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Assessment of Overall Resilience Index of Urban Areas against Earthquake Considering Intra and Interdependencies between Different Sectors

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ارزیابی شاخص تاب‌آوری کلی محیط‌های شهری در برابر زلزله با در نظر داشتن وابستگی‌های درونی و بیرونی بخش‌های مختلف

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Abstract:

Sustainability and resiliency analysis of cities is not completed without considering the whole system of interacting sectors. The purpose of this study is to introduce an algorithm for assessment of overall seismic resiliency increase of urban areas due to the reduction of Intra- and Interdependencies between different sectors and retrofitting infrastructures. The proposed method is versatile, and different dimensions of resiliency, i.e., social, economic, technical, physical, institutional, and security dimensions of resiliency are considered in the study. In this research, the technical dimension, i.e., the functionality of water and power networks are modeled as an example, and some solutions to increase overall resiliency of an urban district against earthquake is investigated. The algorithm is based on the inoperability input-output model, and the interaction between water and power sectors in a metropolitan district is surveyed. Based on the results of a number of Monte Carlo simulations of different dependency scenarios, it is quantitatively shown that the decrease in interdependency has a direct and great effect on the increase in serviceability and overall resiliency indices, but the pattern of this effect is different between various earthquake scenarios. It is concluded that the reduction of interdependency has an increasing effect on the overall resiliency index. Thus, an optimum value for interdependency reduction can be obtained to increase resiliency index using the Pareto principle, and the influence of reducing of interdependency on increasing the resiliency of a region as a whole is investigated. The proposed model may be used in system analysis for other dependent sectors and for different disasters and can also be considered as a helpful measure for decision-makers in sustainability and resiliency enhancement studies.

Keywords: Quantitative Resilience Assessment, Infrastructure, Earthquake, Resilience Index, Input-Output Model.

چکیده:

تحلیل پایداری و تاب‌آوری شهرها بدون در نظر داشتن کل سیستم شامل بخش‌های وابسته به یکدیگر کامل نیست. هدف این تحقیق ارائه الگوریتمی برای ارزیابی شاخص تاب‌آوری کلی محیطهای شهری در برابر زلزله است که توسط آن بتوان افزایش تاب‌آوری را در اثر کاهش وابستگی‌های درونی و بیرونی بخش‌های مختلف و مقاوم‌سازی ارزیابی نمود. روش ارائه شده برای محاسبه تاب‌آوری کل، روشی جامع است که در آن ابعاد مختلف اجتماعی، اقتصادی، فنی، کالبدی، حاکمیتی و امنیتی لحاظ شده است. در این تحقیق بعد فنی عملکرد بخش‌های آب و برق به عنوان نمونه ای از بعد فنی در نظر گرفته شده است و راهکارهایی برای افزایش تاب‌آوری کلی یک محیط شهری در برابر زلزله مورد بررسی قرار گرفته است. الگوریتم پیشنهادی بر اساس مدل داده ستانده عدم عملکرد است و در آن اندرکنش بین بخش‌های آب و برق در منطقه‌ای از یک کلان‌شهر در نظر گرفته شده است. بر اساس نتایج حاصل از شبیه‌سازی‌های مونت کارلو برای سناریوهای وابستگی مختلف، به صورت کمی نشان داده شد که کاهش وابستگی تاثیر مستقیم و قابل توجهی بر اقزایش شاخص عملکرد و شاخص تاب‌آوری کل دارد ولی الگوی آن برای سناریوهای زلزله مختلف متفاوت است. نشان داده شد که کاهش وابستگی‌های بین بخش‌ها باعث افزایش تاب‌آوری کلی میشود. بنابراین با استفاده از اصل پارتو می‌توان میزان بهینه کاهش وابستگی برای افزایش تاب‌آوری کل را به‌دست آورد و تاثیر کاهش وابستگی‌های درون‌بخشی و بین‌بخشی بر شاخص تاب‌آوری کلی یک منطقه محاسبه شده است. مدل ارائه شده همچنین می‌تواند در تحلیل سیستمی سایر بخش‌های وابسته در برابر سوانح دیگر نیز بکار رود و روش پیشنهادی می‌تواند در مطالعات بهبود پایداری و تاب‌آوری به عنوان ابزاری مناسب در دست تصمیم‌گیران قرار گیرد.

واژه‌های کلیدی: ارزیابی کمی تاب‌آوری، زیرساخت، زلزله، شاخص تاب‌آوری، مدل داده ستانده.

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Introduction

According to the Public Safety and Emergency Preparedness Canada office (PSEPC), lifelines are networks, facilities, and physical and informational services related together, and if they sustain damage in any way; health, safety, security and economy of society will be seriously affected (PSEPC, 2006). Lifelines determine urban resiliency status in today’s modern world, and the sustainability of society is strongly dependent on them. These systems, depending on the quality and quantity of their performance, produce and distribute goods and services in urban areas. Water, power, and gas networks are in top priorities of these networks in the context of disaster management. Considering the need to sustainable and resilient cities, the vulnerability of lifelines against disasters is of great importance, because the damage to one of them as a part of the whole society infrastructures system can trigger other disasters and hamper the recovery period.

“*Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables and parameters, and persist (Holling 1973).*” Resilience is referring to the ability of a system to return to a previous or improved state following a disturbance. Urban resilience is a concept of implementing policies against challenges of development and sustainability including major components of climate adaptation, environmental management, regional economic development and strategic planning (Caldarice et al., 2019; Davoudi et al. 2013). In the current disaster management context, a paradigm change from preparedness mission to vulnerability reduction is observed (Normandin et al., 2019). The implementation of resiliency enhancement policies may lead to substantial changes in the underlying social, political and economic drivers of vulnerability influencing education, health, cultural, environmental and infrastructure sectors (Habitat, 2016; Sharma, 2019). City resiliency has social, economic, technical, physical, institutional, and security dimensions, which are interdependent and interconnected (Ghasemi et al., 2019). They must be considered in resiliency study of cities.

Besides the direct vulnerability of infrastructures against disasters, another phenomenon known as the network interdependency can indirectly affect the sectors. To explain this phenomenon, it can be said there is a possibility that some parts of a certain infrastructure which are not damaged in a certain disaster may malfunction or stop working due to their performance interdependency to other infrastructures with severe damages resulting low resilience index. By evolution and improvement of infrastructures, their interdependencies open a new subject in network science. Therefore, in the study of system sustainability and vulnerability, a separate analysis of the parts of one infrastructure network seems to have misleading results and, in order to perform a more realistic resiliency evaluation, considering the entire network along with the other interdependent infrastructure systems seems inevitable.

Interactions among different sectors or infrastructures play an important and basic effect in economics, industrial and social resiliency and sustainability. Not only the active components of a system are linked together, but also systems performances are interdependent. Disregarding the interdependencies and interactions of different infrastructures or sectors in performance assessment leads to an inaccurate estimate of serviceability assessment (Rinaldi et al., 2001; Peerenboom et al., 2002; NERC, 2004).

According to the available studies, some evaluation approaches used in interdependency studies may be classified as:

- Network Model: One approach is network approach; lifelines can be shown as a set of nodes and links which are connected together in a logical order. Loss or damage of one node will affect the others since they follow a logical order (Moselhi et al., 2005). Thus, the Graph Theory is a well-known concept for modeling networks such as infrastructures of a society with which we deal in our everyday life (Watts and Strogatz, 1998). By Graph theory, the probability of removal of nodes or a part of commodity path is determined not only by fragility curves and failure rates but also by considering the reduction or stopping commodity flow, as input to facilities.
- Petri net: The other approach based on the Graph theory is Petri net. Petri net is considered as a powerful tool in modeling and analysis of network properties. Petri net was introduced by Carl Adam Petri in 1960s and has been developed and improved by other researchers since then (Peterson, 1981). Guest and Derochers used Petri net to identify the interdependencies between lifelines presented by Rinaldi and his colleagues in 2001 (Gursesli and Desrochers, 2003; Rinaldi et al., 2001). Omidvar and his colleagues used a Petri net approach in failure risk assessment of interdependent structures against earthquake (Omidvar et al., 2014).
- Probabilistic techniques: probabilistic methods such as Markov Chain, Fault Tree Analysis, and Event Tree analysis are very effective means to determine the interdependency of infrastructures. Nozick and his colleagues introduced a mathematical framework for a network of interdependent lifelines. In order to determine the efficiency of infrastructures, they used algorithms including Markov and semi-Markov models (Nozick et al., 2004; Bao-Hua, 2004; Hwang and Chou, 1998; Ezell et al., 2000).
- Input-Output model: Leontief input-output model was introduced in economics science by Leontief (Leontief, 1951a, 1951b; Leontief, 1986). Many studies and research studies have been launched on financial and economic losses caused by infrastructure service reduction, resulting from increasing interdependencies and interactions (Chang et al., 1996). Haimes and his colleagues expanded the concept of the input-output model from financial exchange between economic sectors to operability dependency concept between interdependent infrastructure sectors called inoperability input-output model (IIM) (Haimes et al., 2005a, 2005b).

This study investigates the interdependency of water to the power network, in one of the districts of a metropolitan district, to assess its vulnerability and serviceability; as important factors in resiliency concept; in the aftermath of probable earthquakes. Then, a general algorithm, combining the inoperability input-output model with the flow model, is presented for measuring the interdependency impact between interdependent infrastructure systems. The proposed model considers both intra-dependency between the elements of each infrastructure and inter-dependency between the elements of different sectors, and it may be used in quantitative performance assessment of the other social sectors. In this study, a combination of graph and inoperability input-output and flow analysis theories are used to model the seismic performance of water and power networks. To do so, first, the networks are modeled by graphs, and then the effects of their dependencies are calculated by inoperability input-output theory, IIM, and the performance of the network is measured by IIM principles. Monte Carlo simulation is used in the considered scenarios to measure network performance and resiliency. An overall resilience index is then used to investigate the resiliency of the sectors and to address the efficiency of the vulnerability and interdependency reduction of the studied infrastructures on resiliency enhancement.

The significance of the proposed model lays in considering networks in a component-by-component solution. Modeling the internal interactions of each network, i.e., intra-dependencies, along with those between the networks in the component level, i.e., inter-dependencies in the scale of a district of a Metropolitan is the salient feature of the proposed algorithm for quantitative performance and resiliency assessment of interdependent sectors.

Methodology:

In this part, the proposed algorithm is presented, and the theories applied in the model are introduced.

Proposed Algorithm

In Figure 1, the steps taken in the proposed algorithm are illustrated. Graph map module, scenario development module, hazard analysis module, vulnerability assessment module, inoperability input-output module, damage estimation, and network flow analysis module, and performance measure distribution module are the main parts of the algorithm. Monte Carlo simulation is used in order to simulate the performance of the interconnected infrastructures, and the serviceability of each system is estimated based on the results of Monte Carlo iterations over all the considered earthquake, dependency and retrofitting scenarios.

In the Graph map module, the networks recognition process is done. First, lifelines are modeled in a set of nodes and links. Then, the adjacency matrix of the networks based on earlier graphs is extracted. The accuracy of generating this matrix guarantees the validity of the procedure and its calculations, and due to the possibility of a vast range of studied components, large matrixes may be developed.

Different scenarios of earthquakes, interdependencies between components of different lifelines and retrofitting strategies are developed in the scenario development module. The performance analysis is repeated for all the possible combinations of these three types of the considered scenarios.

The seismic intensity parameters for each component of the considered lifelines are calculated in the hazard analysis module. The calculated parameters will be used as the input of the vulnerability module in which based on the relevant vulnerability functions and repair rates the independent probability of failure for each component is calculated. The failure probabilities for water network are taken from the availability fragility curves which are modified to exclude implicit power effects (Naemi and Omidvar, 2013) from FEMA fragility curves (FEMA 1997) suspending their relations with power network components in the correspondent fault tree.

Next, the dependent probability of failure for each component is calculated in Leontief-based (inoperability) input-output module for the considered dependency scenario based on the related adjacency matrix. The method is described in the next section.

In order to simulate the performance of the considered systems, it is necessary first to know the damaged configuration of the systems after the earthquake and then calculate the serviceability of each damaged lifeline. This process is done in the damage and network flow analysis module. The damage status for each component is considered in a random manner based on its dependent probability of failure calculated in the previous module. Monte Carlo simulation is used in this module to simulate the performance of the damaged (reduced) networks of lifelines. The algorithm of this module is shown in Figure 2. To calculate the network performance measure, the percentage of each flow path out of total available flow in the network is identified first. Then, knowing the status of all the components, all the flow paths that include damaged components are eliminated. The flows passing on the eliminated paths are subtracted from the total flow, and the residual flow is determined in the calculation of performance measure for the modified network for each Monte Carlo simulation. The networks are analyzed using 200,000,000 iterations for each combination of earthquake, retrofitting, and dependency scenario.

The network performance is described by serviceability index (SI), i.e., the fraction of delivered flow to the service (demand) flow. It is of great importance to assess the effect that removal of any element in the network has on internal network functionality as well as its impacts on end-users (Dueñas-Osorio, 2005). The objective in measuring service reduction is to quantify the amount of service that does not meet the demands. These demands are directly related to the affected population, and therefore, it is more meaningful for decision-making efforts and selection of mitigation strategies. This performance measure provides the link between network performance and potential social impacts. Its uniqueness relies upon the combination of topological information with feasible optimal flow patterns (Dueñas-Osorio, 2005).

The uncertainty of SI for each scenario combination is investigated in the performance distribution module. The probability distribution function of SI is studied, and the mean and variance of this performance factor are calculated.

Leontief-Based Inoperability Input-Output Model

The system is assumed to consist of a group of n interacting sectors, where each ‘‘sector’’ produces one product (commodity). For the proposed model, a system consisting of n complex intra-connected and inter-connected critical infrastructures is considered. The output of this system is its risk of inoperability that can be triggered by one or multiple failures, while the input to the system can be failures due to complexity, accidents, natural hazards, or acts of terrorism.

Vulnerability is the potential of damage extent determined by being exposed to one or more sets of hazards. In other words, the vulnerability of a sector means the failure possibility of a sector facing a threat. Moreover, for a special event, it can be considered from 0 (no damage) to 100 percent (complete failure). In fact, vulnerability is the possibility of being failed or successful after an attack to one component, or quantitative resistance against a threat varying from zero to one hundred percent (Lewis, 2006). With regard to this definition, inoperability of a system is assumed to be a continuous variable evaluated between 0 and 100 percent, with 0 correspondings to a flawless operable/sustainable system state and 100 percent corresponding to the system being completely inoperable/unsustainable.

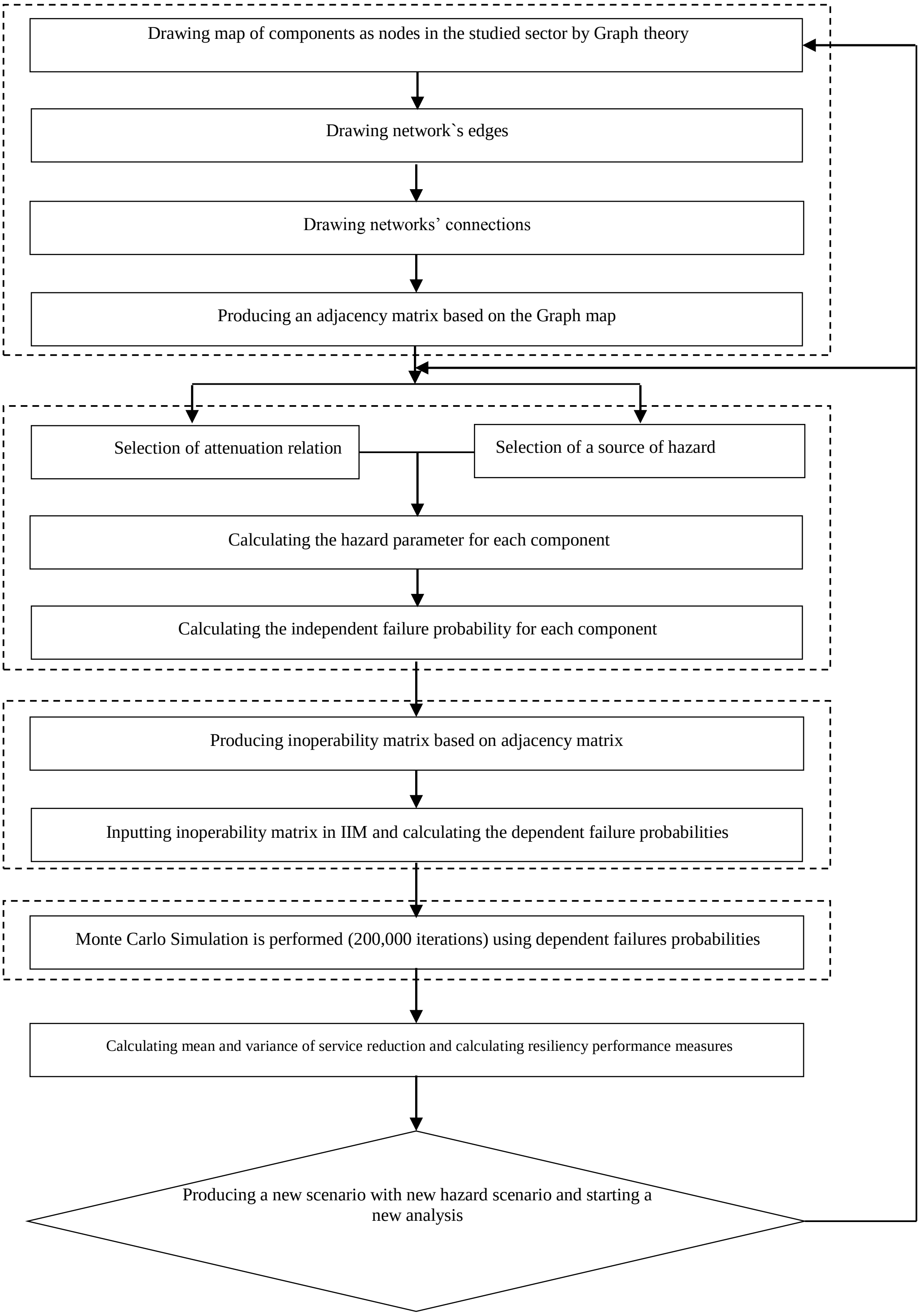

Fig 1. Diagram of the proposed algorithm

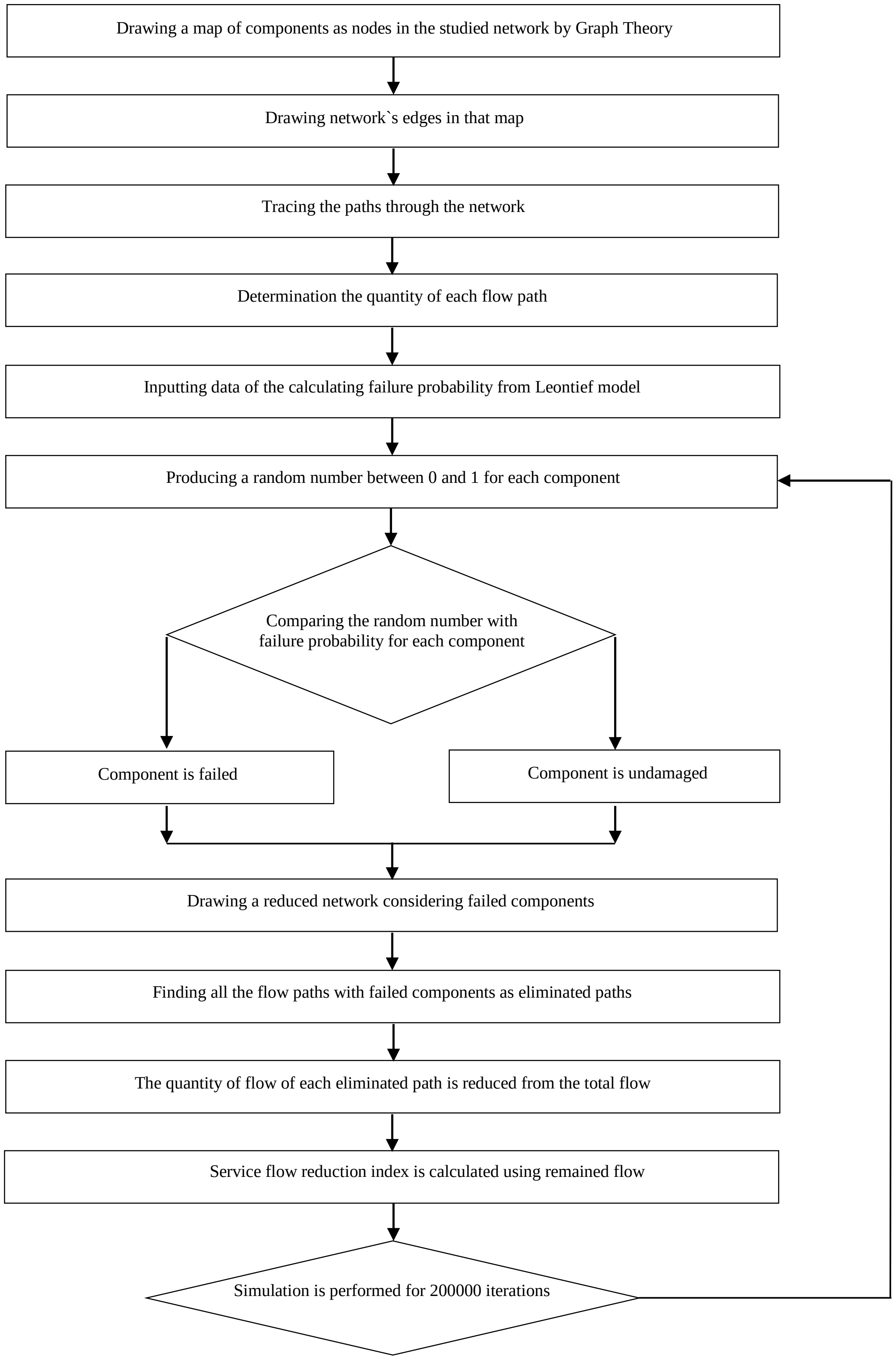

Fig 2. Diagram of Monte-Carlo simulation

Risk of inoperability (considered here as failure probability) is used in the Leontief-based infrastructure model, which is a measure of both the degree of inoperability and its failure probability (Haimes and Jiang, 2001).

In addition, one such Leontief-based infrastructure model may be used to evaluate and measure social or economic consequences in monetary terms, or the risk of inoperability, failure probability or probability of damage to property, production, service, or injury under extreme natural and accidental conditions, or due to acts of terrorism.

Assuming *(I - A)* is nonsingular, in which matrix A is an inoperability matrix, the Leontief-based equation can be solved for the overall probability of inoperability of the infrastructures as follows:

$$\mathbf{x} = (I - A)^{-1}\mathbf{c} \qquad (1)$$

Note that the monetary exchange in the original Leontief economy model now assume a drastically different interpretation as operability dependency and ‘supply" and ‘‘demand" concepts are changed to some extent in the Leontief-based infrastructure model as independent and dependent failure probabilities, i.e., *c* and *x* vectors, respectively (Haimes and Jiang, 2001; Haimes et al.; 2005a, 2005b).

In short, in this model for infrastructure systems, i.e., inoperability input-output model, failure probability is presented with a new perspective based on the Leontief input-output notion instead of monetary exchange between different infrastructures.

Where $\{\boldsymbol{a_{kj}}\}$constitutes the operation dependency of component k of one sector/infrastructure to component j of the same/another sector/infrastructure, and vector $\boldsymbol{x}$ contains dependent failure probabilities of the components of the considered infrastructures/sectors. The inoperability matrix $\boldsymbol{A} = \{\boldsymbol{a_{kj}}\}$ plays a central role in problem-solving, which includes Intra- and inter-dependency measures.

The vector **c** is a perturbation term that covers all effects due to both the malfunction of the components of subsystems (internal perturbation) and any external perturbation from outside the system boundary. It is considered here as the vector of independent failure probabilities of the components of the considered infrastructures/sectors. The threat, which may be accidental events, natural disasters, and intended attacks, is considered an earthquake occurrence in the present study. The dependent failure probability vector (vector $\boldsymbol{x}$) is obtained according to the operability matrix $\boldsymbol{A}$ developed considering Intra- and inter-dependency measures. Operability matrix (*A*) is calculated according to the adjacency matrix and dependency and dependency-reduction retrofitting scenarios. The Interdependent failure probabilities of components (elements of vector $\boldsymbol{x}$) are calculated using equation one based on interdependency scenarios.

Calculating overall resiliency index

Resilience has various definitions, and there is no comprehensive model for its quantitative calculation. The conceptual model introduced in (Ghasemi et al., 2019) for the resiliency of cities against earthquakes is used here. The conceptual model consists of social, economic, technical, physical, institutional, and security dimensions. The weight for each dimension *(D_i)* and related indices *(I_i)* calculated in (Ghasemi et al., 2019) were used to quantify a resilience index (RI) as overall resiliency index. This index covers various dimensions affecting the resilience of the systems under study. In the current study, the amount of the effect of each intervention strategy (retrofitting and interdependency scenarios) on resilience improvement is determined using the following equation.

$$\mathrm{RI} = D_1 \sum_{i=1}^{n_1} I_i R_i + D_2 \sum_{i=1}^{n_2} I_i R_i + \cdots + D_m \sum_{i=1}^{n_m} I_i R_i \qquad (2)$$

In which R_i is a resilience index for component *i* of the relevant dimension. In the current study, the index for the technical dimension is calculated using the proposed algorithms shown in Figures 1 and 2. The indices for the other dimensions i.e., social, economics, physical, institutional, and security dimensions for the studied region are adapted from (Ghasemi et al., 2019).

Therefore, the effect of technical retrofitting and interdependency reduction scenarios in improvement and increase of overall resiliency are measured and compared with each other. It is assumed here there is a strong correlation between serviceability index and technical index. So the results of the numerical simulation may be used in overall resilience quantification considering all the resiliency dimensions.

Case Study

Based on the proposed algorithm, a case study is investigated to illustrate a close connection between water and power sectors in a municipality district of a Metropolitan considering earthquake occurrence.

System Recognition

Power and water networks of the studied district include 43 nodes (33 nodes of the water network and ten nodes of power network). Two water treatment plants (WTP), three wells, eighteen storage tanks, and ten pumping stations are considered parts of the water network of the studied region. These two WTPs are classified into the "large WTP" category. The power network of the studied region includes ten 63/20 KV substations. They are classified into the "low-voltage substation" category. A schematic view of the connections between the power network (sector 1) and water network (sector 2) is illustrated in Figure 3.

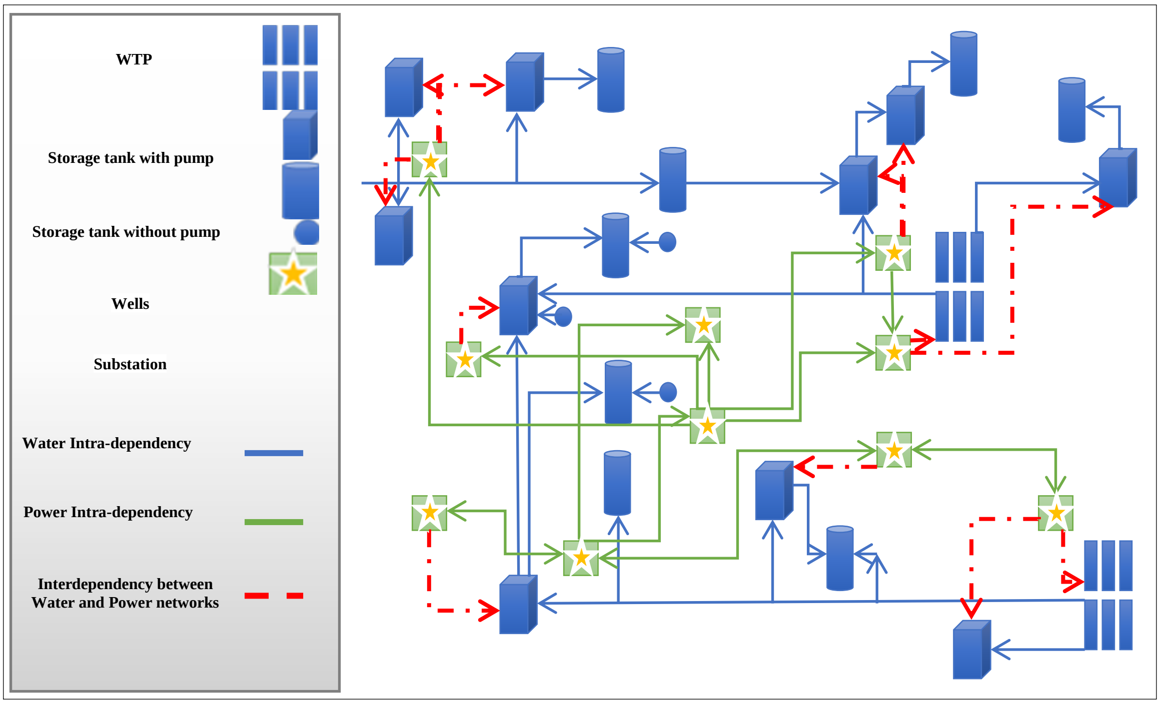

Fig 3. Schematic view of links between two sectors considered in the studied region

Hazard Scenarios

Peak ground acceleration (PGA) is considered as hazard index in the study, and PGA is calculated in the location of each network element. They are used in relevant fragility curves. PGAs are set for earthquake scenarios of three major faults of the region using Campbell-Bozorgnia (Campbell and Bozorgnia, 2003) and Zare' and his colleagues (Zare et al., 1999) attenuation relation. Thus, six hazard scenarios (3 faults and two attenuation relations) are considered in this study.

Retrofitting Scenarios

Four retrofitting scenarios are considered in the study. They are listed as the following:

1. Unanchored components in any of the networks (current situation, labeled as DN)
2. Seismic retrofitting and anchoring the components of sector 1 (The components of water network remain unanchored). (labeled as S1)
3. Seismic retrofitting and anchoring the components of sector 2 (The components of sector one remain unanchored). (labeled as S2)
4. Seismic retrofitting and anchoring of both sectors. (labeled as S3)

Dependency Scenarios

The inoperability matrix is developed, based on the inoperability input-output infrastructure model and according to the adjacency matrix of the networks. This matrix must be written to cope with any dependency scenario. In this study, seven dependency scenarios of water-to-power network are considered:

1. Sector 2 is %100 dependent on Sector 1
2. Sector 2 is %80 dependent on Sector 1
3. Sector 2 is %60 dependent on Sector 1
4. Sector 2 is %40 dependent on Sector 1
5. Sector 2 is %20 dependent on Sector 1
6. Sector 2 is %0 dependent to Sector 1
7. Another scenario is considered in which the components of sector two are assumed to be independent of each other (without intra-dependency) and from sector 1.

Thus, considering all the scenarios of earthquake retrofitting and dependency, the total of 168 scenario combinations are developed in this study.

Monte Carlo Simulation

Monte Carlo simulation is used to calculate the expected value of serviceability. First, the entire inter-network flow paths in sector two are determined by using UCINET software, and the portion of each path is calculated. In this regard, there were 35 flow paths from feeding nodes (WTPs) to consumption nodes (storage tanks). The service flow for each scenario combination is calculated based on the coefficient of inoperability for that scenario. Each of 168 scenario combinations is analyzed 200,000 times (a total of 33,600,000 iterations). The proposed algorithm is developed in the Math lab environment.

Results

Due to a large amount of generated data, only the results for those scenarios with moderate and maximum damage are reflected here labeled as "hazard scenario 1" and "hazard scenario 2", respectively. Figures 4 to 11 display the status of retrofitting and dependency scenarios for both earthquake scenarios.

Network performance measures for different interdependency scenarios are shown in Figures 3 and 6 for hazard scenarios 1 and 2, respectively. According to the presented results in Figures 4 and 5, by comparing the retrofitting scenarios, it can be concluded that retrofitting the sector 2 (S2) has the second-highest effect on increasing the network performance measures and sustainability after retrofitting scenario of both sectors (S3).

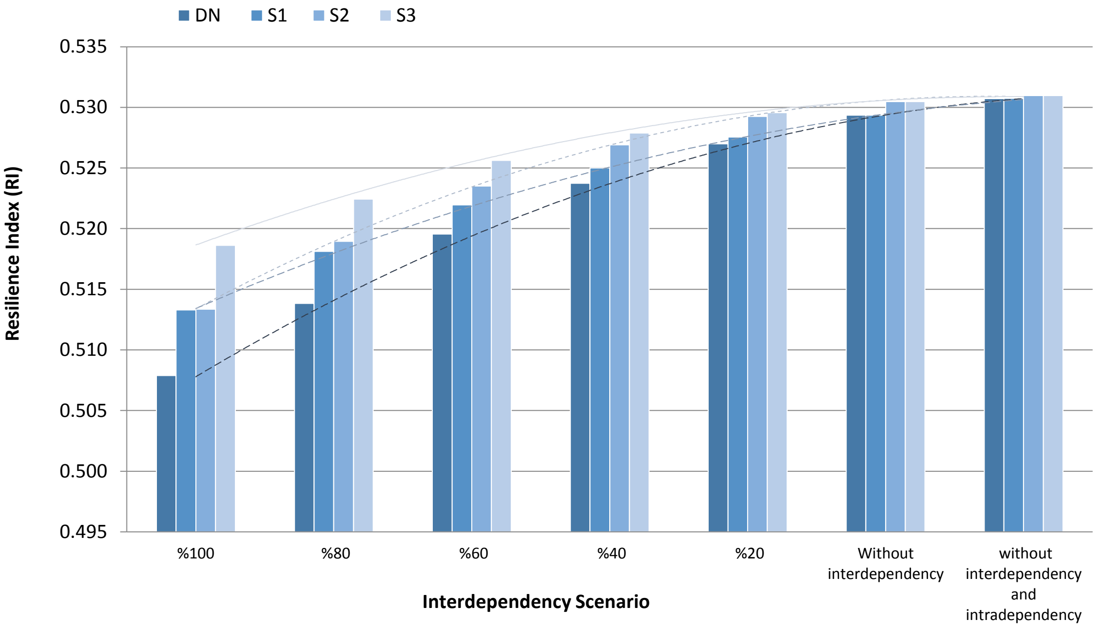

Fig 4. Network performance measure for different interdependency scenarios for hazard scenario 1

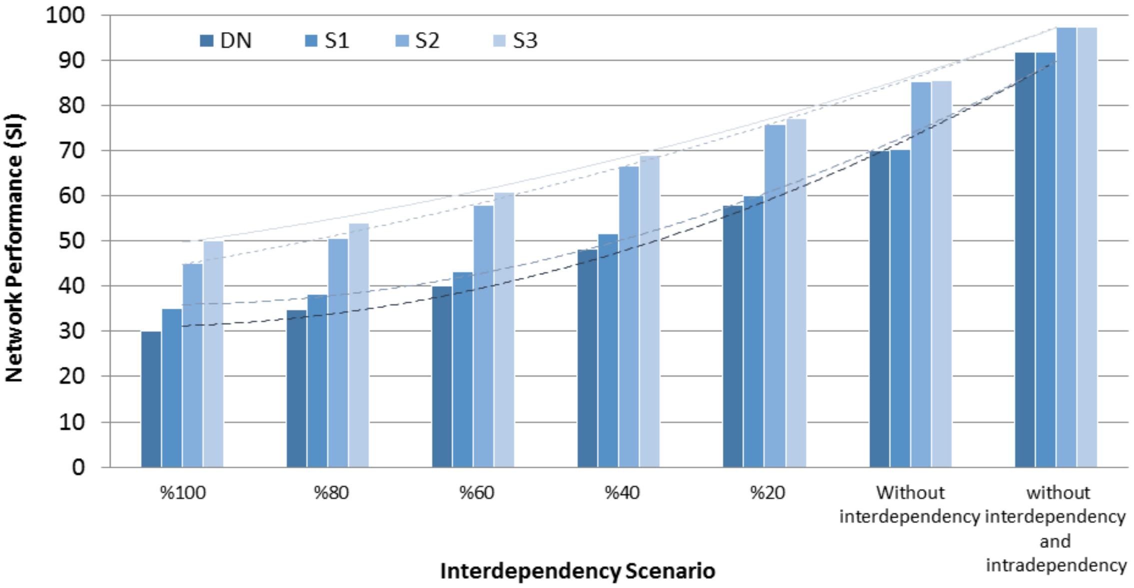

Fig 5. Network performance measure for different interdependency scenarios for hazard scenario 2

What is crystal clear is that various different magnitudes of hazard scenarios will cause different network performance patterns. According to the network properties in small scale earthquakes (hazard scenario 1), the study results indicated that the first 20% reduction of dependency affects service measures more in an increasing manner comparing to the other dependency scenarios (Figure 4); however, such a claim is totally reversed for the hazard scenario 2 (Figure 5), and the last 20% reduction of dependency affects service measures more. It may be interpreted as in a large earthquake where the damage states of infrastructures are high, and they are severely damaged, the interdependency must be totally eliminated to increase the performance level. It may be said that the hazard intensity has a positive correlation with interdependency importance. So, the maximum increase rate in the sector performance measures for hazard scenario 1 or the so-called moderate earthquake damage scenario can be found in the first 20% reduction of interdependency.

However, we cannot acknowledge what is claimed above for the earthquake with maximum damage rate i.e., hazard scenario 2, and for the earthquake scenario with maximum damage in the district, the focus must be on the retrofitting the sectors to increase performance measure effectively as well as a high reduction of their interdependency.

The overall resilience index is investigated next. The values of the resiliency index for hazard scenarios 1 and two are shown in Figures 6 and 7, respectively. The weights of social, economic, technical, physical, institutional, and security dimensions were adapted from Ghasemi and his colleagues for the studied region as 0.198, 0.153, 0.136, 0.202, 0.151 and 0.159, respectively. The technical dimension was considered to be increased equal to serviceability increase as was discussed above. For hazard scenario 1 the resiliency index increases from 50.8% to 51.9% and from 52.9% to 53.0% by retrofitting from DN to S3, for the case of 100% and 0% interdependency, respectively On the other hand, in the case of seismic retrofitting scenarios, the overall resiliency index (RI) was increased from 44% to 47% for the case of 100% dependency and from 50% to 52% for the 0% interdependency scenario for hazard scenario 2. At the best case, the RI is improved about 2.11% and 6.18% by retrofitting in the hazard scenarios 1 and two respectively.

In the case of improvement of technical dimension based on interdependency reduction, the overall resiliency index (RI) is increased as can be seen in Figures 8 and 9 for hazard scenarios 1 and 2, respectively. The effectiveness of each 20% interdependency reduction on resilience increase for retrofitting scenarios is shown in Figures 10 and 11 for hazard scenarios 1 and 2, respectively.

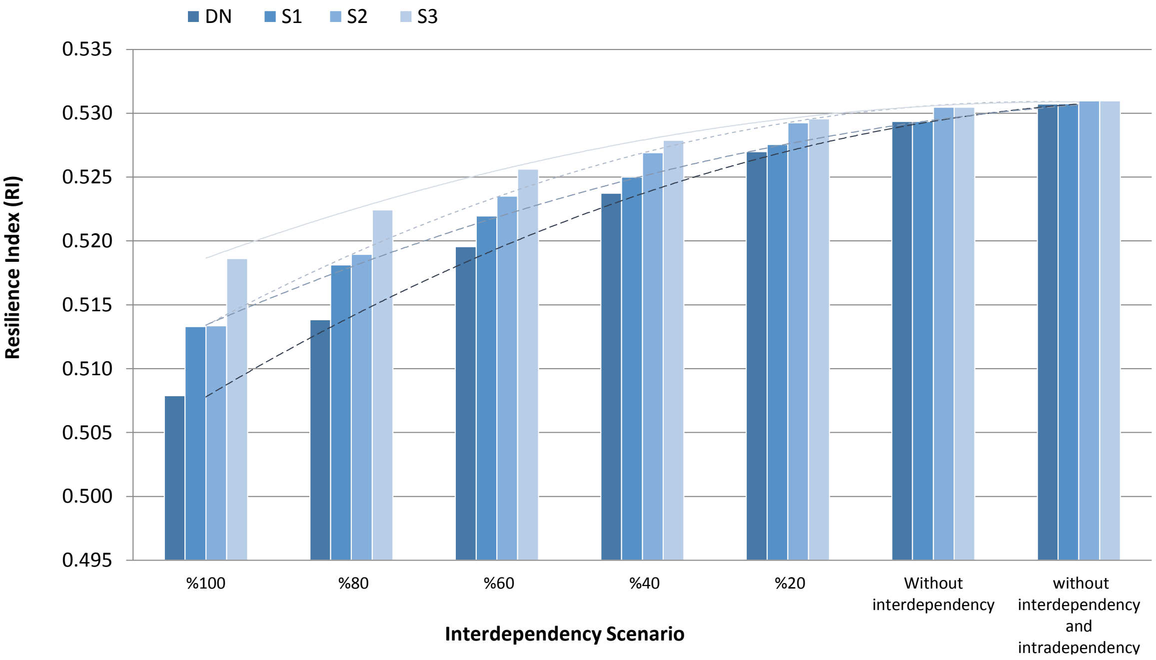

Fig 6. Overall resilience index for hazard scenario 1

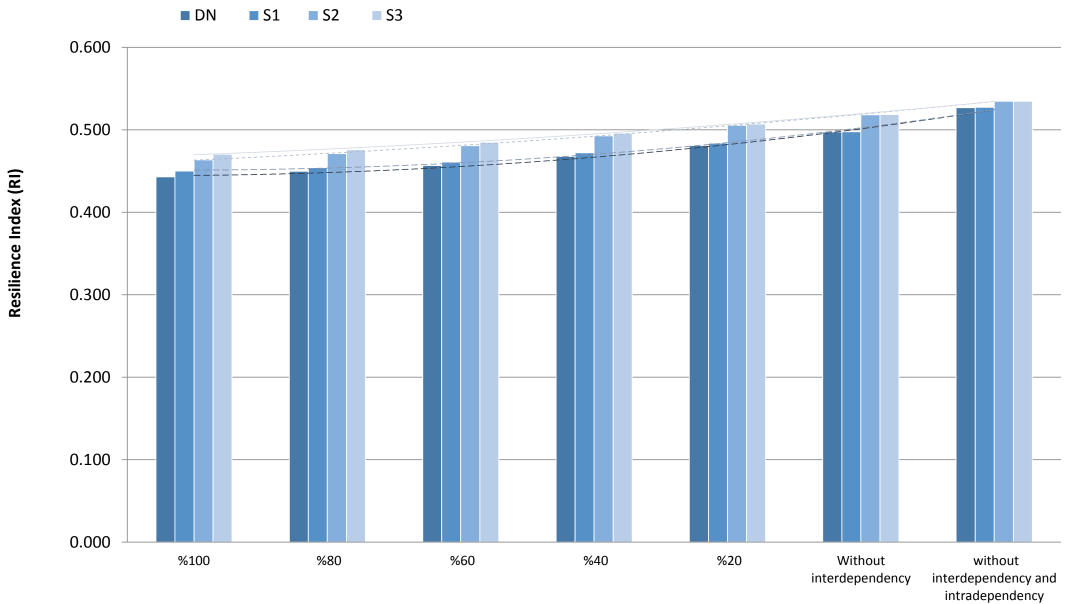

Fig 7. Overall resilience index for hazard scenario 2

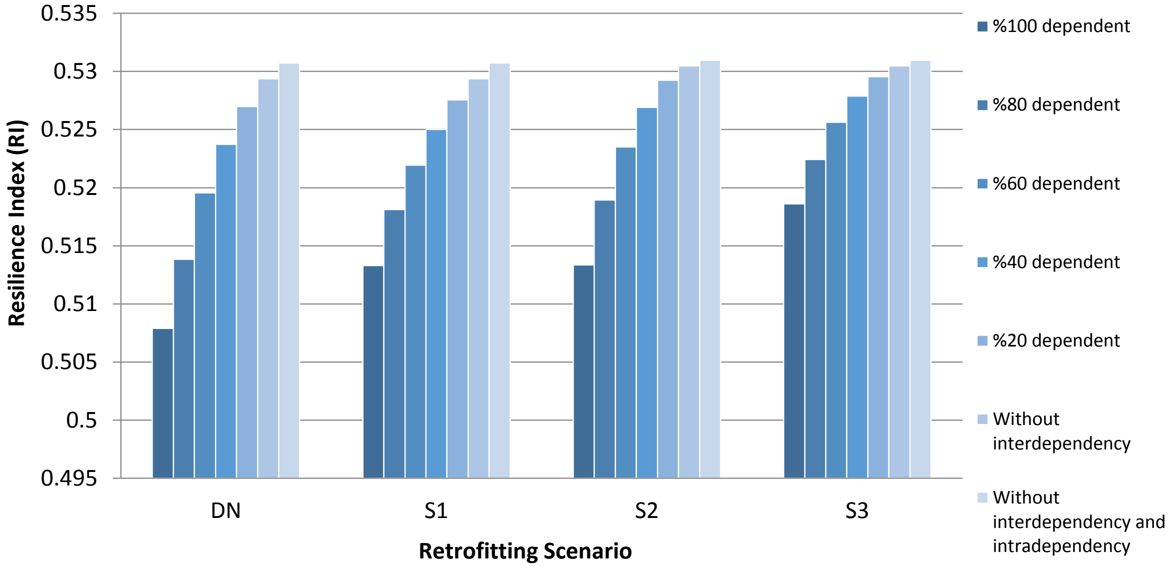

Fig 8. The percentage of effectiveness of each retrofitting scenario in resilience increase with respect to DN scenario for different interdependency scenarios considering hazard scenario 1

The effectiveness of retrofitting is more in the case of a strong earthquake, comparing it with moderate earthquake results. Now it can be concluded that there is a significant difference in selecting the most effective prevention strategy, including reduction of dependencies and preparing seismic anchorage for hazards with different damage levels. In this stage, retrofitting scenarios of both networks simultaneously as well as that of sector two alone have a significant effect on increasing performance and resiliency of this sector with respect to retrofitting scenarios of sector 1. It is necessary to say the damage reduction is the first concern and interdependency reduction strategy is the next one for hazard scenario with maximum damage for resiliency enhancement.

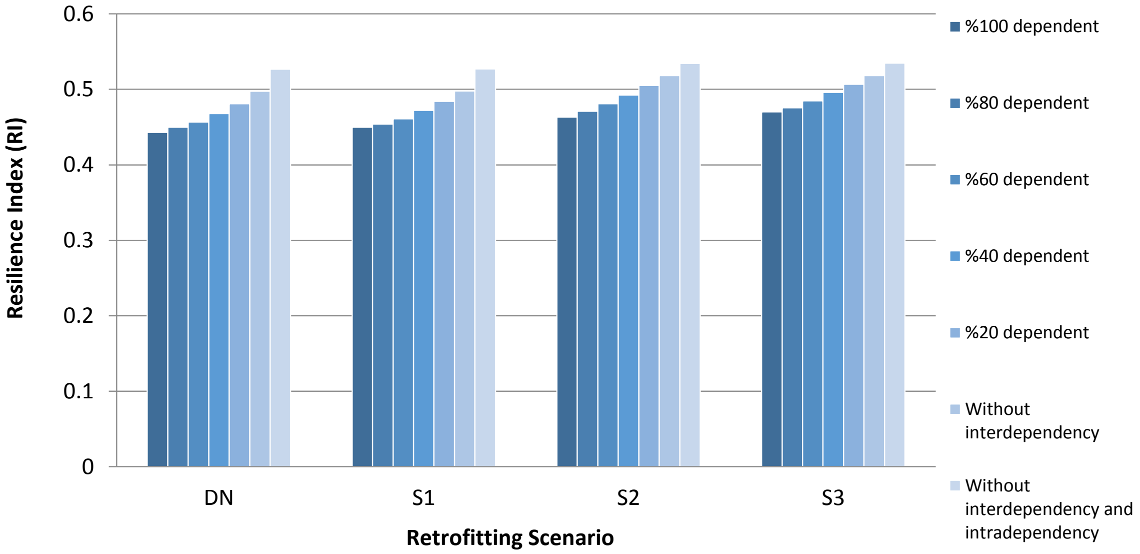

Fig 9. The percentage of effectiveness of each retrofitting scenario in resilience increase with respect to DN scenario for different interdependency scenarios considering hazard scenario 2

Conclusion

In this study, we focused on a modeling algorithm, which is a critical element to control and mitigate the impacts of natural and man-made disasters on interdependent infrastructures and sectors. Accordingly, the infrastructure interactions of the past experiences were discussed, and different methods for modeling of interdependent infrastructures were briefly introduced.

Then the developed algorithm for modeling the interactions between infrastructures in this study was introduced, and its steps were explained. This algorithm was implemented to investigate the interdependency of the water sector to power sector in a Metropolitan district and, finally, the dependent performance of the sectors was assessed after an earthquake and the effectiveness of some management solutions on performance measure and resilience index were investigated.

The followings scenarios were considered in the study of the seismic performance and resiliency assessment of the sectors:

6 Earthquakes as hazard scenarios: 3 faults and two attenuation relations

4 Retrofitting scenarios:

Unanchored networks
Retrofitting and anchoring sector 1
Retrofitting and anchoring sector 2
Retrofitting and anchoring both sectors

7 Dependency scenarios: (i.e., 100, 80, 60, 40, 20, 0 percent dependency of sector 2 to power network and independent components of water network to each other (without inter- and intra-dependency).

As a result, 168 scenario combinations of hazard, retrofitting, and dependency scenarios were investigated. In order to simulate the performance and resiliency, each scenario combination was analyzed 200,000 times using Monte Carlo simulation.

The effects of inter-dependency on performance and resiliency are sometimes dramatic, but increasing the interdependency have an increasing effect on the failure probability of sectors in all cases, except in those cases which the components have neither intra-dependency (between components in one network) nor inter-dependency (between components of different networks) whatsoever. Thus, the more independent elements in a network, the better the performance and resiliency conditions in the case of earthquakes. So, the very first and best solution is to enhance sector two performance and resiliency is using power backup systems to reduce the negative effects of inter-dependencies with sector 1 in the case of strong earthquakes.

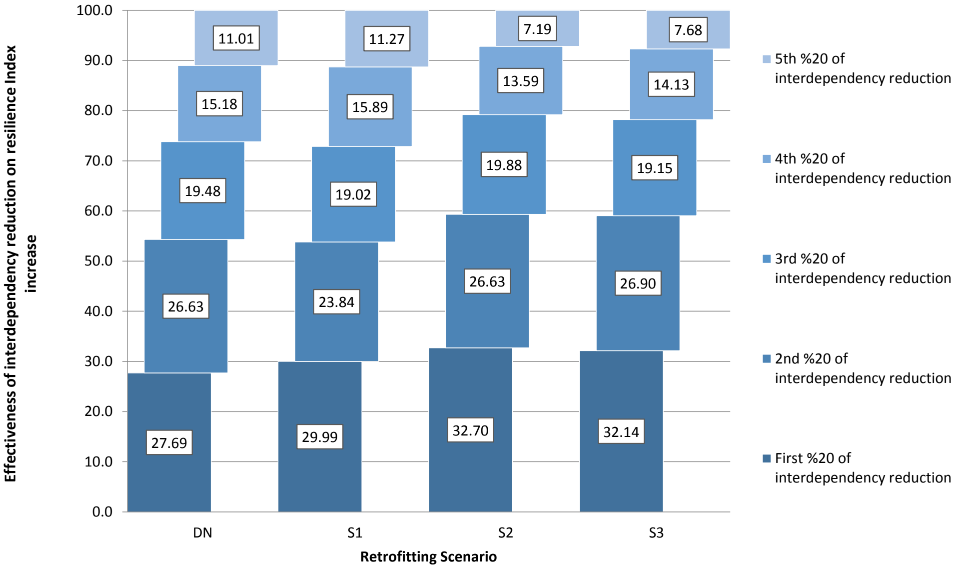

Fig 10. Effectiveness of interdependencyden reduction on resilience index increase for hazard scenario 1

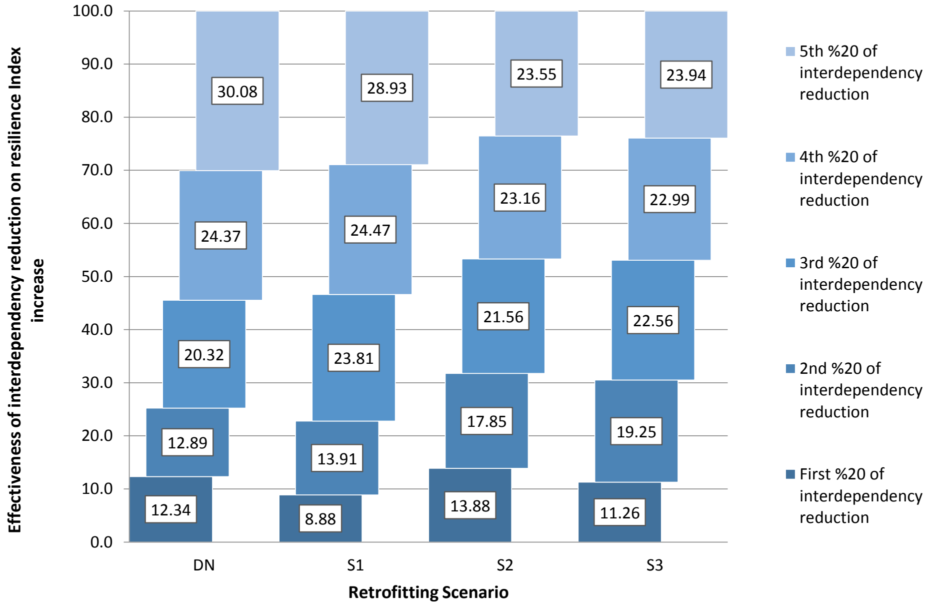

Fig 11. Effectiveness of interdepency reduction on resilience index increase for hazard scenario 2

The effect of interaction is numerically significant in a small-magnitude earthquake (Fig 8). In earthquakes with large-magnitude, components of sector 2 (water network) are severely damaged, and their interaction with sector 1 (power network) is no longer concerned (Fig 9).

Moreover, for moderate earthquakes, a small reduction of inter-dependency has a significant effect on increasing performance and resiliency. Fig 10 shows that the first 20% reduction of inter-dependency has its utmost increasing effect in the overall resiliency measure. Thus, an optimum value for interdependency reduction to increase the overall resiliency can be obtained using the Pareto principle.

Connecting the components of sector 2 (water network) to only one component of sector 1 (low-voltage substation) is the reason of high inter-dependency of sector 2 to sector 1 and failure of sector one will cause major impacts on the components of sector 2 in the district. In order to deal with and manage this problem, connecting components of sector 2 to two or more components of sector 1, instead of connecting to only one, can solve the problem.

Thus, as expected in retrofitting strategies for upgrading the seismic performance of sector 2, retrofitting the sector shows a better efficiency due to its direct effect comparing to the sector one retrofitting. This is ranked as the first strategy for strong earthquakes. Besides, inter-dependency reduction, in any way, causes the reduction of failure probability, but it is ranked second for the case of strong earthquakes.

As it is shown in Figures 10 and 11, overall resiliency improvements in the district are achieved more by interdependency reduction strategy for moderate earthquakes and by seismic retrofitting strategy for maximum earthquakes. However, a single strategy cannot be considered as an optimal one. Choosing an optimal strategy for a city is related to various factors and dimensions. Only a technical or solution cannot guarantee the success of resiliency improvements.

Developing the proposed model is one of the important steps to know more about the sectors, their interrelations, and enhance our knowledge on the issue of sectors performance and overall resiliency considering social, economic, technical, physical, institutional, and security dimensions of resiliency. The proposed method may be used for any set of sectors i.e., economic, technical, governance, institutional, social, and physical dimensions of resiliency for natural and unnatural incidents in a GIS database platform.

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