PPwoP median for different PPwoP threshold values for the M=7.5 earthquake

5. Conclusion

Modern CI-Community system is a complex and interconnected socio-technical network. A compositional supply/demand for modeling the post-earthquake recovery process of the CI-Community system and measuring its resilience [10, 11] is extended in this study to analyze the interdependencies occurring during the post-disaster recovery process. To achieve this goal, the recovery paths of the CIs are modeled using an Agent-Based Modeling paradigm to account for the different strategies and capabilities of the entities involved in the recovery process. A case study based on the IEEE-118 Benchmark System was constructed and **EPSS Operator, TS Operator,** and **Administrator** agents were defined. Monte Carlo simulations were carried out to test the framework and to examine the impact of different earthquake scenarios and agent attributes on the resilience of the integrated CI-Community system. The simulations show that the proposed framework can be used to model the seismic resilience of the complex Socio-Technical system including the interaction among different infrastructure systems and the community during the post-earthquake recovery process. The interdependence among the infrastructure systems, as well as the interplay with the community post-earthquake recovery performance objectives, was shown significantly affect the CI-Community system recovery path. Future work is focused on calibrating the number and the attributes of the agents, the component recovery functions and the seismic emergency electric power dispatch algorithms.

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