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Climate Change Impact on Urban Resilience under Typhoon Disasters Considering Interdependent Infrastructure Systems

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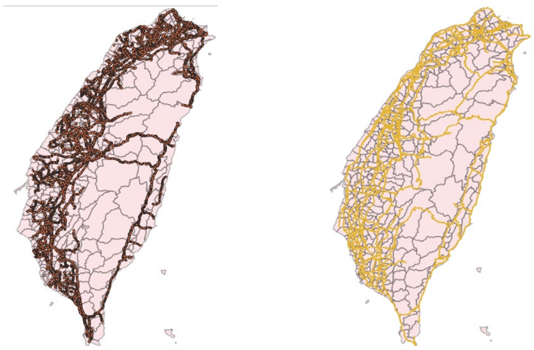
ABSTRACT: The functionality of a resilient infrastructure system would be less impacted and quicker recovery under disasters. This study aims to investigate the resilience of a city in Taiwan under typhoon disasters and the potential climate change impact on its resilience measures. This study simplifies electric power and road networks to establish an interdependent mathematical model of these two systems of Kaohsiung, Taiwan. The hazard models, fragility models, and recovery models under typhoon disasters of the two systems are established, and the recovery of functionality of all nodes after a typhoon event is used to evaluate the resilience of the system. The interdependent matrices of the two systems and the network connectivity after disasters are used to analyze the restoration time of the city. Then, the system's performance and repair time differences between separate and interdependent models are compared. In addition, as typhoon wind speed intensifies due to climate change, it is possible to confront more severe typhoons in the future. Thus, the wind speed in the hazard model is increased to investigate its potential impact on urban resilience and to serve as a reference for future community resilience planning.

1. INTRODUCTION

Highly developed societies rely heavily on critical infrastructure systems (CISs) that provide residents with safety, security of property, and quality of life (Hosseini et al., 2016). However, these systems are vulnerable to natural hazards, leading to reduced functionality and severe consequences. In recent years, natural disasters have become increasingly unpredictable and inevitable with climate change. For example, an average of 4.6 typhoons hit Taiwan each year. Strong winds from typhoons cause trees to fall and destroy utility power facilities (as shown in Figure 1), causing road congestion and large-scale power outages. In addition, CISs, such as electricity, transportation, telecommunications, etc., are usually not isolated but highly dependent and interconnected. The proper operability of a facility in a single system often depends on the operation of several other facilities. Therefore, when one critical system suffers damage and loses function, the outage can spread to other related systems and cause widespread disruption of lifeline services.

Figure 1. Typhoon Nepartak caused the power tower to collapse (Taipower, 2016)

As climate change takes place, CISs might encounter more intense typhoon hazards, and the resilience of a city might be impacted accordingly. However, few studies have explored the climate change impact on urban resilience under wind disasters. As a starting point, this study evaluates the urban resilience of a city in Taiwan by constructing a model of interdependent power and transportation systems, as shown in Figure 2, and exploring the linkages between the two systems. Reliable mathematical models, metrics, and decision-making frameworks should be feasible, reasonable, applicable to a variety of interdependent infrastructure systems under a hazard model, and capable of validating historical conditions.



(a) (b)

Figure 2. (a)Taipower System and Power Grid Distribution, and (b) Taiwan road network map from Directorate General of Highway, Ministry of Transportation and Communications

Post-disaster infrastructure recovery faces three major challenges. The first is to develop a mathematical model that includes connectivity and dependencies within and between systems and to develop a measure of the probability of damage relative to recovery time. The second is to quantify the performance of infrastructure systems to inform post-disaster recovery decisions (Adjetey-Bahun et al., 2016). The third is to improve the details of the model, such as regional terrain differences and the process of maintenance organizations, to make it closer to the real situation. In addition to the common resilience assessment framework, this study discusses the issue of climate change and conducts the sensitivity analysis of the hazard model by increasing the wind speed of the typhoon to discuss the potential impact of climate change on urban resilience. This result will help to improve the understanding of the co-systems and the system itself providing effective suggestions for pre-disaster prevention and post-disaster restoration.

2. CRITICAL INFRASTRUCTURE SYSTEMS MODELING

2.1. Electric Power System

This study focuses on the transmission system, not only because of its importance in the power system but also because of its wide distribution and complicated subsequent processing. Transmission lines are key elements of the electrical power system for transferring bulk power from generators to communities and industries. Thus, tower safety and reliability assessment are necessary to plan for minimization of the risk of disruption of power supply resulting from in-service tower failure. Simultaneously, electricity transmission lines are linear assets exposed to wind hazards, and the magnitude and direction of wind on the conductors and the cascading failure mechanisms determine its damage. Cai et al. (2019) presented a novel methodology developed for the Critical Infrastructure Protection Modelling and Analysis (CIPMA), which is capable of assessing local wind speeds and the likelihood of tower failure for a range of transmission tower and conductor types.

2.2. Transportation System

In this study, the traffic network focuses on the topological characteristics of the road network, where connectivity and shortest traffic paths are important for assessing the ability of the system to cope with disasters (Adjetey-Bahun et al., 2016). However, road networks are vulnerable to widespread damage due to natural disasters, which can hamper emergency response and economic recovery efforts. Therefore, this study combines Kaohsiung's vulnerable hilly areas and road systems to identify roads which are likely to be closed when a typhoon strikes. Based on wind fragility curves of traffic signs of the road system, we can assess whether there will be damage to traffic performance.

2.3. Kaohsiung's CIS Modeling

The traffic and power network models are established using open data platforms provided by the Taiwan government. The milepost coordinates of Kaohsiung's national highways, expressways, and provincial highways are collected, and a road association network is established through the connectivity between the mileposts and intersections, as shown in Figure 3(a). On the other hand, a power network comprises a power plant, transmission system, and distribution system. This study first focuses on the transmission power network to evaluate the resilience of the regional power system. The transmission power network model is rooted from power plants to substations as end users, as shown in Figure 3(b).

3. RESILIENCE MODELING UNDER WIND HAZARDS

3.1. Resilience Assessment

To quantify the concept of resilience, quantitative resilience assessment methods for civil infrastructure systems can assess the performance of infrastructure systems under disasters and compare the effectiveness of different pre-disaster risk mitigation or post-disaster recovery plans. The definition of resilience used in this study is adopted from Tinebra et al. (2016), where the resilience index R of the system is defined as the normalized area below the function of the system (e.g., inoperability), as shown in Figure. 4, which is performance function $Q_{TOT}(t)$ in Eq. (1). While T_{LC} is the control time for the period of interest (emergency response versus long-term reconstruction phase); t_{0E} is the time instant when the event happens; $\vec{r}$ is the spatial vector defining the position, and Res is the region in which the resilience index is evaluated.

$$R(\vec{r}) = \frac{1}{T_{LC}} \int_{t_{0E}}^{t_{0E}+T_{LC}} Q_{TOT}(\vec{r}, t)\, dt \qquad (1)$$

3.2. Wind Fragility Curve

Using Monte Carlo simulation, during a typhoon event, the network system subjected to the same wind speed is damaged at random points based on modified fragility curves. Nodes related to the

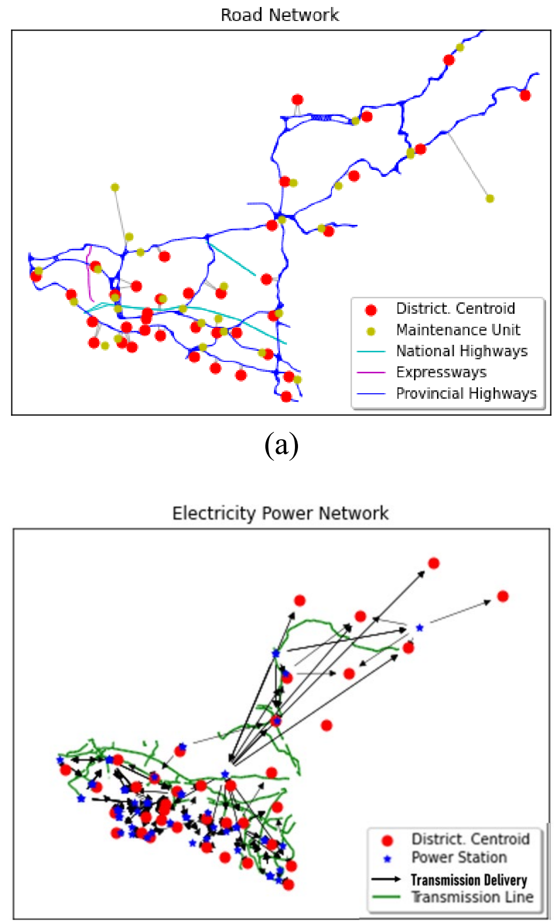


Figure 3. (a)Road and (b) Power network of Kaohsiung, Taiwan.

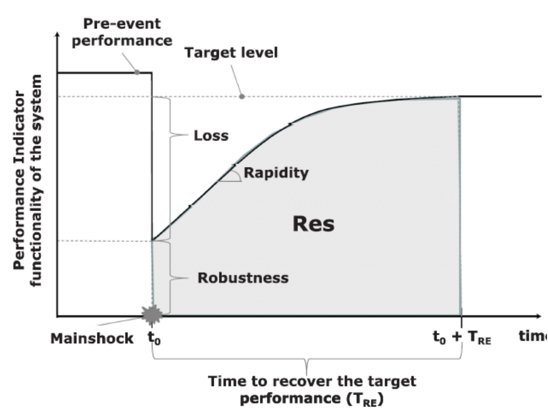


Figure 4. The concept of resilience. (Cimellaro et al., 2010)

destructed nodes will also drop and lose their functionality.

Nodes' corresponding damage probability under varying wind speeds is determined using fragility curves adopted from Wang et al. (2021), Fu et al. (2016), and Applied Technology Council (1985) as shown in Figure 5. The initial inoperability of each node can be determined according to the level of physical damage, which can be captured by the vulnerability curve. The cumulative distribution function is used to describe the conditional probability of facilities experiencing different damage states under a given hazard intensity. According to the conditional probability of different levels in fixed wind speed, the physical damage level of each node is simulated after being impacted by the typhoon.

Each node's initial inoperability and repair time is generated using the dependency matrix and restoring coefficient matrices that show average repair time corresponding to different damage levels based on probabilistic models, as shown in Table 1. The table is obtained from statistics of historical data from the Taiwan government's open data platform.

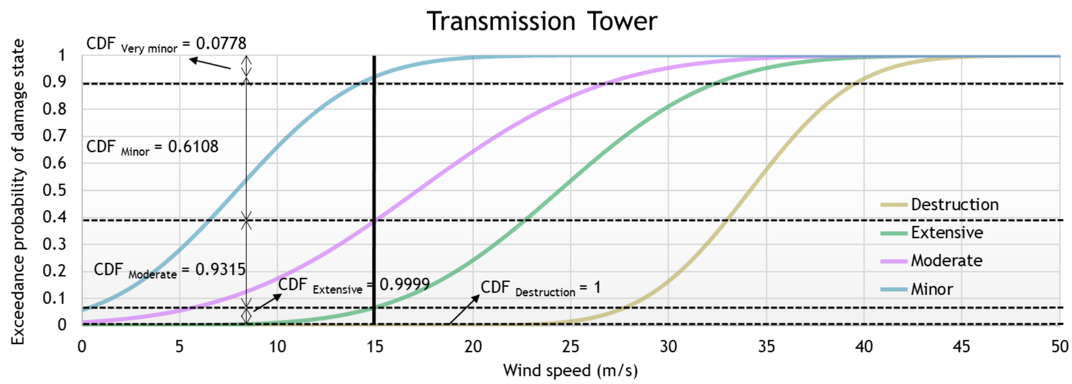


Figure 5. Cumulative distribution function of damage levels obtained from fragility curves for towers to estimate the probability of exceeding certain damage states. (He & Cha, 2018; Applied Technology Council, 1985)

Table 1. Probabilistic information for attributes of vulnerability and repair time

System	Node	Damage Level	Fragility Parameter (lognormal distribution)	Repair Parameter (Linear model)
Power network (PN)	Station	Moderate	Median: 89.0 m/s, COV: 5.64	Mean: 19.4 h, COV:0.05
	Transmission	Minor	Median: 17.15 m/s, COV:7.64	Mean: 2 h, COV:0.5
		Destruction	Median: 84.44 m/s, COV:0.15	Mean: 72 h, COV:1.5
	Distribution	Destruction	Median: 52.22 m/s, COV:0.15	Mean: 5 h, COV:0.5
Traffic network (TN)	Road	Minor	Median: 35.25 m/s, COV:4.1	Mean: 2 h, COV:0.5
		Moderate (traffic control device)	Median: 41.4 m/s, COV:6.5	Mean: 4 h, COV:0.5
		Fully blocked	Median: 50.6 m/s, COV:11.5	Mean: 8 h, COV:1.5

3.3. Dependency and Recovery Coefficient

For the power system and the transportation system, three types of interdependencies are considered in this study shown in Figure 6 (A. Salman, 2016):

1. *Physical and geographic interdependency (Type I):* The function of traffic lights and road monitoring systems depends on the electricity supply of the regional power distribution system.
2. *Geographic interdependency (Type II):* The function of some roadway arcs in the transportation network depends on whether the strong wind results in towers or poles collapsing, blocking the roadway. Relatively, some falling facilities on the road will also affect the link of the power system.
3. *Physical interdependency (Type III):* The accessibility to damaged sites in the electric power system in the recovery process depends on the function of the transportation network.

Table 2. Dependency consideration in Taiwan based on Cimellaro et al.(2016)

	Source Node Type	Damage level	Repair time
Type I	Substation (A)	$A_{level} > 0.6$	A_{time}
Type II	Transmission Line (B)	B_{level}	B_{time}
	Road (C)	C_{level}	C_{time}
Type III	Road (D)	$A_{level} > 0.6$	D_{time}
	Target Node Type	**Damage level**	**Repair time**
Type I	Traffic control devices	$+ 1.0{*}A_{level}$	$+ A_{time}$
Type II	Road	$+ 0.5{*}B_{level}$	+ 4 h
	Transmission Line	$+ 0.45{*}C_{level}$	+ 2 h
Type III	Power Nodes	0	$+0.79{*} D_{time}$

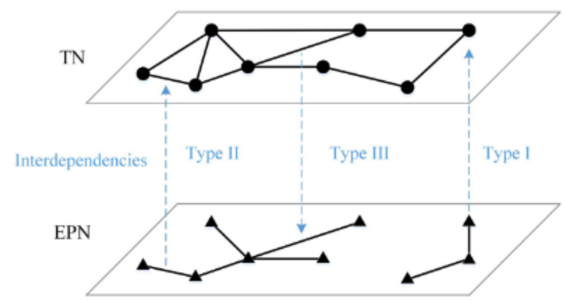


Figure 6. Interdependencies between transportation system and electric power system. (Zou& Chen, 2020)

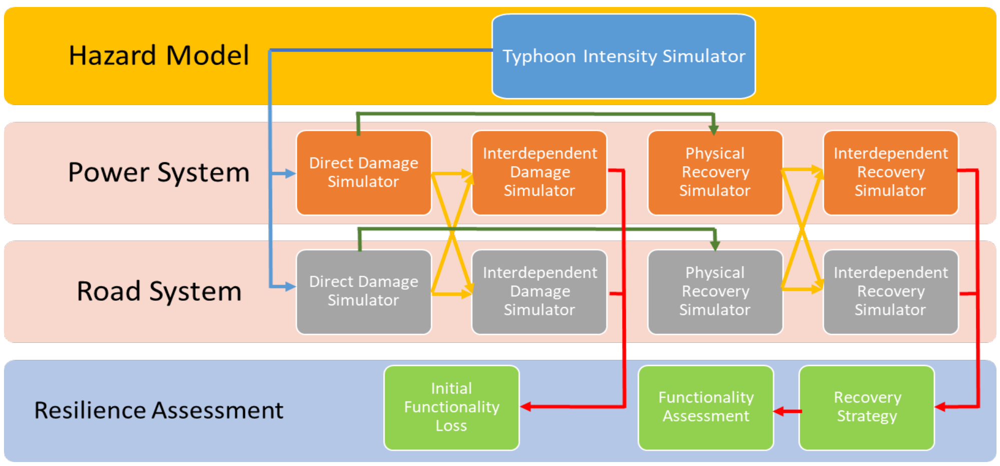


Figure 7. Simulation framework and message flow

3.4. Post-disaster Recovery Modeling

Since the interaction between the two systems affects the sequencing of repair, developing models incorporating the interaction effect to simulate the post-disaster damage and recovery of the infrastructure systems are essential to analyze community resilience (He & Cha, 2018; Nguyen & Akerkar, 2020; Ouyang, 2014). In the decision-making for restoration, this study models the prioritization based on the weights of nodes, and the weights of nodes are determined by their functionalities, location (i.e., if it is a centroid of networks), and repair time. Furthermore, after considering interdependency, the repair time is modified because of the blocked paths. For instance, when an electric tower collapse and blocks the traffic, the recovery unit of the power system needs to remove it first, and then the recovery unit of the traffic system can move on to remove the remaining debris and roadblocks. Figure 7 shows the damage and recovery flow chart to simulate the post-disaster recovery process.

In this study, infrastructure systems with maintenance units affect each other since the restoration strategies plan depends on the damaged nodes' statistics after the disaster's shortest route selection and the repair teams' resource allocation. Power nodes usually have higher priority for repair for regions with less traffic. During typhoons, the number of people staying at home increases, resulting in a higher demand for household electricity. Therefore, the repair of power nodes becomes more critical.

Hence, the model will prioritize restoring the power system at the intersection between the two systems.

3.5. Kaohsiung City's Power-Traffic systems under Typhoon disasters

Typhoon simulation using historical typhoon records is used to assess the system resilience of Kaohsiung's power and transportation networks after typhoon damage, and the effect of dependencies on the two systems is evaluated. In a typhoon event, the network system is subjected to local wind speed damages at random points according to the modified vulnerability curve, and the interdependent nodes will also fail and lose their functions. The functionality of a component depends on the amount of damage it has sustained and the functionality of the interdependent elements. Additionally, the restoration time of a component depends not only on the degree of physical damage but also on correlation matrices formed by the shortest paths of the maintenance teams to the damaged nodes, which can assess the efficiency and speed of repair measures. Finally, comparing the recovery curves of two systems with and without interdependencies can provide valuable insights into the role of dependencies in post-typhoon reconstruction.

Figure 8 compares the traffic and power systems with and without considering interdependence after a simulated typhoon event. First, the total functions of the remaining nodes in the power and transportation system after impact are 100% and 93%, respectively. While considering the interdependence between the two systems, it respectively drops to 99% and 93%. Among them, 132 traffic nodes declined in functionality due to the wreckage of falling traffic signs and signals. The repair time was 0.4 days longer due to the loss of power to traffic lights and monitoring systems. In contrast, two transmission towers suffered declines in functionality due to traffic debris. At the same time, the shortest path from Taipower Maintenance Department to the transmission line was blocked by obstacles, causing roadblock delays of about 0.8 days. The details can be seen in Table 3.

Table 3. Comparison of results with and without consideration of interdependency

	# of Node's Operability <0.4	# of Node's Operability<0.4 (Interdependent)	System's Functionality	System's Functionality (Interdependent)	Total Repair Days	Total Repair Days (Interdependent)
TN	0	4	100%	98.51%	13.608	14.020
PN	107	107	92.69%	92.66%	72.110	72.945
Resilience Assessment	98.47%		Initial Loss		4.84%	
Resilience Assessment (Interdependent)	98.39%		Initial Loss (Interdependent)		5.14%	

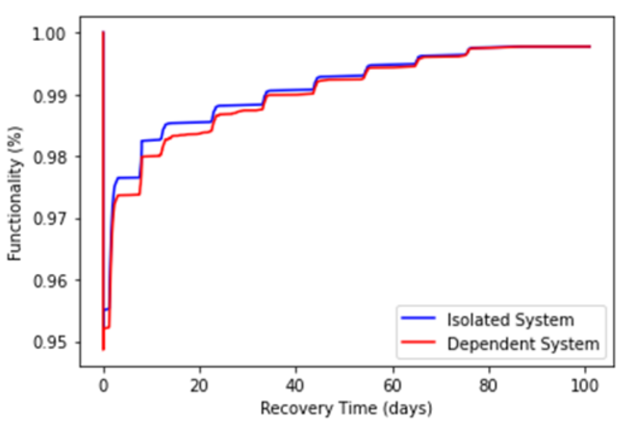


Figure 8. Performance and Recovery difference between dependent relationships.

4. RESILIENCE ASSESSMENT UNDER CLIMATE CHANGE

4.1. Typhoon Simulation Model

Typhoons are tropical cyclones, low-pressure vortexes in tropical or subtropical oceans. Typhoons consist of three parts: the peripheral area of the typhoon, maximum wind speed, and typhoon eye (Shi et al., 2019). To accurately assess the impact of the typhoon model on nodes, this study establishes a typhoon model based on the location of the typhoon eye, central pressure difference, maximum wind speed, maximum radius, and typhoon movement speed (Wang et al., 2021). This study uses the historical records of the Joint Typhoon Warning Center (JTWC) invading typhoons, including the parameters mentioned above. Eq (2) is adopted to determine the local maximum wind speed, where D is the distance between the node and typhoon eye, and η equals 0.5 in Taiwan.

$$\mathrm{v(t)} = \begin{cases} v_{max} \times [D/R_{max}] & , if\ D \leq R_{max} \\ v_{max} \times [R_{max}/D]^{\eta} & , if\ D > R_{max} \end{cases} \quad (2)$$

4.2. Climate Change Impact Investigation

According to Walsh et al. (2015), at the end of the 21st century, although the occurrence of typhoons decreases by 5–30%, an increase of 0-5% in typical lifetime maximum intensity. A recent study (Pandey and Liou, 2022) suggested a 35% increase in the strength of typhoons that hit Taiwan was observed during 1977–2016. Therefore, this study introduces a 20% increase in the typhoon wind speed to resemble the climate change impact and to investigate the influence on urban resilience.

4.3. Impact of Climate Change

Historical typhoon events are adapted to simulate typhoon risk with and without considering climate change. In normal conditions, 4,298 typhoons occurred in a 1,000-year simulation, of which 628 events had a strong impact on Kaohsiung City. An average typhoon causes 6.70% Loss, and its average maintenance time is 152.38 days. On the contrary, wind speed is assumed to increase by 20% under climate change, and 4,278 typhoons occurred in a 1,000-year simulation, of which 1087 typhoons resulted in more than 15% functionality loss in the traffic-power interdependent. Relatively, one typhoon causes an average of 8.03% system damage with a maintenance time of about 187.43 days.

The result shows that reinforced typhoons are devoted to greater loss and longer repairing time. This can be a practical reference for future policy and resource strategy formulation, such as how much maintenance resources are needed.

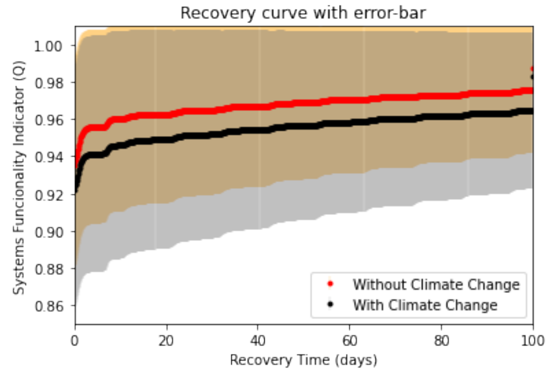


Figure 9. 1000-year simulation of recovery curves under typhoon events

5. CONCLUSIONS

Recent disasters worldwide have demonstrated the inevitability of disasters, and modern societies are increasing their resilience to extreme events by managing risks and adapting to minimize their impact. This study discusses the resilience characteristics of transportation and power network in Kaohsiung and their potential climate change impact. It belongs to interdisciplinary studies and provides a reference for interdepartmental coordination for disaster risk management.

In addition, through the typhoon hazard model and resilience assessment, the evaluation of system damage can point out the regional resilience characteristics under wind speed and suggest the direction for regional resilience improvement. However, the interdependency between the two systems is complex, and there are numerous factors to consider, so this study simplified the system to reduce the computational complexity of the model. For instance, this study assumes power and transportation networks are at the same elevation to reduce the complexity for wind speed calculation, which leads to a less accurate estimation in damage and recovery assessments.

From the results, although the isolated system has the higher resilience assessment, nodes in the system do not reflect their functionality which depends on other systems. Besides, transportation plays an important role in the recovery phase, which may affect the repair time. On the other hand, compare the influence of nowadays and future typhoons to discuss the impact of climate change. In this study, typhoons with increased wind speed increased the interdependent initial loss by 20% and prolonged repairing time by 23%.

Confronting climate change, the resilience of systems should be enhanced. There should be more options or backup plans to strengthen the robustness. To better understand the characteristics of the network, we should increase the sophistication of the network models and calculate the network's connectivity and efficiency to measure system operability under disasters. When constructing the network models, we can consider geologically sensitive areas (e.g., hillsides and riverbanks) and incorporate the geological and topographical information system to modify the vulnerability of nodes.

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