Wang F., Magoua J. and Li N. (2020). "Impact of systemic heterogeneity on the failure propagation of networked critical infrastructure systems: an explorative study considering the heterogeneity in susceptibility to overload failure" In: *Proc. 37th CIB W78 Information Technology for Construction Conference* (CIB W78), São Paulo, Brazil, pp. 465-476. DOI: http://dx.doi.org/10.46421/2706-6568.37.2020.paper034

IMPACT OF SYSTEMIC HETEROGENEITY ON THE FAILURE PROPAGATION OF NETWORKED CRITICAL INFRASTRUCTURE SYSTEMS: AN EXPLORATIVE STUDY CONSIDERING THE HETEROGENEITY IN SUSCEPTIBILITY TO OVERLOAD FAILURE

Fei Wang[1], Joseph Jonathan Magoua[2] and Nan Li[3]

Abstract: Modern CISs are becoming increasingly topologically interconnected and functionally interdependent. As a result, failure in one system may cause dependent components in other systems to fail, triggering cascading failures in networked CISs. Different CISs are heterogeneous in a variety of aspects, such as their topological characteristics and disaster resistance capacities. For instance, power grids are more susceptible than water supply systems to overload failure due to flow redistribution under disaster. Such systemic heterogeneity may significantly influence the failure propagation process across different CISs. However, despite the increasing volume of literature that examines failure propagation risks in networked CISs, few studies have accounted for systemic heterogeneity and its potential effects on cascading failures. The aim of this study is to assess the significance of such effects using one typical heterogeneity factor between the power and water supply systems. Firstly, a representative modeling approach of failure propagation, namely artificial flow based (AFB) approach, is selected through a thorough literature review. Secondly, two different artificial flow models (AFM) are developed using the AFB approach. Both models represent two interdependent, district-scale power and water systems, and they are distinguished by whether the systemic heterogeneity in susceptibility to overload damage is modeled by proper parameter settings. Lastly, both models are subjected to a simulated earthquake scenario, and three metrics are proposed to assess the overall responses of the two systems. The results from the two models are compared, which reveals that the magnitude of disaster impact of CISs would be notably overestimated when the systemic heterogeneity is not taken into consideration. The practical implications of the results are also discussed in the paper.

Keywords: Systemic Heterogeneity, Failure Propagation, Networked Critical Infrastructure Systems, Disaster Impact.

1 INTRODUCTION

Critical infrastructure systems (CISs), such as power and water supply systems, play a significant role in our daily life (Wang et al., 2013). Modern CISs are becoming more and

---

[1] Ph.D. Student, Department of Construction Management, Tsinghua University, Beijing, China, f-wang18@mails.tsinghua.edu.cn

[2] Ph.D. Student, Department of Construction Management, Tsinghua University, Beijing, China, mag19@mails.tsinghua.edu.cn

[3] Associate Professor, Department of Construction Management, Tsinghua University, Beijing, China, nanli@tsinghua.edu.cn

more networked and dependent on each other for proper functioning (Buldyrev et al., 2010). This has resulted in many bi- or multi-directional dependences, also referred to as interdependencies, between different CISs. Due to the presence of these interdependencies between CISs, the failure of a component in one system may cause failure of components in another system (Zhang et al., 2018). As a result, local failure may unpredictably propagate throughout the entire system-of-systems and could result in global failure.

Systemic heterogeneity of interdependent CISs refers to the differences between the CISs in terms of their physical network features, transported material properties, operational characteristics and responses to disaster (De et al., 2008; Wang et al., 2019). Systemic heterogeneity is the main cause of difference in failure propagation mechanisms among different CISs (Duenas-Osorio et al., 2007). A typical example of systemic heterogeneity factor is the heterogeneity in system susceptibility to overload failure. For instance, when disasters happen, compared to the water supply system, the power grid is more susceptible to component overload failure due to power flow redistribution (Zuloaga et al., 2019). Overload failure is easier to avoid in the water supply system because proper technical or managerial measures can be taken in a timely manner to prevent the amplification of damage in the network. That being said, the impact of systemic heterogeneity on failure propagation across CISs has not been adequately recognized and addressed in prior research. While several studies have pointed out the possible impact of systemic heterogeneity and the need to account for this impact in the modeling of CISs failure propagation and the estimation of CISs disaster losses (De et al., 2008), the extent of this impact and its mechanism have largely remained unknown. CISs are largely considered homogenous in these models with respect to their disaster response patterns, which inevitably leads to significant inaccuracies in the simulated failure propagation processes and estimated overall disaster impacts (Duan et al., 2020).

In this study, one typical systemic heterogeneity factor, namely heterogeneity in system susceptibility to overload failure, is examined based on a case study. The impact of this factor on the failure propagation of an interdependent CISs network, which is comprised of a water supply system and a power supply system and represented using a widely adopted CISs modeling approach (i.e. artificial flow-based (AFB) network modeling), is assessed and analyzed. Results from this study are expected to raise the awareness of drawbacks in current CISs failure propagation models, and serve as a foundation for the development of more reliable failure propagation modeling approaches in future research.

2 RELATED WORK

2.1 Network-based Modeling of Interdependent CISs

Interdependent CISs are easily modeled using network-based approaches with nodes and links representing system components and their connections respectively. Hence, with the progress made in network science over the years, it has become easier to model interdependent CISs (Ouyang, 2014).

The network-based modeling approaches can be classified under two main categories. In the first category, only the topology of the network is modeled. This approach is known as the topology-based (TB) approach. A typical model based on the TB approach is the percolation model (Buldyrev et al., 2010). In the second category, both the network topology and material flow across system components are modeled. The main approach under this category is the network flow-based approach (Ouyang, 2014). The typical models based on the flow-based approach are AFB network model (Wu et al., 2016) and real flow-based (RFB) network model (Ouyang et al., 2009), which are differentiated based on whether the model settings adopt real flow attributes of CISs or their proxy parameters and indices. Typical indices used to represent system flow in AFB models include betweeness (Wu et al., 2016) and path number (Wang et al., 2018). RFB models use real flow indices such as water flow rate and current flow rate to analyze the operation characteristics of systems. A few other network models have also been proposed in prior research, that integrate other logical algorithms to describe interactions between network components. Examples include the petri-net (PN) (Ouyang et al., 2009) and Bayesian network (BN) models (Wang et al., 2018).

2.2 Simulation of Failure Propagation Across Networked CISs

Researchers proposed a few TB approaches to model the mechanism of failure propagation through CISs networks. One common insight of these approaches is that failure of a node would lead to the failure of all edges connected to the node, and vice versa (Buldyrev et al., 2010). Failure will stop propagating when all nodes within a spanning cluster remain functional under the disaster simulation. Network flow-based approaches are used to model the functionality of CISs. However, since it is difficult to precisely model the flow within the CIS (Chowdhury and Zhu, 2019), some flow indices were introduced. This has led to the development of two variants of the network flow approach, namely AFB network model (Johansson and Hassel, 2010) and RFB network model (Ouyang et al., 2009). The failure propagation process of network flow-based approach can be summarized as a redistribution of flow within a system when a node fails. Consequently, some other nodes may suffer overload damage if their capacity is exceeding. This process is repeated iteratively until the actual load at every remaining node in the network is no larger than its capacity.

Other models, such as agent-based model (ABM), system dynamics (SD) model and input-output model (IOM), have also been adopted to model failure propagation of CIS-related systems. However, most of these studies focused on the interactions between different CISs, or between CISs and economic system or social systems (Thompson et al., 2019; Bagheri et al., 2007; Rai and Henry, 2016), while paying little attention to modeling failure propagation across interdependent CISs.

Four criteria, namely effectiveness, complexity, maturity, and replicability, are used to compare the existing approaches for modeling failure propagation across CISs. Effectiveness refers to the ability of the modeling approach to accurately model failure propagation (Duan et al., 2020); Complexity mainly refers to computational complexity in modeling the failure propagation (Ouyang, 2014; Duan et al., 2020); Maturity refers to the development level of each approach, which can be measured by the number of existing publications and applications (Ouyang, 2014; Duan et al., 2020); Replicability describes the difficulty in replicating an approach based on the descriptions available in relevant prior publications and accessing relevant empirical data (Ouyang, 2014). The effectiveness, complexity, maturity and replicability of each modeling approach are assessed and rated “L” (low), “M” (medium) or “H” (high) based on the rating criteria proposed in prior research (Ouyang, 2014; Duan et al., 2020). The assessment results are summarized in Table 1.

Although a bulk of research has been conducted to advance the understanding of the mechanism of failure propagation across CISs, however, the impact of system heterogeneity on this mechanism is still a relatively unexplored topic. Failure to consider systemic heterogeneity when modeling interdependent CISs would result in inaccuracies in the simulated disaster response behaviors of the systems. This paper therefore aims to reveal and assess the importance of systemic heterogeneity when modeling failure propagation across interdependent CISs.

Table 1: Assessment of approaches for modeling failure propagation across CISs.

Approach	Criteria			
	Effectiveness	Complexity	Maturity	Replicability
TB	L	L	H	H
AFB	M	M	H	H
RFB	H	H	M	L

3 METHODOLOGY

In this study, one typical heterogeneity factor existing between the power and water supply systems, namely heterogeneity in system susceptibility to overload failure, is examined for its impact on failure propagation in an interdependent CISs network comprised of the above two systems. Firstly, a baseline model is built, using a typical and easily replicable modeling approach, to simulate the failure propagation in the CISs. Secondly, a modified version of the baseline model is built, by taking into consideration the systemic heterogeneity factor. Lastly, three impact metrics are introduced to compare the failure propagation process and outcomes obtained from both models when they are subjected to a simulated disaster. The above methodology is further explained below.

3.1 Baseline Model

The approach for modeling the baseline model is selected based on the four criteria described in Section 2.2. Specifically, in the best case the selected approach should be of high effectiveness, low complexity, high maturity and high replicability. The ratings of the AFB approach in the four criteria are the closest to the best case among all existing approaches, with medium effectiveness, medium complexity, high maturity and high replicability as can be observed in Table 1. Therefore, the AFB approach is selected for this study. The modeling of CISs using the AFB approach is described in detail below.

The networked power-water supply system can be denoted as $S = \{S_p, S_w\}$, where $S_p = (V_p, E_p)$ and $S_w = (V_w, E_w)$. The element $V_p(V_w)$ represents the system nodes and $E_p(E_w)$ represents the system links. The flow relationship R^{ik} between nodes i and k in each CIS can be expressed as follows:

$$R^{ik} = \begin{cases} 1 & if\ there\ is\ flow\ from\ node\ i\ to\ node\ k \\ 0 & if\ there\ is\ no\ flow\ from\ node\ i\ to\ node\ k \end{cases} \tag{1}$$

The interdependencies between power and water supply systems can be described as unidirectional dependency links between them. Interdependency I_{ij} between node i in S_p and node j in S_w can be expressed as follows:

$$I_{ij} = \begin{cases} 1 & if\ node\ i\ (i \in V_p)\ is\ dependent\ on\ node\ j\ (j \in V_w) \\ 0 & if\ there\ is\ no\ relationship\ between\ node\ i\ (i \in V_p)\ and\ node\ j\ (j \in V_w) \\ -1 & if\ node\ j\ (j \in V_w)\ is\ dependent\ on\ node\ i\ (i \in V_p) \end{cases} \tag{2}$$

Betweenness is a widely used index to represent the flow within a system (Wu et al., 2016). The betweenness of node t, denoted as $BV(t)$, which is defined as:

$$BV(t) = \sum_{i \neq k, i \neq t, k \neq t} \frac{g_{ik}^{t}}{g_{ik}} \tag{3}$$

where g_{ik} denotes the number of shortest paths starting from node i and ending at node k, and g_{ik}^{t} denotes the number of shortest paths from node i to node k and passing through node t.

The load of node t, denoted as $LV(t)$, can be represented by its betweenness value $BV(t)$ (Wu et al., 2016). At the same time, the capacity of node t, denoted as $CV(t)$, is assumed to be proportional to the initial load $BV_0\,(t)$ (Wu et al., 2016):

$$CV(t) = (1 + \beta) \cdot BV_0\,(t) \tag{4}$$

The model setting of the baseline model, which includes all the parameters constituting Eq (1)-(4), is designed based on descriptions reported in prior research (Chowdhury and Zhu, 2019). Failure propagation can be modeled as follows: if actual load $BV(t)$ of node t exceeds its capacity $CV(t)$, the node will experience overload damage. Overload damage is possible in both CISs. Failed nodes are automatically removed from the network and the betweenness value of every remaining node in the redistributed network is recalculated and updated. The above process is repeated iteratively until the actual load at every remaining node in the network is no larger than its capacity. Links are not subject to failure. The tolerance parameter in Eq (4) is set to be 0.02 based on China standard (2009).

3.2 Modified Model

As the second step of the methodology, the baseline model is modified to consider the systemic heterogeneity factor selected in this study. The heterogeneity factor proposes that overload damage would not occur to components in the water supply system. This proposition is explained by the way components in both systems are designed. In power grids each component has a flow capacity that cannot be exceeded or else the component would be damaged almost instantly. Power flow redistribution under disaster may cause the actual flow through certain components to exceed their capacity and hence cause overload damage of the components. However, in water supply systems, flow rates are continually adjusted by the pump stations and in case of any disruptions, timely measures can be taken to avoid overload damage of components.

To incorporate this heterogeneity factor in failure propagation simulation, the capacity $CV(t)$ of node t should always be larger than its actual load $BV(t)$. Hence, Eq (4) is modified to be:

$$CV(t) = \begin{cases} (1 + \beta(p)).BV_0(t) & if\ t\ \in V_p \\ (1 + \beta(w)).BV_0(t) & if\ t\ \in V_w \end{cases} \tag{5}$$

where $\beta(p)$ and $\beta(w)$ are the tolerance parameters of power and water supply system, respectively. In this modified model, $\beta(w)$ is set at a large value of 10. This value is determined after several test simulations, and is chosen to ensure that for every node in the network its actual artificial flow never exceeds its capacity, such that no overload damage would occur. All other parameters in the modified model are same as in the baseline model.

3.3 Impacts Metrics

Three metrics, namely impact on failure scale (Wu et al., 2016), propagation time (Mao and Li, 2018), and failure order (Chang et al., 2002) are adopted to assess the impact of the studied heterogeneity factor on the failure propagation in the power-water CISs.

Failure scale refers to the number of nodes damaged during the simulated disaster. The impact of the heterogeneity factor on failure scale, denoted as p_1, can be calculated as follows:

$$p_1 = \left|\frac{n'-n_0}{n}\right| \tag{6}$$

where n' and n_0 are the number of failed nodes of the modified model and baseline model, respectively and n is the total number of nodes in the network.

Propagation time is measured by the number of propagation steps in the simulation before the network reaches a post-disaster steady state. Propagation time would attain a maximum value if a single node fails at every failure propagation step. The impact of the heterogeneity factor on propagation time, denoted as p_2, can be calculated as follows:

$$p_2 = \left|\frac{\eta-\eta_0}{n}\right| \tag{7}$$

where η and η_0 are the propagation time obtained from the modified model and baseline model, respectively.

Node failure order refers to the failure propagation step at which the node fails. The failure order of all nodes in a system can be denoted as a sequence $\theta = (o_1 \cdots, o_m, \cdots, o_n)$ (the order of an operational node is 0). Taking $\theta^0 = ({o_1}^0 \cdots, {o_m}^0, \cdots, {o_n}^0)$ to be the node failure order obtained from the baseline model, the impact of the heterogeneity factor on failure order, denoted as p_3, can be calculated as follows:

$$p_3 = \sqrt{\sum_{m=1}^{n} (o_m - o_m^0)^2} \tag{8}$$

Larger values of p_1, p_2 and p_3 indicate larger impacts of the heterogeneity factor on the failure scale, propagation time and node failure order, respectively.

4 CASE STUDY

4.1 Case Description

A case study of the interdependent water and power supply systems on the Tsinghua University campus was conducted to illustrate the impact of systemic heterogeneity on failure propagation across the CISs. The number and location of each CIS's facilities as well as the links between them were obtained from available design documents of both systems. The layout of both systems superimposed over the campus map is illustrated in Fig. 1. All facilities and major components of the two systems were regarded as nodes, whilst power cables and water pipes were regarded as links. A total of 86 nodes and 148 links were identified, as summarized in Table 2. Nodes belonging to the power supply network were labeled nodes 1 through 42, and those belonging to the water supply system were labeled nodes 43 through 86. In addition, there are two types of interdependency links in this case, and their layouts are presented in Fig. 2.

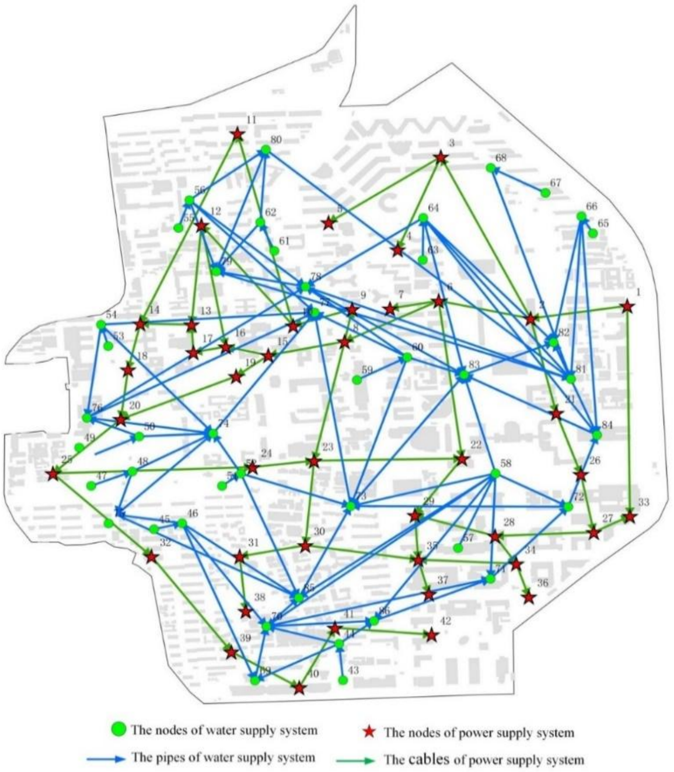

Figure 1: Layout of case systems

Table 2: Summary of facilities and connections in the case systems.

System	Facility (acronym and number)	Link (number)	
		Connectivity within systems	Dependency between systems
Power supply system	Electric substation - 110kv-10kv (ES,1) Switching station (SS,12) End user (EU,29)	Power cable (51)	Water pipe (1)
Water supply system	Groundwater well (GW,13) Pump station (PS,13) End user (EU,18)	Water pipe (83)	Power cable (13)

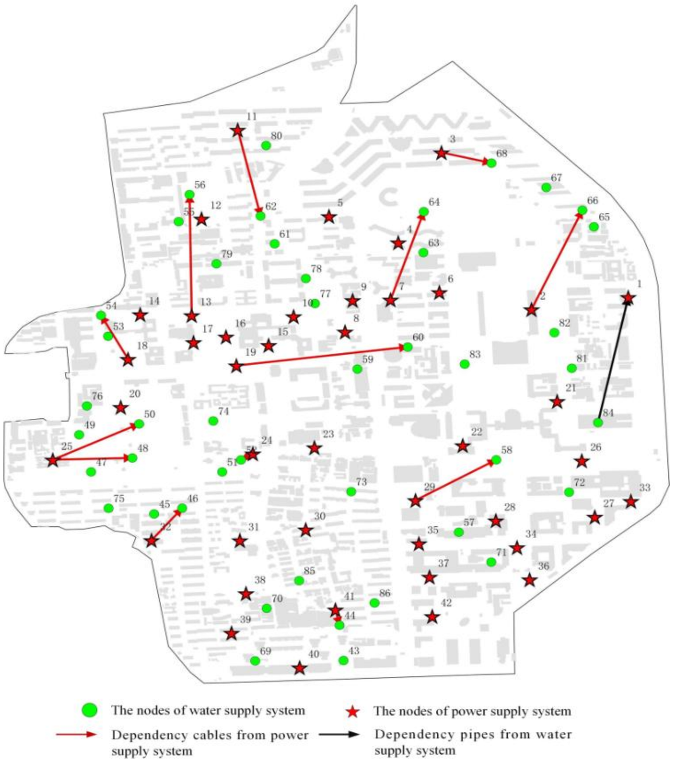

Figure 2: Dependency links of water and power supply system in study case.

4.2 Simulated Disaster Scenario

An earthquake scenario was chosen as external disruption. Peak ground acceleration (PGA) was the input parameter used to represent the earthquake disaster in simulation. PGA represents the ground motion induced by the seismic waves. According to the Seismic Ground Motion Parameters Zonation Map of China (2015), the PGA of Beijing is 0.3g, where g is taken as 10m/s2. It was assumed in the simulation that a node would fail when the inputted PGA value was larger than the seismic resistance of the component represented by this node. The seismic resistance of all facilities and major components (including ES, GW, PS and SS) was obtained from their design documents. Their values varied between 0.2g and 0.4 g.

5 RESULTS AND DISCUSSIONS

The failure propagation of the power-water CISs was simulated, based on the baseline model and modified model respectively, using MATLAB. The simulation results are summarized in Fig. 3. As can be seen in the Fig. 3, the failure propagation patterns in the two models showed obvious differences. The baseline model propagated four steps to reach a steady state and a total of 21 nodes were damaged. In the modified model, only three failure propagation steps were necessary to bring the system to a steady state and the number of damaged nodes decreased by 10, which was nearly half of that observed in the baseline model. These results indicated that the impact of the studied systemic heterogeneity factor was considerable.

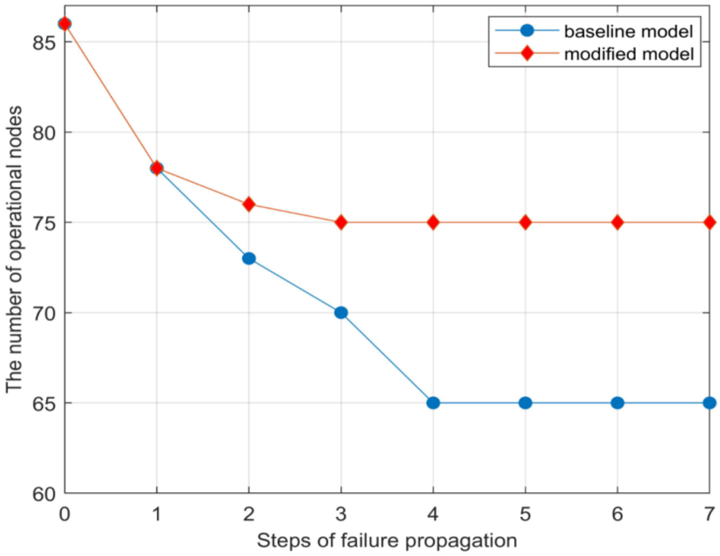

Figure 3: Failure propagation pattern observed in each model

Based on the simulation results, the failure order of every node in both models are summarized and presented in Fig. 4.

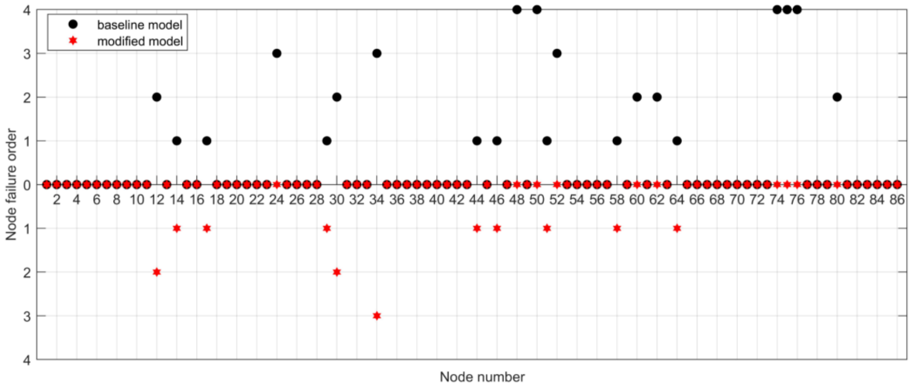

Figure 4: Node failure order sequence in each model

It can be observed from Fig. 4 that nodes 12, 14, 17, 29, 30, 34, 44, 46, 51, 58, 64 failed in both models. Among them, nodes 14, 17, 29, 44, 46, 51, 58 and 64 failed in the first failure propagation step of both models, whilst nodes 12, 30 and 34 failed due to the ripple effect of damages incurred from the seismic waves. Specifically, nodes 14, 17 and 29 were switching stations of the power supply system, nodes 44, 46, 58 and 64 were pump stations and node 51 was a groundwater well. These nodes failed in both models, which indicated that these components were highly vulnerable to earthquake.

In addition, based on the simulation results, the impact metrics were calculated and the results are presented in Table 3.

Table 3: Impact assessment results.

Impact on failure scale (p1)	Impact on propagation time (p2)	Impact on failure order (p3)
0.1163	0.0116	10.4886

Results from Table 3 show that the heterogeneity in system susceptibility to overload failure had a considerable impact on failure propagation across the power-water supply system. In the baseline model, 21 nodes failed, of which seven were from the power supply system and 14 were from the water supply system. However, when was heterogeneity factor was considered, only five nodes from the water supply system were damaged, which indicated that the disaster impact in the baseline model was overestimated.

Based on the assessment results obtained in this study, it can be reasonably inferred that systemic heterogeneity has a significant impact on failure propagation across interdependent CISs. This finding is consistent with the findings reported in related studies (Buldyrev et al., 2010; Buldyrev et al., 2011; Duan et al., 2019). Among these studies, a typical example is the work by Buldyrev et al. (Buldyrev et al., 2010), which simulated failure propagation through two tightly interdependent CISs each modeled using power-law degree distributions. The conclusions from their work was that the more heterogeneous the networks, the smaller the damage that can be sustained before functional integrity is totally compromised. Their results strongly support the conclusion of this paper, which argues that systemic heterogeneity indeed has an impact on failure propagation across CISs.

In this study, when systemic heterogeneity was taken into consideration, both power and water supply systems experienced less damaged nodes than in the baseline model. Failed nodes in water supply system were all damaged by the seismic waves since no overload damage could occur. As the number of failed nodes decreased in the water supply system, the number of damage nodes in power supply system also decreased because of the interdependency between them. This finding indicates that disaster impact would be overestimated if systemic heterogeneity were not taken into consideration, and also that the disaster impact of one system can be controlled by the state of other systems due to the interdependency existing between them. It is therefore important to design systems with reliable inner-dependency and interdependency links.

6 CONCLUSION

With rapid urbanization worldwide, modern CISs are becoming increasingly topologically networked and functionally interdependent. Every CIS has its unique physical network features, transported materials, operation mechanism and disaster response patterns, which differentiates it from other CISs. This systemic heterogeneity between CISs, particularly its impact on failure propagation, has been largely overlooked in prior research. This study therefore aimed at assessing the impact of systemic heterogeneity on failure propagation across interdependent CISs, by comparing simulation results for an AFB model in which a typical heterogeneity factor was considered, to that from a baseline model in which heterogeneity was not considered.

Results from a power-water CISs case study showed that the impact of systemic heterogeneity on failure propagation across interdependent CISs should not be overlooked. More specifically, the results showed that overlooking systemic heterogeneity could amplify the overall impact of a disaster event on the interdependent CISs, therefore, systemic heterogeneity should be appropriately incorporated when modeling failure propagation across CISs. In-depth knowledge on systemic heterogeneity and how to consider it in the modeling process is imperative to ensure the accuracy and reliability of models used in assessing disaster response behavior of CISs. Results from this study not only provided a better understanding of the three studied HFs but also highlighted the importance of addressing systemic heterogeneity in general when modelling CISs.

7 ACKNOWLEDGMENTS

This material is based on work supported by the National Key R&D Program of China under Grant No. 2016YFC0802001, the Beijing Natural Science Foundation (BJNSF) under Grant No. 8202027, the National Natural Science Foundation of China (NSFC) under Grant No. U1709212, and the Tsinghua University-Glodon Joint Research Centre for Building Information Model (RCBIM). The authors are grateful for the support of the Ministry of Science and Technology of China (MOST), BJNSF, NSFC and RCBIM. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies.

8 REFERENCES

Bagheri, E., Baghi, H., Ghorbani, A. A. & Yari, A. (2007), "An agent-based service-oriented simulation suite for critical infrastructure behaviour analysis", International Journal of Business Process Integration and Management, 2(4), pp. 312-326.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E. & Havlin, S. (2010), "Catastrophic cascade of failures in interdependent networks", Nature, 464(7291), pp. 1025-1028.

Buldyrev, S. V., Shere, N. W. & Cwilich, G. A. (2011), "Interdependent networks with identical degrees of mutually dependent nodes", Physical Review E Statistical Nonlinear & Soft Matter Physics, 83(1), 016112.

Chang, C. C., Lu, P. W. & Hsiao, J. Y. (2002).A hybrid method for estimating the Euclidean distance between two vectors. In: First International Symposium on Cyber Worlds, 2002. [online] Tokyo, Japan: IEEE, pp. 183-190. Available at: https://ieeexplore.ieee.org/abstract/document/1180878.

National Standardization Administration of China. (2009) Power quality - Deviation of supply voltage. GB/T 12325-2008. China.

National Standardization Administration of China. (2015) Seismic ground motion parameters zonation map of China. GB 18306-2015. China.

Chowdhury, S. & Zhu, J. (2019) Heterogeneous Network flow model for optimized restoration planning of interdependent infrastructure system-of-systems. In: ASCE International Conference on Computing in Civil Engineering 2019.[online] Atlanta:ASCE, pp.791-796. Available at: https://ascelibrary.org/doi/abs/10.1061/9780784482445.069.

De Porcellinis, S., Setola, R., Panzieri, S. & Ulivi, G. (2008), "Simulation of heterogeneous and interdependent critical infrastructures", International Journal of Critical Infrastructures, 4(2), pp. 110-28.

Duan, D., Lv, C., Si, S., Wang, Z., Li, D., Gao, J., Havlin, S., Stanley, H. E. & Boccaletti, S. (2019), "Universal behavior of cascading failures in interdependent networks", Proceedings of The National Academy of Sciences of The United States of America, 116(45), pp. 22452-22457.

Duan, S., Ayyub, B. M. & P. E., D. (2020), "Assessment methods of network resilience for cyber-human-physical systems", ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 6(1), 03119001.

Duenas-Osorio, L., Craig, J. I., Goodno, B. J. & Bostrom, A. (2007), "Interdependent response of networked systems", Journal of Infrastructure Systems, 13(3), pp. 185-194.

Dunn, S. & Holmes, M. (2019), "Development of a hierarchical approach to analyse interdependent infrastructure system failures", Reliability Engineering & System Safety, 191, 106530.

Johansson, J. & Hassel, H. (2010), "An approach for modelling interdependent infrastructures in the context of vulnerability analysis", Reliability Engineering & System Safety, 95(12), pp. 1335-1344.

Mao, Q. & Li, N. (2018), "Assessment of the impact of interdependencies on the resilience of networked critical infrastructure systems", Natural Hazards, 93(1), pp. 315-337.

Ouyang, M. (2014), "Review on modeling and simulation of interdependent critical infrastructure systems", Reliability Engineering & System Safety, 121, pp.43-60.

Ouyang, M., Hong, L., Mao, Z., Yu, M. & Qi, F. (2009), "A methodological approach to analyze vulnerability of interdependent infrastructures", Simulation Modelling Practice and Theory, 17(5), pp. 817-828.

Rai, V. & Henry, A. D. (2016), "Agent-based modelling of consumer energy choices", Nature Climate Change, 6(6), pp. 556-562.

Thompson, J. R., Frezza, D., Necioglu, B., Cohen, M. L., Hoffman, K. & Rosfjord, K. (2019), "Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure", International Journal of Critical Infrastructure Protection, 24, pp.144-165.

Wang, F., Zheng, X., Li, N. & Shen, X. (2019), "Systemic vulnerability assessment of urban water distribution networks considering failure scenario uncertainty", International Journal of Critical Infrastructure Protection, 26, 100299.

Wang, S., Hong, L., Ouyang, M., Zhang, J. & Chen, X. (2013), "Vulnerability analysis of interdependent infrastructure systems under edge attack strategies", Safety Science, 51(1), pp. 328-337.

Wang, W., Yang, S., Hu, F., Stanley, H. E., He, S. & Shi, M. (2018), "An approach for cascading effects within critical infrastructure systems", Physica A-Statistical Mechanics and Its Applications, 51(510), pp. 164-177.

Wu, B., Tang, A. & Wu, J. (2016), "Modeling cascading failures in interdependent infrastructures under terrorist attacks", Reliability Engineering & System Safety, 147, pp.1-8.

Zhang, C., Kong, J. & Simonovic, S. P. (2018), "Modeling joint restoration strategies for interdependent infrastructure systems", PLOS ONE, 3(4), e01957274.

Zuloaga, S., Khatavkar, P., Mays, L. & Vittal, V. (2019), "Resilience of cyber-enabled electrical energy and water distribution systems considering infrastructural robustness under conditions of limited water and/or energy availability", IEEE Transactions on Engineering Management, pp.1-17.