國立臺灣大學工學院土木工程學系

碩士論文

Department of Civil Engineering
College of Engineering
National Taiwan University

Master Thesis

基於系統韌性最佳化之相依基礎設施災後修復作業

Optimizing Resilience of Restoring Disrupted Interdependent Infrastructure Systems

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中華民國 108 年 10 月

October 2019

doi:10.6342/NTU201904193

doi:10.6342/NTU201904193

國立臺灣大學碩士學位論文

口試委員會審定書

基於系統韌性最佳化之
相依基礎設施災後修復作業
Optimizing Resilience of Restoring Disrupted Interdependent Infrastructure Systems

本論文係陳譽仁君（學號 R06521504）在國立臺灣大學土木工程學系碩士班完成之碩士學位論文，於民國 108 年 7 月 4 日承下列考試委員審查通過及口試及格，特此證明

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doi:10.6342/NTU201904193

doi:10.6342/NTU201904193

致謝

感謝指導教授許聿廷教授的悉心指導與協助、來自父母與妹妹的支持與鼓勵、以及朋友、316 研究室夥伴的扶持，缺少這些幫助，本篇研究不可能在兩年內形成、發展並撰寫成論文。同時，也感謝口試委員朱致遠教授與盧宗成教授在口試時的提問與建議，使得這份論文從初稿到定稿的修訂有了方向與依據。

回顧研究所的兩年，許聿廷教授寬鬆卻不失嚴謹的指導風格塑造我執行研究的觀念，研究也隨著每次 individual meeting 與每篇讀過的文獻逐漸聚焦，而幸運地找到一個新穎的主題，發現前人尚未處理的部分。研究進行到一定程度時，老師便鼓勵將現有成果投稿，才有機會分別前往日本參與 KKHTCNN 的研討會及遠赴美國參加 TRB 的年會，同時在會後探索外國風情，與朋友留下深刻回憶。研究生涯能夠在小許家度過確實是一件幸福的事，研究之外，老師會抽空與學生們聚餐，也不時會關心學生們的生活，更在一年一度的鐵道接力馬拉松與小賴家競逐，今年更在天時地利人和之下迎來首次勝利。

這份研究的完成同時要感謝家人與親戚的支持。在臺北從大學到研究所的這六年，每星期通往家裡的電話傳送家的溫暖與鼓勵，更是前進的動力。同時，父母在經濟上與生活上的支持則使我不需顧慮太多雜事，只要心無旁騖面對學業就好。

研究生涯中，316 研究室夥伴的相互扶持也是完成論文不可或缺的助力。透過諧音冷笑話、同學間相互消遣可以暫時忘卻研究進度的壓力；透過同學之間的討論可以釐清研究上的盲點，在言談間獲得靈感，進而使研究有所突破。

過去這一年，應該是我目前人生中特殊而富有轉折的一年：首次參加國際研討會而在日本報告這篇研究的早期版本，並濫用 Pass 狂搭新幹線；為了不要搭夜間巴士、不要只能搭巴士離開機場（IAD）進市區、也不要在美國境內轉機，迂迴地在東京轉機、多倫多過夜、透過 DCA 進入華盛頓特區參加 TRB 的年會，回程也轉機兩次，最後拿著六張機票去報帳；而過去一年，多了幾位親密朋友，更加明確地認識自我，體重也創了新高；但是，卻在今年五月面對阿公的過世與隨之而來的悲傷。碩二這年，增添許多經歷、精神生活得到富足，也承受悲慟。如今，多樣的

doi:10.6342/NTU201904193

一年再加上本篇論文，更凸顯今年在我人生中的意涵，並體認到師長、家人、同學與朋友在這些事背後的協助與不可或缺。

本篇論文的完成承蒙指導教授、家人與同學的支持與協助，也希望這份研究在未來對災後修復問題的處理上能有些微的貢獻。

陳譽仁 謹誌

民國 108 年 10 月

doi:10.6342/NTU201904193

摘要

相依基礎設施系統遭受災害之後，需要透過修復作業以回復其原始功能，本研究宗旨即為討論相依基礎設施系統的災後修復作業，並以最小化修復過程中的系統韌性為目標。為計算、規劃系統內損壞元件的修復排程並以系統韌性評估該基礎設施系統的效能，本研究考慮由道路、電力及電信系統所組成、包含各系統間複雜交互關係的相依基礎設施系統，提出以網路流為基礎的混合整數二次規劃模式。模式中以各系統提供的服務需求未滿足量評估系統的韌性損失，並將目標函數定義為最小化整體修復過程中的任性損失與需求資訊不完整的懲罰項。其中，模式透過網路流計算各基礎設施系統中的服務遞送量與受損元件修復的可行選項，並以決策變數描述系統中元件功能狀態，而其數值隨時間的變化即為修復受損元件的時序。其中，本研究與既有文獻不同處為考慮資訊傳遞與修復過程的相依性。資訊傳遞的相依性涵蓋因通訊中斷而導致需求資訊的不完整，本研究以邏輯限制式、期望系統性能損失與迭代修復過程進行考量。修復過程的相依性則與修復班隊基地能否透過路網與各基礎設施系統損壞節線連通有關，本研究係利用網路流於模式中計算，而此種相依性將直接影響到修復排程的可行性。為展示模式的能力與說明相依性對修復過程造成的影響，本研究以臺灣新北市土城區為基礎進行案例分析，利用參考當地管線資料所建立的多層相依基礎設施網路進行數值實驗，並設想兩種不同型態的破壞模式，以說明資訊傳遞與修復過程的相依性對修復過程的影響。實驗結果顯示本模式可透過系統性的觀點評估相依基礎設施系統的韌性，進而以系統韌性最佳化的角度規劃修復作業。

關鍵字：系統韌性、基礎設施系統、相依性、災後修復、網路流模型

doi:10.6342/NTU201904193

doi:10.6342/NTU201904193

ABSTRACT

This study proposes the problem of restoring interdependent infrastructure systems after disaster impact, seeking to minimize the resilience loss and the penalty for the incomplete information of the amount of demand throughout the horizon of a restoration schedule. In order to solve the proposed problem, this study develops a mixed integer quadratic programming model, which applies the network flow method to describe the dynamics of commodity delivery, restoration crews and functional states of components in the interdependent infrastructure systems, including the roadway, electric power, and telecommunication systems. The performance of each system is defined based on the met demand for relevant service to assess resilience loss, and the objective function is defined to minimize the expected unmet demand throughout the recovery phase. This model also reflects several types of interdependencies. First, the cyber interdependency is factored by the logical constraints, the expected performance loss, and the iterative process when updating the state of certainty for the demand. Then, the restoration interdependency is addressed through the network flow method to determine the connectivity of the restoration crews from restoration depots to the disrupted components of different systems in the roadway network, which can directly affect the feasibility of a restoration schedule. In order to exemplify the capability of the model, this study conducts numerical experiments using test infrastructure networks built based on the infrastructure systems in Tucheng District, New Taipei City, Taiwan and conceives two cases of different patterns of system disruption. The results of the experiments demonstrate that the proposed model can optimize the restoration schedule based on the assessment of system resilience from a holistic perspective.

doi:10.6342/NTU201904193

Keywords: Resilience, Infrastructure systems, Interdependency, Restoration, Network flow model

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CHAPTER 1

INTRODUCTION

In recent years, the increasing frequency of severe natural disasters has greatly threatened people's lives and properties, and disaster management has become a vital issue for the sustainability of urban and regional development. One of the major purposes of disaster management is to recover and/or ensure the functionality of a society and essential life support upon disaster impact, which relies on the normal operation of relevant infrastructure systems, such as roadway system (for delivering rescues, relief materials, or even for evacuation), telecommunication system, systems of electric power and water supply. Each infrastructure system may be subject to a distinctive level of vulnerability that can lead to full or partial disruption of system service over a certain period and thereby affect the operation of disaster response as well. Hence, to enhance these critical infrastructure systems in terms of their resilience to withstand disaster impact or quickly recover from disruption is crucial for disaster management in both pre-disaster and post-disaster contexts. In this chapter, the motivation and the goal of this research are specified, and the organization of this thesis is presented.

1.1 Research motivation

As the infrastructure systems become more complicated and interrelated, the raising frequency and strength of natural disasters can cause severe impact and disruption to the community. For instance, in August 2015, Typhoon Soudelor devastated the outreach connection of Wulai District, New Taipei City, where both the telecommunication service and roadway connection were disconnected, isolating the villages in Wulai District (Shan,

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2015). While the natural disaster can directly impact the infrastructure system, the complicated interrelations among different infrastructure systems could cause a cascading effect toward other infrastructure systems from an infrastructure system directly disrupted by the disaster. For example, the functionality of the telecommunication service relies on the essence of the supply of electric power. Inspired by the abovementioned factors, this study covers two major aspects: resilience, describing the capability of the infrastructure systems withstanding and recovering from the disaster, and the interdependency among several infrastructure systems.

1.1.1 Resilience

From the engineering perspective, resilience is the speed of returning to the steady state after a disruption (Batabyal et al., 2007), which is an index to assess the performance of an infrastructure system. Unlike the conventional risk analysis that pursues fail-safe, resilience represents a "safe-to-fail" position to contain and minimize the failure that may result from unpredictable disturbance and impact (Ahern, 2011; Fang and Zio, 2019). When an infrastructure system is affected by a disaster, it is first disrupted, suffering a loss of performance; then, it may adapt to the disruption with the available components in the infrastructure system, such as the previously redundant facilities and capacities; last, the external effort intervenes to restore the affected component, assisting the system to recover to its original functionality. Hence, the performance status' transition of the infrastructure system influenced by disruption can be divided into three phases as in Figure 1.1: normal ($T < t_e$), deterioration ($T = t_e \sim t_s$) and recovery ($T = t_s \sim t_f$).

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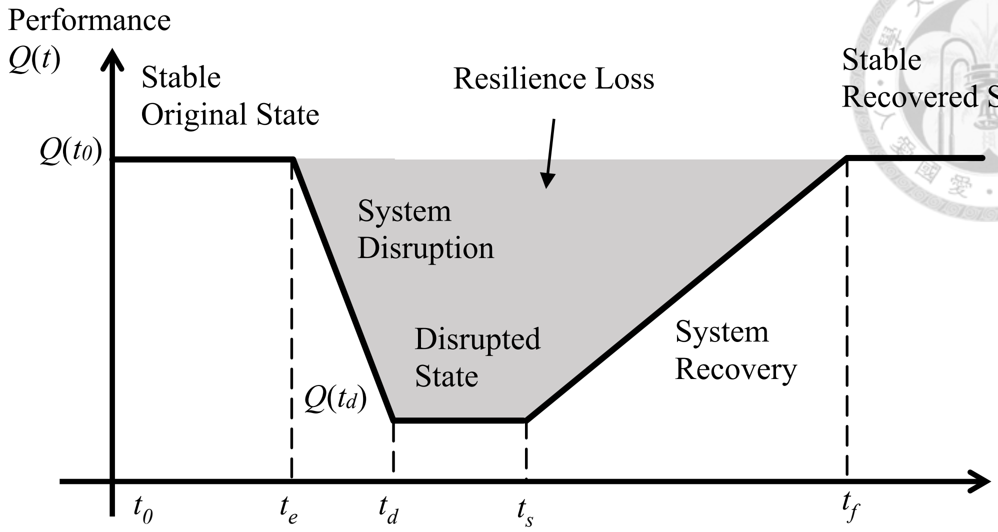

Figure 1.1 System performance transition under the disruption

(adapted from Henry and Emmanuel Ramirez-Marquez (2012))

1.1.2 Interdependent infrastructure systems

Interdependency is generally illustrated as two infrastructure systems dependent on each other (Rinaldi et al., 2001). That is, it describes the complex interrelation among different infrastructure systems, which can cause the cascading effect during the disruption and constrain the restoration schedule. The infrastructure systems may be interdependent from the perspective of either physical connection or functional association. Due to such interdependency, the failure of a component in a network may cause cascading effects within the network or even across interdependent networks. For instance, the disconnection of electric power transmission can result in the malfunction of the telecommunication system, but such malfunction can block the transmission of the system status of the electric power system, and thus the telecommunication system influences the electric power system reversely.

In this study, four kinds of interdependency are introduced and considered following the categorizing method by Rinaldi et al. (2001), which are physical, cyber, geographic,

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and logical, and the relative method will be reviewed and discussed in Section 2.2. Herein, the considered interdependencies covers the interrelations among the roadway, electric power, and telecommunication systems. In summary, the considered interdependencies are presented in Figure 1.2.

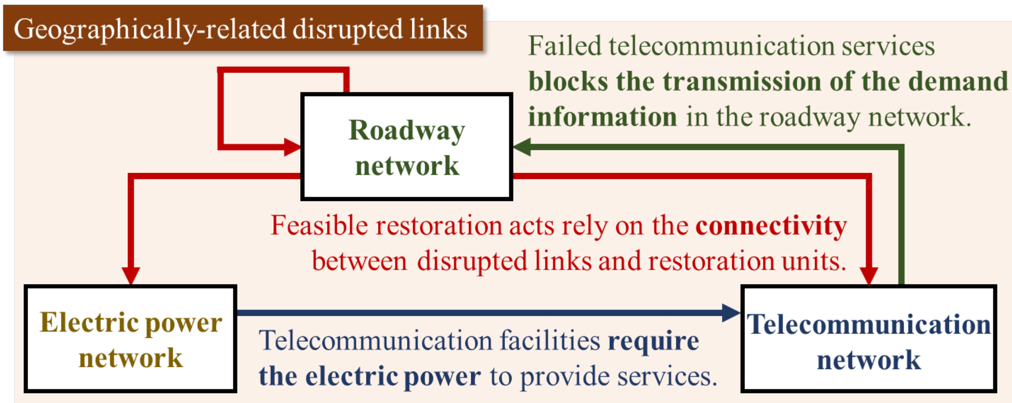

Figure 1.2 Summary of the considered interdependencies

1.1.3 Restoring interdependent infrastructure systems

Of three phases in the transition of system performance as Figure 1.1, this study focuses on the phase regarding the external efforts, the restoration in the phase of system recovery. As the restoration is to recover the functionality of the infrastructure system, optimizing the schedule of the restoration can reduce the loss of resilience, which is to boost the recovery of the infrastructure system through the external effort. That is, through optimizing the sequence of the disrupted components to be restored, the resilience loss can be minimized, and the grey area in Figure 1.1 is thus lessened.

However, the interrelation among different infrastructure systems complicates the optimization of the restoration. In order to restore some parts of the telecommunication facilities, some specific electric power components should first be recovered, but with the limited amount of the restoration resource, this consideration may contradict the goal to

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recover the electric power network as restoring such electric power components could not benefit the recovery of the electric power network.

1.2 Research goal

In light of the growing needs of emergency response for natural disasters and the research gap in the restoration of the interdependent infrastructure networks, this study proposes a problem for infrastructure resilience optimization, which focuses on the recovery phase of system performance after a given disruption. In contrast to the studies regarding restoring the interdependent infrastructure networks in the existing literature, this study further considers two types of interdependency which are still rarely modeled and accordingly optimizes the restoration of three infrastructure networks in one objective function: (i) incomplete information of the amount of demand as the cyber interdependency (ii) the restoration interdependency over multi-layer networks.

(i) *Cyber interdependency*: the transmission of the demand information in the roadway network relies on the telecommunication services. If the telecommunication services are failed, it can cause the difficulty to the optimization of the restoration schedule due to the incomplete information of the amount of demand.

(ii) *Restoration interdependency*: the roadway network provides the restoration crews of all the infrastructure networks with the connection between their depots and the disrupted components. If the disrupted components in any infrastructure systems are not accessible to the depot through the roadway network, the restoration on those components is not feasible.

Additionally, the cross-network interdependency further increases problem complexity and collectively presents the methodologically challenging perspectives. A

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network flow approach is applied to capture network dynamics and interactive effects between multi-layer networks explicitly. Numerical experiments are conducted for the restoration of the roadway, electric power supply, and telecommunication systems (three-layer networks) under the impact of flood-related disruption.

1.3 Thesis organization

The organization of this thesis is demonstrated in Figure 1.3. Chapter 2 covers the concept and the assessment method for resilience, and the interdependency is categorized and studied. In the same chapter, the relevant studies of the restoration of the interdependent infrastructure systems are reviewed, where the research gap in the existing literature is discussed. Next, in Chapter 3, the characteristic of the restoration of the interdependent infrastructure networks and the interdependent network restoration problem, are stated and analyzed. Then, a mathematical model is developed to solve the problem. In Chapter 4, the test multi-layer interdependent infrastructure networks are implemented to manifest the implementation of the stated problem and the capability of the developed model. Last, the conclusion is presented in Chapter 5 to summarize the findings of this research and provide some recommendation for future studies.

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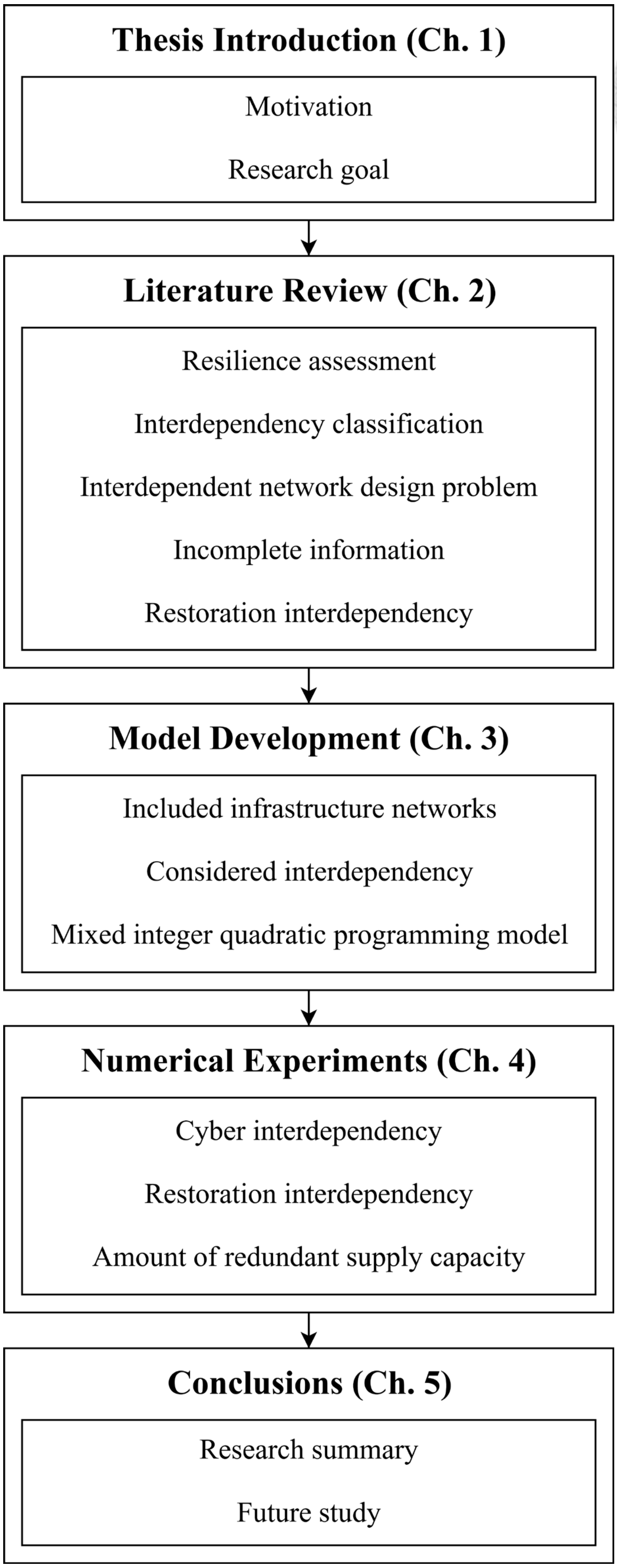

Figure 1.3 Thesis organization

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CHAPTER 2

LITERATURE REVIEW

From the perspective of disaster management, recovering the functionality of the community through the restoration after severe disasters is an essential task, and resilience is a concept and an index to measure the process of the restoration of the infrastructure systems. In this chapter, the assessment approaches for resilience, several types of classification for the interdependency, and the methods to model optimize the restoration schedule of the interdependent infrastructure systems are summarized; last, the research gap in the existing literature is outlined.

2.1 Resilience assessment

Following the introduction of the resilience in Section 1.1.1, resilience is an index to analyze the capability of the infrastructure systems. Conceptually, a system is considered as being resilient for its capabilities in three aspects (Fiksel, 2003; Nan and Sansavini, 2017; Vugrin et al., 2010):

(i) *Absorptive capability* is to reduce the initial impact of a disaster.

(ii) *Adaptive capability* is to adjust the system to balance disaster impact and maintain a certain level of system performance.

(iii) *Restorative capability* is to repair the failed system components.

These capabilities are highly related to system structure and the strengths of system components against disaster impact. For instance, a structure designed with higher redundancy is more likely to improve the adaptive capability, as redundant components may share the workload of the damaged ones and continue the functionality of the system.

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Woods (2015) also sorted the resilience into four concepts:

(i) *Resilience as rebound*: it refers to how a system rebounds from disruption and returns to previous or normal states.

(ii) *Resilience as robustness*: some researches label resilience as robustness, which is the ability to absorb perturbations.

(iii) *Resilience as graceful extensibility*: this concept views resilience as how to extend adaptive capacity in the face of surprise.

(iv) *Resilience as sustained adaptability*: it indicates the ability to manage the adaptive capacities of systems.

From the description of those four concepts, they can all be categorized into the three capabilities mentioned above: robustness as the absorptive capability, graceful extensibility, and sustained adaptability as the adaptive capability, and rebound as the restorative capability.

Vugrin et al. (2010) concluded the distinguishing characteristic for the abovementioned capabilities: the absorptive capability and the adaptive capability are the internal measurements for the system impact, while the restorative capability is the exogenous measurement through total recovery effort which often requires external effort. This study aims at studying the external effort that can fortify the resilience of the infrastructure systems, which is the restorative capability through optimizing the restoration process. In order to analyze the restorative capability, an assessment approach is needed, and thus, the assessment approaches are reviewed as followed.

2.1.1 Resilience assessment approaches

The resilience assessment approaches can be classified into two categories from the

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review paper (Hosseini et al., 2016): qualitative and quantitative. The qualitative category includes methods according to conceptual frameworks, which provide some guiding principles or offering the semi-quantitative indices from the questions for experts' assessment. The quantitative assessment approaches contain two sub-categories: general measures and structural-based models, while the quantitative approaches are more suitable for this thesis because they can quantify the performance of the optimization of the infrastructure restoration schedule.

General measures are one type of quantitative assessment approaches for resilience; they quantify the performance of a system regardless of the system structure (Hosseini et al., 2016). Herein, based on the concept of service stability, several studies (Ghosn et al., 2016) also converge on a formula for the quantification of resilience (*RES*) defined as Equation (1), which is the integral of the performance of a system over time:

$$RES = \frac{\int_{t_0}^{t_0+t_h} Q(t)dt}{t_h} \tag{1}$$

Bruneau et al. (2003) proposed a deterministic static metric corresponding to the grey area in Figure 1.1 for measuring the resilience loss *R* as defined in Equation (2), where $Q(t)$ measures the functionality level of the integrated system.

$$R = \int_{t_0}^{t_f} [100 - Q(t)]\,dt \tag{2}$$

2.1.2 Performance indicators for infrastructure networks

From Equations (1) and (2), the definition of the performance indicators ($Q(t)$) for the infrastructure networks is required to evaluate the resilience of the infrastructure system. The network-performance indicators are suggested to be considered either the

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topology or the functionality of networks (Ghosn et al., 2016). The topology-based performance metrics study the performance from the perspectives of connectivity and efficiency; herein, the connectivity is considered as the number of the connecting paths from the supply node to the consumption nodes; the efficiency is measured as to how efficient the transmission of the utility between different nodes. However, the topology-based metrics cannot capture the functional aspect of the infrastructure networks.

The flow-based functional performance metrics combine network topology with flow patterns, which are considered as the amount of flow that a damaged network can deliver to the demand nodes comparing to what it delivers before the disruption. Such metrics consider the flow capacity and the supply and demand constraints in an optimization framework (Ghosn et al., 2016).

2.2 Interdependency categorization

With the preface to the interdependency in Section 1.1.2, interdependency illustrates the interrelations among the infrastructure systems, and it can be presented in many different aspects. Rinaldi et al. (2001) categorized interdependencies into four types: physical, cyber, geographic, and logical interdependencies.

(i) *Physical interdependency* means that the state of one infrastructure system is dependent on the material output(s) of another.

(ii) *Cyber interdependency* implies the relationships between infrastructure systems based on information transmitted through the relevant infrastructure.

(iii) *Geographic interdependency* means that a local environmental event can cause state changes in all infrastructure systems.

(iv) *Logical interdependency* includes other state dependencies between different

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infrastructure systems, which is not via the physical, cyber, or geographic connection. It is recognized that such classification can well sort out the interdependency related issues in several practical cases.

Lee et al. (2007) identified five types of interrelationship between infrastructure systems, where these authors denoted those types of dependence as the interdependency in their studies.

(i) *Input dependence* indicates the infrastructure components requires the services from another infrastructure component as the input.

(ii) *Mutual dependence* implies that a group of infrastructure components are dependent on the activities of each other.

(iii) *Shared dependence* means that some infrastructure systems share the same physical components or activities.

(iv) *EXCLUSIVE OR dependence* illustrates the activities that some specific infrastructures are the exclusive providers.

(v) *Collocated dependence* specifies that the components of two or more infrastructure systems are located in a similar geographical region.

P. Zhang and Peeta (2011) also proposed a way to categorize interdependencies.

(i) *Functional interdependency* indicates that the functioning of one system requires inputs from or can be substituted by another system.

(ii) *Physical interdependency* means some infrastructure systems are coupled through shared physical attributes.

(iii) *Budgetary interdependency* implies that several infrastructure systems share the same resource allocation budget, especially during disaster recovery.

(iv) *Market interdependency* means that all of the infrastructure systems are interacting

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in the same economic system.

Ouyang (2014) reviewed the abovementioned and other types of interdependencies through studying some extreme events, such as extreme natural disaster and large-scale terrorist attack. However, the classification by Lee et al. and Zhang and Peeta does not cover some scenarios. For instance, the classification by Lee et al. cannot sort the scenario that the electric power systems and the telecommunication services are prioritized during the restoration process, and the categorization by Zhang and Peeta cannot sort the event that the debris-covered streets could block the emergency response personnel. Herein, Ouyang (2014) recognized that the classification proposed by Rinaldi et al. could well sort out the interdependency related issues in several practical cases.

2.3 Modeling interdependent infrastructure systems

In the review paper of modeling interdependent critical infrastructure systems (Ouyang, 2014), five major types of approaches have been adopted for analyzing interdependency across infrastructure systems:

(i) *Empirical approaches* analyze the interdependencies of the infrastructure systems through historical data and expert experience.

(ii) *Agent-based approaches* implement a bottom-up method that contains autonomous agents and their interactions to analyze the decision-making processes in the infrastructure systems. Herein, the reaction of the agents is based on their objectives, the pricing strategies, learning, and adaptation to the simulation environment, and the capacity expansion decisions (P. Zhang et al., 2011). However, the result of the simulation highly depends on the assumptions about the behaviors of the agent.

(iii) *System-dynamics-based approaches* model the dynamic behavior of the

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interdependent infrastructure systems by capturing important causes, effects, and factors under the scenarios of disruption.

(iv) *Economic-theory-based approaches* view the operation of the infrastructure systems as the intermediate goods in the market of the economy, where the interdependencies are analyzed through economic interdependencies.

(v) *Network-based approaches* exploit the network structure, a common characteristic of infrastructure systems, and they are useful for analyzing physical interdependencies and the cascading disruptions (P. Zhang et al., 2011).

Herein, network-based approaches model each single infrastructure system by a respective network and describe the interdependencies between them by inter-links. Depending on whether particle flows in the networks are de facto modeled, network-based approaches can be further categorized into two groups: topology-based methods and flow-based methods.

To explicitly describe the interdependencies in the infrastructure systems, this research adopts the network flow method to capture the dynamics of system evolution in terms of how restoration units and relevant resources move across systems. Accordingly, infrastructure systems are represented as the combination of networks, and the interdependencies are modeled using logical constraints in the formulation.

2.4 Restoring interdependent infrastructure networks

The relevant literature of modeling the interdependent infrastructure networks can be generally grouped according to research goals: performance evaluation, design, mitigation, and recovery models. For recovery models, most studies focus on analyzing the changing functional states of systems upon the restoration of failed components

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(Ouyang, 2014). To optimize restoration can be viewed as a network design problem to add (restore) links to the disrupted network, while the scheduling of restoration also needs to be addressed. Lee et al. (2007) modeled the restoration of services in interdependent infrastructure systems by explicitly identifying interdependencies using network flow approaches. Nurre et al. (2012) proposed an integrated network design and scheduling problem to optimize the restoration of a single infrastructure network to maximize weighted total arrived demand. Cavdaroglu et al. (2013) optimized integrating restoration and scheduling decisions with the objective function of the performance over the horizon of the restoration plan and implemented logical constraints to describe the interdependencies. González et al. (2016) optimized the restoration strategy of selecting the components to be restored through minimizing the cost of preparation, reconstruction, surplus or deficit supply, and commodity flow, and they also developed the iterative use of the interdependent network design problem to account for the order of the reconstruction. Almoghathawi et al. (2019) proposed a resilience-driven restoration model with multiple objectives, including maximizing the resilience and minimizing the restoration cost. In their study, they used ε-constraint method to generate Pareto-optimal solutions and demonstrated the tradeoff between the resilience and the restoration cost. Karakoc et al. (2019) integrated a resilience-driven mixed integer programming model to schedule the restoration process of the disrupted interdependent infrastructure networks with the index of geographically distributed social vulnerability. Herein, this study incorporated the concept of community resilience to the restoration process.

These studies mostly model and discuss the complication of disruption patterns over interdependent infrastructure systems at a conceptual level and focusing on the perspective of system functionality. Other than functional interdependency, however, restoration interdependency which can be manifested as the accessibility/feasibility of

doi:10.6342/NTU201904193

components in the different system required for the deployment of restoration is rarely considered in the existing literature. That is, the disruption to the roadway network which enables the restoration crews to access the disrupted components in other infrastructure networks is rarely included in the existing literature.

2.5 Restoration with incomplete information

In Section 2.2, the cyber interdependency regards the interaction between infrastructure systems through the information. That is, if the infrastructure system transmitting the information, such as the telecommunication systems, fails after the disruption, some information in other infrastructure systems can be incomplete, influencing the decision process for the restoration. However, the relevant literature is emerging but still rare, and few studies consider the factor of incomplete information involving in the restoration process.

There is some literature analyzed the incomplete information during the restoration from different perspectives. Çelik et al. (2015) addressed incomplete information about the debris amounts along the roads in the debris clearance problem using a partially observable Markov decision model. X. Zhang et al. (2018) optimized the resilience-based network design under uncertainty and developed a nonlinear function to consider the non-deterministic case about the disrupted capacity, the restoration speed, and the degree to which the component can recover of the system component. Fang and Sansavini (2019) formulated a two-stage stochastic programming model to minimize the expected system resilience loss, considering the uncertainty of the repair time and the total amount of repair resource units.

doi:10.6342/NTU201904193

2.6 Restoration interdependency

Sharkey et al. (2016) identified restoration interdependencies by analyzing several news reports/articles about the restoration efforts after Hurricane Sandy. This study provides a classification scheme including five distinct classes of restoration interdependency: traditional precedence, effectiveness, options precedence, time-sensitive options, and competition for resources. Herein, the most frequently observed restoration interdependency is traditional precedence. It means that the restoration task in an infrastructure system cannot be started until the restoration task in another one is complete. That is, the feasibility of restoring the specific component requires the connectivity between the depot of the restoration crews and the location of that component through the roadway network.

In the existing literature about the interdependent network design problem introduced in Section 2.4, the interdependencies are all revealed in the form of logical constraints indicating the functional association between different infrastructure components. However, the restoration of the roadway network, which the connectivity evolves through the restoration of the road links, has not considered. In this study, the restoration interdependency is reflected by limiting the restoration act to components accessible for restoration units from the roadway network.

2.7 Summary

In this chapter, the measuring approaches for resilience are first reviewed. Second, since the interdependencies among infrastructure systems can complicatedly influence the performance of the infrastructure systems, the methods to classify the interdependencies are reviewed, which can assist this thesis in inferring and modeling the

doi:10.6342/NTU201904193

interdependencies existed in the infrastructure systems. Third, to analyze the resilience of the infrastructure restoration after severe disruption, the conventional approaches to modeling the infrastructure systems and the similar existing studies for optimizing the restoration process are reviewed. Last, in the existing literature, some aspects, including the incomplete information due to the failure of the telecommunication service and the restoration interdependency, have not studied and explored in depth. This research thus focuses on closing the abovementioned research gap.

doi:10.6342/NTU201904193

doi:10.6342/NTU201904193

CHAPTER 3

MODEL DEVELOPMENT

In this chapter, a problem about recovering the disrupted interdependent infrastructure networks is first proposed. Then, the mixed integer quadratic programming model to schedule the restoration of infrastructure systems is developed, seeking to maximize the combined resilience after a severe disruption.

3.1 Problem statement

This study seeks to develop an interdependent network restoration problem considering resilience optimization over multiple infrastructure systems to provide relevant Emergency Management Agencies (EMA) with a holistic perspective for disaster response. After the disaster strikes the infrastructure systems, each layer of the infrastructure systems can be partially disrupted. Hence, the manager, such as the authorities in the area, would start scheduling the restoration of the infrastructure to recover its performance. Herein, the problem proposed in this section is to optimize the restoration process considering the resilience loss.

In order to highlight the importance of factoring the interdependency across different infrastructure systems, a problem context of three-layer infrastructure upon disaster impact is established, which consists of the roadway network, electric power network, and telecommunication network. As explicitly accounting for interdependency, the infrastructure systems are modeled using network-based approach, and the characteristics of each infrastructure system as a network are detailed in this section.

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3.1.1 Objective

The objective of the problem is to minimize the weighted sum of two components, where the formulation of the objective is introduced in the objective (8) in Section 3.4.2:

(i) *Resilience loss* is the summation of the ratio of the performance loss over the modeling horizon as introduced in Section 2.1.1. Herein, the performance loss in this problem is defined as the expected unmet demand on each demand node at all infrastructure network layers, and the performance loss would be constrained to be positive or zero through the constraints to avoid surplus demand.

(ii) *Penalty for incomplete information* is defined as the ratio of the amount of demand in the roadway network which is without the telecommunication service. This part of the objective is to examine the influence of the incomplete information to the manager of the restoration schedule. Herein, if the demand information is known for a demand node, its expected unmet demand is a deterministic value.

3.1.2 Infrastructure networks

In this study, three infrastructure networks are considered, which are the roadway network, the electric power network, and the telecommunication network.

(i) Roadway network

In the roadway network, a link represents a section of road between two intersections, and a node represents an intersection. The roadway network is indispensable for emergency logistics, including the delivery of relief materials, rescue teams, and restoration units for affected infrastructure systems. If the failure or capacity reduction of a system component occurs due to disaster impact, it may cause severe delay to the logistics mentioned above for disaster response or even disrupt the network and isolate

doi:10.6342/NTU201904193

some areas from outer supports.

In this study, the roadway network is used to transport emergency relief and the restoration crews for all the infrastructure networks. Herein, this study regards the restoration of the basic functionality of the infrastructure, and thus it only considers the recovery of the infrastructure to the level of fulfilling the basic needs of the community.

(ii) Electric power network

A typical electric power network is composed of facilities at three levels: power generation, power transmission, and power distribution. The analysis of the electric power network in this study focuses on the restoration of power distribution from substations to each household in the disaster-affected areas. Here, the substation plays the role as an interface to transfer power from the transmission system to the distribution system of an area. The disruption of power distribution can significantly impact people's lives, as it can cause the malfunction of any electricity-dependent systems. On the other hand, restoring electric power can help households accelerate the recovery of the standard of living and capture the latest information, which is virtual but another critical form of relief.

(iii) Telecommunication network

This study considers both mobile and data services for the telecommunication network. The telecommunication network transmits data or communication needs, where the internet service provider is at supply nodes, and base stations act as demand nodes to provide service to surrounding area wirelessly. However, base stations require electric power to transmit a signal through antennas. Although they are generally equipped with emergency power generators, when the fuel in the generator is exhausted, even if the facility is intact, it cannot provide telecommunication service.

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(iv) Summary

In summary, the characteristics of each infrastructure network are listed in Table 3.1.

Table 3.1 Summary of the considered infrastructure networks

Infrastructure network	**Transmitted utility**	**Supply node**	**Demand node**
Roadway	Emergency logistics	Dispatch center	Townships
Electric power	Electric power	Power generator and major substations	Substations
Telecommunication	Telecommunication service	Internet service provider	Base stations

3.1.3 Interdependency

In this study, the interdependencies among the infrastructure networks are considered following the classification by Rinaldi et al. introduced in Section 2.2.

(i) Physical interdependency

The physical interdependency between electric power and telecommunication network is accounted, as the functionality of the telecommunication network (particularly the mobile network) is electricity-dependent. Although the facilities in the telecommunication system, such as the base stations, may be equipped with the backup electric power sources (i.e., the emergency generators), when the backup electric power is exhausted, even if the base station is functional and connected to the supply nodes through the telecommunication network can it not provide the telecommunication service.

(ii) Geographical interdependency

Natural disasters can generally cause geographically-related disruption areas (such as flooded areas) and thereby impact the associated infrastructure networks. This type of

doi:10.6342/NTU201904193

interdependency is manifested through the outcome of the natural disaster, and it will be presented in the numerical experiment, Chapter 4.

(iii) Cyber interdependency

As addressed in Section 2.5, the cyber interdependency describes the transmission of the demand information in the roadway network through the telecommunication network. If the telecommunication service of a demand node in the roadway network is failed, the demand information of that node is uncertain to the manager of the restoration process. Hence, in this situation, the manager can only optimize the restoration schedule based on the prior probability of the demand information about the telecommunication-service-blocked nodes in the roadway network rather than the deterministic demand information.

In this study, the probability distribution of the emergency demand in the roadway network is assumed to be known to the manager of the restoration schedule; besides, the study assumed a sectioned uniform probability distribution to accommodate the low, medium, and high estimation to the possible amount of demand with the probability of $P^{\mathrm{r}}_{\mathrm{i},2}$, $P^{\mathrm{r}}_{\mathrm{i},3}$, and $P^{\mathrm{r}}_{\mathrm{i},4}$ respectively. The assumed distribution of the demand is presented in Figure 3.1.

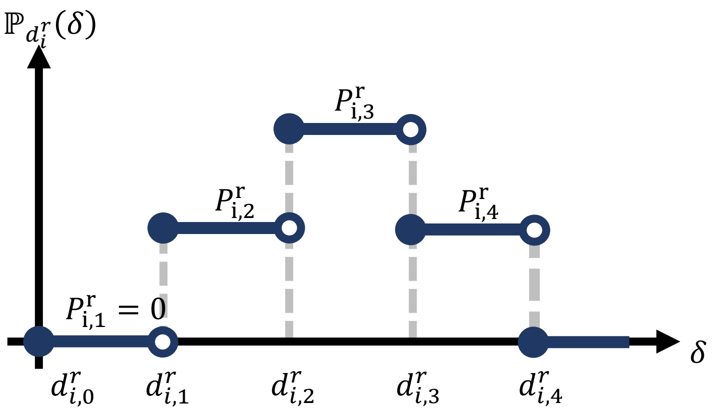

Figure 3.1 Probability distribution for the demand in the roadway network

doi:10.6342/NTU201904193

(iv) Logical interdependency

Additionally, this study seeks to address the research gap by factoring the effect of the restoration interdependency between the roadway network and other networks in the system recovery phase. When system restoration is implemented after the disruption due to disaster impact, restoration interdependency, which can be viewed as the logical interdependency defined by Rinaldi et al., becomes a critical issue affecting how restoration tasks should be scheduled within or across the interdependent network.

3.2 Assumptions

The assumptions for the developed model are listed as follows.

- The disruption to the infrastructure networks is given at the beginning of the planning horizon for the restoration.
- The failure of the component in the networks primarily occurs on the links.
- The performance of each infrastructure network is time-dependent and evaluated on a staged basis.
- The functional states of the links in the network are assumed to have two state: fully functional and fully disrupted.
- The restoration of each component in the networks takes a single time stage and single restoration crew.
- The links in each network are bidirectional, but the variable for the functional state of a link is unidirectional. Hence, the restoration of a link recovers the functionality of links for both directions.
- The incompleteness of the demand information is only considered in the roadway network.

doi:10.6342/NTU201904193

- The purpose of the restoration is to fulfill the basic need of the population in the disaster-affected areas, which includes the delivery of relief materials and necessities of life. As such operation should be the priority of using road capacity over general traffic, the travel time of each link in the roadway network is assumed to be constant if the resilience of the infrastructure systems is not fully recovered to the original state.
- The probability distribution of all the demand in the roadway network is known to the manager of the restoration prior to the disruption.
- The manager of the restoration optimizes the resilience based on the known information. If the state of the telecommunication service of a roadway demand node is changed during the restoration, the manager then reorganizes the restoration based on the updated information of the demand.
- Although the traditional precedence of restoration interdependency is considered, the restoration crews for each infrastructure system work independently.

3.3 Notation

The developed model is a mixed integer quadratic programming problem, which uses binary variables to determine the functional states of links. There are three interdependent networks in the model, including roadway network, electric power network, and telecommunication network. Their topologies are given as $G^r = (N^r, A^r)$, $G^e = (N^e, A^e)$ and $G^c = (N^c, A^c)$. The links are associated with capacities for corresponding flows. This model also considers the connectivity between failed links and restoration depots using the network flow method. The notation of sets, parameters, and variables are listed in Table 3.2, Table 3.3, Table 3.4, and Table 3.5.

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Table 3.2 Notation for indices

Indices	
g	Infrastructure network, $g \in I$
i, j	Node, $i, j \in \{N_A^r \cup N_A^p \cup N_A^c\}$
k	k-th section of the demand in the roadway network, $k \in \{1,2,3,4\}$
t	Time stage, $t \in T$

Table 3.3 Notation for sets

Sets	
I	Set of infrastructure systems, $I = \{r, e, c\}$, which includes roadway, electric power, and telecommunication networks, in the model
N_A^g	Set of all nodes in infrastructure network $g \in I$
N_O^g	Set of supply nodes in infrastructure network $g \in I$, $N_O^g \subset N_A^g$
N_T^g	Set of transshipment nodes in infrastructure network $g \in I$, $N_T^g \subset N_A^g$
N_D^g	Set of demand nodes in infrastructure network $g \in I$, $N_D^g \subset N_A^g$
N_{RS}^g	Set of the depots of the restoration units in infrastructure network $g \in I$
N_{DN}^g	Set of nodes connected to disrupted links in infrastructure network $g \in I$
N_C^g	Set of demand nodes connected telecommunication services in infrastructure network $g \in I$, $N_C^g \subset N_D^g$
A^g	Set of links in infrastructure network $g \in I$
R^g	Set of failed links in infrastructure network $g \in I$
$\psi^{p,c}$	Set of demand nodes in the electric power network and the telecommunication network with physical interdependency
$\psi^{c,r}$	Set of demand nodes in the telecommunication networks and the roadway network with cyber interdependency
T	Set of time stage t, $T = [t_c, t_h]$

Table 3.4 Notation for parameters

Parameters	
s_i^g	Supply limit for supply node $i \in N_O^g$ in infrastructure network $g \in I$
$d_{i,Actl}^g$	Actual demand for demand node $i \in N_D^g$ in infrastructure network $g \in I$
$d_{i,k}^r$	k-th demand boundary for demand node $i \in N_D^r$ in the roadway network
$P_{i,k}^r$	Probability of demand section k for node $i \in N_D^r$ in the roadway network

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$d_{i,Eqm}^{r}$	Demand of zero expected unmet demand if $x_{it}^{g} = d_{i,Eqm}^{r}$ for demand node $i \in N_D^r$ in the roadway network
u_{ij}^{g}	Capacity of link $(i,j) \in A^g$ in infrastructure network $g \epsilon I$
b_i	Backup time of electric power for telecommunication demand node $i \in N_D^g$
w^g	Weight for the performance function of infrastructure network $g \epsilon I$
ω_{RL}	Weight for the resilience loss
ω_{PI}	Weight for the penalty for incomplete information
t_c	Initial time stage
t_h	Maximum time stage
ϵ	A very small positive number
n^g	Total number of restoration units for infrastructure network $g \epsilon I$

Table 3.5 Notation for decision variables

Decision variables	
f_{ijt}^{g}	Variable for commodity flow on link $(i,j) \in A^g$ in infrastructure network g ϵ I at time stage t
x_{it}^{g}	Variable for the delivered commodity at destination node $i \in N_D^g$ in infrastructure network $g \epsilon I$ at time stage t
$\phi_{ijt}^{r,g}$	Variable for connection flow on road link $(i,j) \in A^r$ for the restoration of infrastructure network $g \epsilon I$ at time stage t
$\xi_{it}^{r,g}$	Variable indicating whether node $i \in N^g \setminus N_R^g$ being connected to the depot of the restoration units for infrastructure network g ϵ I at time stage t; non-zero $\xi_{it}^{r,g}$ indicates node i is connected to the restoration depot.
α_{ijt}^{g}	Binary variable indicating the functional state of link $(i,j) \in A^g$ in infrastructure network g ϵ I at time stage t; $\alpha_{ijt}^{g} = 1$ indicates that link (i,j) is functional
γ_{it}^{r}	Binary variable indicating whether roadway demand node $i \in N_D^r$ in at time stage t being disconnected from telecommunication services; $\gamma_{it}^{r} = 1$ indicates that node i is disconnected
$\lambda_{it,k}^{r}$	Variable indicating the k-th section of x_{it}^{r} for roadway demand node $i \in N_D^r$ in at time stage *t*, while $k \in \{1,2,3,4\}$
$\beta_{it,k}^{r}$	Binary variable indicating whether $\lambda_{it,k}^{r}$ is equal to or less than $d_{i,k}^{r} - d_{i,k-1}^{r}$ for roadway demand node $i \in N_D^r$ in at time stage *t*, while $k \in \{1,2,3,4\}$; $\beta_{it,k}^{r} = 1$ if and only if $\lambda_{it,k}^{r} = d_{i,k}^{r} - d_{i,k-1}^{r}$.

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3.4 Problem formulation

In the main model, the restoration process is optimized based on the known information for the manager of the restoration schedule. As the restoration being undertaken, some nodes may re-gain the telecommunication service, and thus, the model will reoptimize based on the updated information, which is introduced in Section 3.5.

3.4.1 Expected unmet demand

For the demand nodes in the roadway network without the telecommunication services, the formulation of their expected unmet demand is calculated as (3), while d_i^r is the demand at the demand node *i* in the roadway network.

$$\begin{aligned}
&\sum_{i\in N_D^r\setminus N_C^r} \mathbb{E}[(d_i^r - x_{it}^r)^+] \\
&= \sum_{i\in N_D^r\setminus N_C^r} \int_{x_{it}^r}^{\infty} (\delta - x_{it}^r)\mathbb{P}_{d_i^r}(\delta)d\delta \\
&= \sum_{i\in N_D^r\setminus N_C^r} \left[\int_0^{\infty} (\delta - x_{it}^r)\mathbb{P}_{d_i^r}(\delta)d\delta - \int_0^{x_{it}^r} (\delta - x_{it}^r)\mathbb{P}_{d_i^r}(\delta)d\delta\right] \\
&= \sum_{i\in N_D^r\setminus N_C^r} \left[\mathbb{E}[d_i^r] - x_{it}^r + \int_0^{x_{it}^r} (x_{it}^r - \delta)\mathbb{P}_{d_i^r}(\delta)d\delta\right]
\end{aligned} \tag{3}$$

From (3), the expected unmet demand can be represented by two parts: the *expected demand minus the delivered commodity* and the *expected demand surplus*. Herein, the expected demand surplus for the probability defined in Section 3.1.3 is calculated in Table 3.6. Moreover, if the demand information is deterministic, the known demand can be viewed as the expected demand, while there is no expected demand surplus.

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Table 3.6 Probability density function for demand and expected demand surplus

x_{it}^r	$\mathbb{P}_{d_i^r}(x_t^i)$	$\int_0^{x_{it}^r}(x_{it}^r-\delta)\mathbb{P}_{d_i^r}(x_t^i)d\delta$
$[d_{i,0}^r, d_{i,1}^r)$	$P_{\mathrm{i},1}^{\mathrm{r}}=0$	$\int_{d_{i,0}^r}^{x_{it}^r}(x_{it}^r-\delta)\,P_{i,1}^r d\delta=\frac{1}{2}P_{i,1}^r(x_{it}^r-d_{i,0}^r)^2$
$[d_{i,1}^r, d_{i,2}^r)$	$P_{\mathrm{i},2}^{\mathrm{r}}$	$\frac{1}{2}P_{i,1}^r(d_{i,1}^r-d_{i,0}^r)^2+\int_{d_{i,1}^r}^{x_{it}^r}(x_{it}^r-\delta)\,P_{i,2}^r d\delta$ $=\frac{1}{2}P_{i,1}^r(d_{i,1}^r-d_{i,0}^r)^2+\frac{1}{2}P_{i,2}^r(x_{it}^r-d_{i,1}^r)^2$
$[d_{i,2}^r, d_{i,3}^r)$	$P_{\mathrm{i},3}^{\mathrm{r}}$	$\sum_{k=1}^{2}\frac{1}{2}\,P_{i,k}^r\,(d_{i,k}^r-d_{i,k-1}^r)^2+\frac{1}{2}P_{i,3}^r(x_{it}^r-d_{i,2}^r)^2$
$[d_{i,3}^r, d_{i,4}^r)$	$P_{\mathrm{i},4}^{\mathrm{r}}$	$\sum_{k=1}^{3}\frac{1}{2}\,P_{i,k}^r\,(d_{i,k}^r-d_{i,k-1}^r)^2+\frac{1}{2}P_{i,4}^r(x_{it}^r-d_{i,3}^r)^2$
$[d_{i,4}^r, \infty)$	0	$\sum_{k=1}^{4}\frac{1}{2}\,P_{i,k}^r\,(d_{i,k}^r-d_{i,k-1}^r)^2$

With the additional variables $\lambda_{it,k}^r$, the assumption in Equations (4)-(5), and the derivation in Table 3.6, the expected demand surplus is formulated as Equation (6). Hence, the expected unmet demand is expressed as Equation (7).

$$x_{it}^r=\sum\nolimits_{k=1}^{4}\lambda_{it,k}^r \quad \forall t\in T,\ i\in N_D^g\backslash N_C^g \tag{4}$$

$$\lambda_{it,k}^r=min\big(d_{i,k}^r-d_{it,k-1}^r, max\big(0, x_{it,k}^r-d_{it,k-1}^r\big)\big), \quad \forall t\in T,\ i\in N_D^g\backslash N_C^g,\ k\in\{1,2,3,4\} \tag{5}$$

$$\int_0^{x_{it}^r}(x_{it}^r-\delta)\mathbb{P}_{d_i^r}(\delta)d\delta=\sum\nolimits_{k=1}^{4}\frac{1}{2}P_{i,k}^r{\lambda_{it,k}^r}^2, \quad \forall t\in T,\ i\in N_D^g\backslash N_C^g,\ k\in\{1,2,3,4\} \tag{6}$$

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$$\sum_{i\in N_D^r\setminus N_C^r} \mathbb{E}[(d_i^r - x_{it}^r)^+]$$

$$= \sum_{i\in N_D^r\setminus N_C^r} \left[\mathbb{E}[d_i^r] - x_{it}^r + \int_0^{x_{it}^r} (x_{it}^r - \delta)\mathbb{P}_{d_i^r}(\delta)d\delta\right] \qquad (7)$$

$$= \sum_{i\in N_D^r\setminus N_C^r} \left[\mathbb{E}[d_i^r] - x_{it}^r + \sum_{k=1}^{4}\frac{1}{2}P_{i,k}^r {\lambda_{it,k}^r}^2\right]$$

3.4.2 Objective function and initial condition

Combining the problem stated in Section 3.1 and the assumption of the probability distribution for demand in Section 3.4.1, a model of the interdependent network restoration problem is then developed.

$$min \sum_{t\in T}\left[\omega_{RL}\cdot\sum_{g\in I}\left(w^g\cdot\frac{\sum_{i\in N_D^g}\mathbb{E}\left[\left(d_i^g - x_{it}^g\right)^+\right]}{\sum_{i\in N_D^g}\mathbb{E}\left[d_i^g\right]}\right)+\omega_{PI}\cdot\frac{\sum_{i\in N_D^g}\gamma_{it}\cdot\mathbb{E}[d_i^r]}{\sum_{i\in N_D^g}\mathbb{E}[d_i^r]}\right] \qquad (8)$$

Subject to

$$\alpha_{ijt_c}^g = 0 \quad \forall g\in I,\ (i,j)\in R^g \qquad (9)$$

As defined in Section 3.1.1, the objective of the interdependent network restoration problem is formulated as Objective (8), minimizing the weighted sum of the resilience loss and the penalty for the incomplete information. Constraint (9) identifies the initial condition of the functional state of the links in each infrastructure network, where the initial time stage is t_c.

After the probability density function for the roadway demand nodes without deterministic demand information is defined, the formulation of the expected unmet demand from Equation (7) is plugged into Objective (8) and thus have the objective function in the form of Objective (10). Objective (10) consists of three components, which

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are the resilience loss of the electric power and telecommunication networks, the resilience loss of the roadway network, including demand nodes with and without deterministic demand information, and the penalty for the incomplete information.

$$min\sum_{t\in T}\omega_{RL}\cdot\left\{\left[\sum_{g\in\{p,c\}}\left(w^g\cdot\frac{\sum_{i\in N_D^g}\left(d_i^g-x_{it}^g\right)}{\sum_{i\in N_D^g}d_{i,Actl}^g}\right)+\right.\right.$$
$$\left.w^r\cdot\frac{\sum_{i\in N_D^r\cap N_C^r}\left(d_{i,Actl}^r-x_{it}^r\right)+\sum_{i\in N_D^r\setminus N_C^r}\left(\mathbb{E}[d_i^r]-x_{it}^r+\sum_{k=1}^4\frac{1}{2}P_{i,k}^r\cdot{\lambda_{it,k}^r}^2\right)}{\sum_{i\in N_D^r\cap N_C^r}d_{i,Actl}^r+\sum_{i\in N_D^r\setminus N_C^r}\mathbb{E}[d_i^r]}\right] \quad (10)$$
$$\left.+\omega_{PI}\cdot\frac{\sum_{i\in N_D^g}\gamma_{it}\cdot\mathbb{E}[d_i^r]}{\sum_{i\in N_D^g}\mathbb{E}[d_i^r]}\right\}$$

3.4.3 Flow conservation for commodity

Following constraints are about the flow conservation for the commodity delivered in each infrastructure network.

$$\sum_{(j,k)\in L^g}f_{jkt}^g-\sum_{(i,j)\in L^g}f_{ijt}^g\le s_j^g\quad\forall t\in T,\ g\in I,\ j\in N_O^g \quad (11)$$

$$\sum_{(j,k)\in L^g}f_{jkt}^g-\sum_{(i,j)\in L^g}f_{ijt}^g=0\quad\forall t\in T,\ g\in I,\ j\in N_T^g \quad (12)$$

$$\sum_{(j,k)\in L^g}f_{jkt}^g-\sum_{(i,j)\in L^g}f_{ijt}^g=-x_{jt}^g\quad\forall t\in T,\ g\in I,\ j\in N_D^g \quad (13)$$

Constraints (11)-(13) regulate the flow conservation within each infrastructure network. From the perspective of network flow modeling, there are three types of nodes: supply, transshipment, and demand nodes. Constraint (11) is for the supply nodes which provide the commodities to the links passing by. Constraint (12) is for the transshipment

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nodes, and the amount of inflow and outflow commodities at these nodes must be equal. Constraint (13) is for the demand nodes, requesting a certain number of commodities.

3.4.4 Flow conservation for restoration crews

For the consideration of the restoration interdependency, the calculation of the connectivity between the depot for the restoration crews and the disrupted links is required in every time stages to exclude the infeasible restoration acts for the restoration crews. Herein, this study implements the network-flow approach to assess the connectivity for each time stage.

$$\sum_{(j,k)\in L^g} \phi_{jkt}^{r,g} - \sum_{(i,j)\in L^g} \phi_{ijt}^{r,g} \le n^g \quad \forall t \in T,\ g \in I,\ j \in N_{RS}^g \tag{14}$$

$$\sum_{(j,k)\in L^g} \phi_{jkt}^{r,g} - \sum_{(i,j)\in L^g} \phi_{ijt}^{r,g} = 0 \quad \forall t \in T,\ g \in I,\ j \in N_A^g \backslash \{N_{RS}^g \cup N_{DN}^g\} \tag{15}$$

$$\sum_{(j,k)\in L^g} \phi_{jkt}^{r,g} - \sum_{(i,j)\in L^g} \phi_{ijt}^{r,g} = -\xi_{jt}^{r,g} \quad \forall t \in T,\ g \in I,\ j \in N_{DN}^g \tag{16}$$

Constraints (14)-(16) use the network flow method to determine whether a node is connected to the depots of restoration crews. As the model considers the restoration interdependency, the available restoration action is limited to the reachable links for the restoration units. Hence, in order to model the connectivity between nodes, a continuous flow/path for the node pair must be identified. This study views the depot of restoration crews as the source of the flow and the subjected nodes as the sinks. As attaining the connectivity from the source to the sink, the continuity of flow at each node along a path must be confirmed. Besides, as the model seeks to minimize the unmet demand, some links need to be restored to improve the objective value because of Constraint (27). Therefore, the $\xi_{jt}^{r,g}$ must be maximized to let some disrupted links become feasible, and

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the maximum flow problem is formed.

3.4.5 Calculating expected unmet demand

For the inclusion of the incomplete information and the cyber interdependency, following constraints evaluate the variables required for calculating expected unmet demand for the demand nodes with incomplete information.

$$x_{it}^r = \sum_{k=1}^{4} \lambda_{it,k}^r \quad \forall t \in T,\ i \in N_D^r \backslash N_C^r \tag{17}$$

$$0 \le \lambda_{it,k}^r \le d_{i,k}^r - d_{i,k-1}^r \quad \forall t \in T,\ i \in N_D^r \backslash N_C^r,\ k \in \{1,2,3,4\} \tag{18}$$

$$\lambda_{it,k}^r \ge \left(d_{i,k}^r - d_{i,k-1}^r\right) \cdot \beta_{it,k}^r \quad \forall t \in T,\ i \in N_D^r \backslash N_C^r,\ k \in \{1,2,3\} \tag{19}$$

$$\left(d_{i,k}^r - d_{i,k-1}^r\right) - \lambda_{it,k}^r \ge \epsilon \cdot \left(1 - \beta_{it,k}^r\right) \quad \forall t \in T,\ i \in N_D^r \backslash N_C^r,\ k \in \{1,2,3\} \tag{20}$$

$$\lambda_{it,(k+1)}^r \le \left(d_{i,k}^r - d_{i,k-1}^r\right) \cdot \beta_{it,k}^r \quad \forall t \in T,\ i \in N_D^r \backslash N_C^r,\ k \in \{1,2,3\} \tag{21}$$

$$\beta_{it,k+1}^r \le \beta_{it,k}^r \quad \forall t \in T,\ i \in N_D^r \backslash N_C^r,\ k \in \{1,2\} \tag{22}$$

From Section 3.4.1, the expected unmet demand is calculated as (7) with the decision variable $\lambda_{it,k}^r$. In order to define $\lambda_{it,k}^r$, Constraints (17)-(22) are set, and the binary variable $\beta_{it,k}^r$ is introduced. Herein, Constraints (19) and (20) define the value of $\beta_{it,k}^r$: $\beta_{it,k}^r = 1$ if and only if $\lambda_{it,k}^r = d_{i,k}^r - d_{i,k-1}^r$; Constraint (21) limits $\lambda_{it,k}^r$ to 0 as $\beta_{it,k}^r = 0$; Constraint (22) specifies that if $\beta_{it,k+1}^r$ is equal to 1, $\beta_{it,k}^r$ is also equal to 1 because when $x_{it}^r \ge d_{i,k+1}^r$, it indicates that $x_{it}^r \ge d_{i,k}^r$.

3.4.6 Physical interdependency

Constraint (23) regulates the physical interdependency between the electric power network and the telecommunication network. Herein, this constraint considers the backup

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electric power attached to the telecommunication facilities. If the electric power failure ($x_{i\tau}^{p} = 0$) at a facility is longer than its backup time (b_i), the corresponding demand node in the telecommunication network will stop to provide service ($\mathrm{x}_{\mathrm{jt}}^{\mathrm{c}} = 0$); thereby, it cannot fulfill the demand onsite.

$$x_{jt}^{c} \leq d_{j,Actl}^{c} \cdot \sum_{\tau=max(0,t-b_j)}^{t} x_{i\tau}^{p} \quad \forall t \in T,\ (i,j) \in \Psi^{p,c} \tag{23}$$

3.4.7 Cyber interdependency

Constraints (24)-(26) define the values of binary variables γ_{it}^{r}. These variables indicate the status of the telecommunication service of the demand nodes in the roadway network. Herein, the penalty of the incomplete information is calculated based on these variables. For Constraint (24), if the demand node in the roadway network is connected to the telecommunication service ($\gamma_{jt}^{r} = 0$), the telecommunication service must have been delivered to the corresponding demand node in the telecommunication network before the current time stage ($\sum_{\tau=0}^{t} x_{i\tau}^{c} > 0$). For Constraint (25), if the telecommunication service must have been delivered to the corresponding demand node in the telecommunication network before the current time stage ($\sum_{\tau=0}^{t} x_{i\tau}^{c} > 0$), the demand node in the roadway network is connected to the telecommunication service ($\gamma_{jt}^{r} = 0$). For Constraint (26), if the demand node in the roadway network is connected to the telecommunication service in the current time stage ($\gamma_{\mathrm{jt}}^{r} = 0$), such node is also connected in the next time stage ($\gamma_{j(t+1)}^{r} = 0$).

$$\sum_{\tau=0}^{t} x_{i\tau}^{c} \geq \epsilon \cdot \left(1 - \gamma_{jt}^{r}\right) \quad \forall t \in T,\ (i,j) \in \Psi^{c,r} \tag{24}$$

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$$\sum_{\tau=0}^{t} x_{i\tau}^{c} \leq \left(\sum_{\tau=0}^{t} d_{i,Actl}^{c}\right) \cdot \left(1-\gamma_{jt}^{r}\right) \quad \forall t \in T,\ (i,j) \in \Psi^{c,r} \tag{25}$$

$$\gamma_{it}^{r} \geq \gamma_{i(t+1)}^{r} \quad \forall t \in T \backslash \{t_h\},\ i \in N_D^r \backslash N_C^r \tag{26}$$

3.4.8 Logical/restoration interdependency

Constraint (27) sets the limit on the restoration: one of the end nodes of a failed link must be connected to a depot of restoration units through the roadway network so that restoration can be executed on it. That is, if both ends of the disrupted link is disconnected from the depot of the restoration crews ($\xi_{it}^{r,g} = \xi_{jt}^{r,g} = 0$), that link cannot be restored at the current time stage ($\alpha_{ij(t+1)}^{g} - \alpha_{ijt}^{g} = 0$).

$$\alpha_{ij(t+1)}^{g} - \alpha_{ijt}^{g} \leq \xi_{it}^{r,g} + \xi_{jt}^{r,g} \quad \forall t \in T \backslash \{t_h\},\ (i,j) \in R^g \tag{27}$$

3.4.9 Restoration constraints

Constraint (28) limits the number of restored links in one stage to be less than the total number of restoration units. Constraint (29) assumes that the restored links will not be damaged again after restoration.

$$\alpha_{ij(t+1)}^{g} - \alpha_{ijt}^{g} \leq n^g \quad \forall t \in T \backslash \{t_h\},\ g \in I,\ (i,j) \in R^g \tag{28}$$

$$\alpha_{ij(t+1)}^{g} \geq \alpha_{ijt}^{g} \quad \forall t \in T \backslash \{t_h\},\ g \in I,\ (i,j) \in R^g \tag{29}$$

3.4.10 Capacity and decision variables

Following constraints define the link capacity and the binary variables.

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$$0 \le f_{ijt}^{g} \le \alpha_{ijt}^{g} \cdot u_{ij}^{g} \quad \forall t \in T,\ g \in I,\ (i,j) \in R^{g} \tag{30}$$

$$0 \le f_{ijt}^{g} \le u_{ij}^{g} \quad \forall t \in T,\ g \in I,\ (i,j) \in A^{g} \tag{31}$$

$$0 \le x_{it}^{g} \le d_{i,Actl}^{g} \quad \forall t \in T,\ g \in I,\ i \in N_{D}^{g} \cap N_{C}^{g} \tag{32}$$

$$0 \le x_{it}^{g} \le d_{i,Eqm}^{g} \quad \forall t \in T,\ g \in I,\ i \in N_{D}^{g} \backslash N_{C}^{g} \tag{33}$$

$$0 \le \phi_{ijt}^{r,g} \le \alpha_{ijt}^{r} \cdot n^{g} \quad \forall t \in T,\ g \in I,\ (i,j) \in R^{r} \tag{34}$$

$$0 \le \phi_{ijt}^{r,g} \le n^{g} \quad \forall t \in T,\ g \in I,\ (i,j) \in A^{r} \tag{35}$$

$$0 \le \xi_{it}^{r,g} \le 1 \quad \forall t \in T,\ g \in I,\ i \in N_{DN}^{g} \tag{36}$$

$$\alpha_{ijt}^{g} \in \{0,1\} \quad \forall t \in T,\ g \in I,\ (i,j) \in R^{g} \tag{37}$$

$$\gamma_{it}^{r} \in \{0,1\} \quad \forall t \in T,\ i \in N_{D}^{r} \tag{38}$$

$$\beta_{it,k}^{r} \in \{0,1\} \quad \forall t \in T,\ i \in N_{D}^{r} \backslash N_{C}^{r},\ k \in \{1,2,3\} \tag{39}$$

Constraints (30), (31), (34) and (35) regulate link capacities, and Constraints (30) and (34) are specifically for failed links whose capacities are determined by both their normal capacities and their functional states. Constraints (32), (33) and (36) limit the amounts of commodities delivered to demand nodes. Herein, the constraint (32) is about the demand nodes with complete demand information that delivered commodities are constrained by their actual demand; Constraint (33) limits the delivered commodity for the nodes with uncertain demand to their maximum possible demand. Furthermore, Constraints (30)-(33) are associated with the commodity flows in each infrastructure

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networks, while constraints (34)-(36) govern the connection flow for restoration units on the roadway network. Constraints (37)-(39) define the binary variables.

3.4.11 Summary of model development

In summary, the developed model to solve the proposed interdependent network restoration problem in Section 3.1 is demonstrated in Section 3.4.2 to 3.4.10. The objective function of the model is (9), while the constraints are (10)-(39).

3.5 Iterative restoration process

In order to manage the known and unknown information of the demand in the road network, this study evaluates the resilience loss iteratively, which optimizes the restoration process only based on the information known in the initial time stage of the optimization. In Section 3.4, a model is developed to solve the interdependent network restoration problem with the known information in the initial time stage, t_c. As the restoration starts from $t_c = 0$, the performance of each infrastructure network is restored incrementally, resulting in the restored telecommunication services of some demand nodes in the roadway network and the update of the corresponding demand information at some proceeding time stage. In order to manifest the update of the demand information and avoid the optimization using the information unknown in the initial time stage, this study analyzes the resilience loss of the whole restoration process heuristically. Herein, this study defines an iterative restoration process, as shown in Figure 3.2, which re-optimizes the restoration schedule when the demand information is updated. Hence, the restoration schedule is only optimized based on the information known in the initial time stage.

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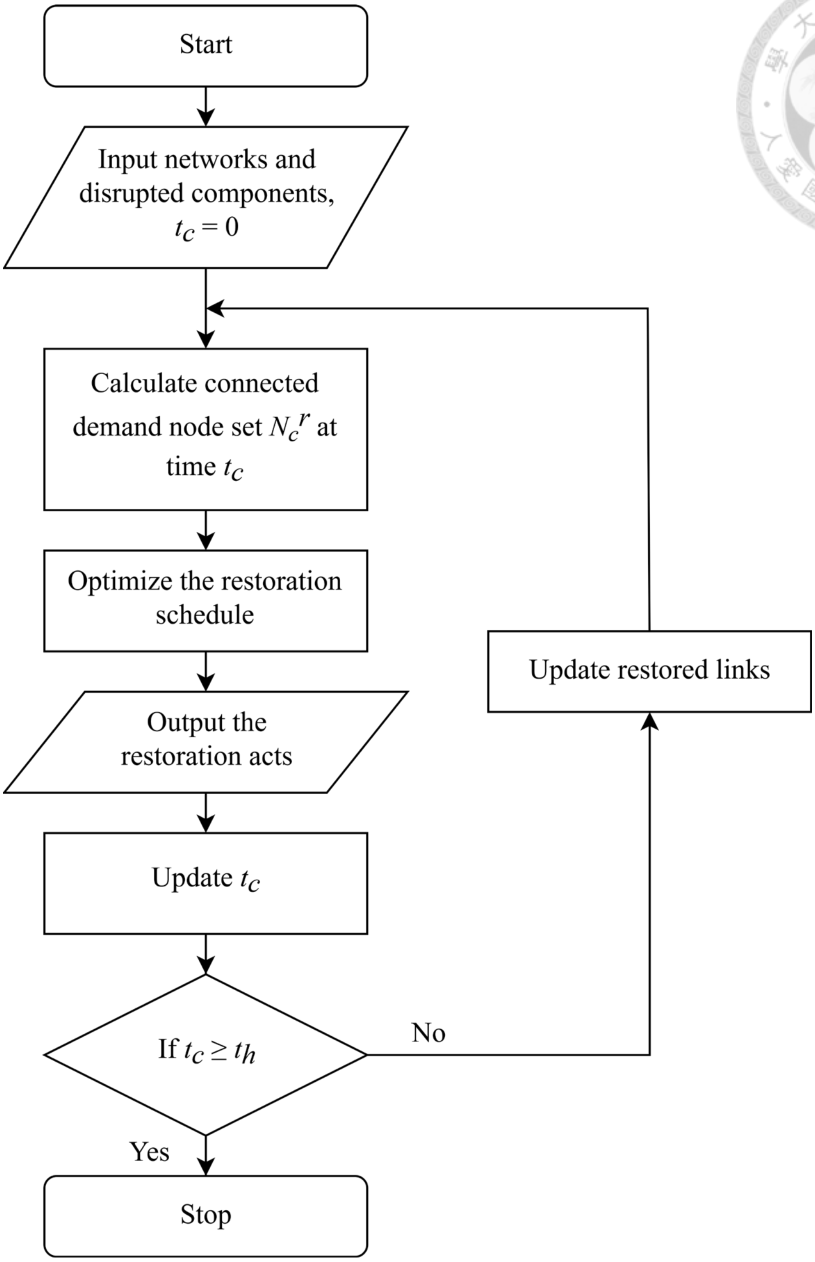

Figure 3.2 Iterative restoration process

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CHAPTER 4

NUMERICAL EXPERIMENTS

In order to illustrate the importance of considering interdependency and test the capability of the proposed model, this study designs two severe disruptions after the flood-related disaster to the test infrastructure networks, which are with severe telecommunication disruption and severe roadway disruption, to demonstrate the influence of the cyber and restoration interdependency in the restoration process.

In this chapter, the resilience-related network characteristics are highlighted. The disruptions in two cases are all assumed to result from the subsidence after a flood. Hence, the disrupted links in each network are in the areas of the vicinity, which implicates the geographical interdependency among networks. Furthermore, all of the cases are programmed using Python 3.7.3 and solved by Gurobi 8.1; moreover, the experiments are executed with eight-core 3.7 GHz CPU, AMD Ryzen 7 2700X, and 32 GB of RAM. Herein, the Gurobi is a solver for mathematical programming, which includes the solvers for mixed-integer quadratic programming.

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4.1 Test infrastructure networks

The test infrastructure networks are built based on the infrastructure systems of Tucheng District, New Taipei City, Taiwan, with a total population of 237,316 ("Statistic on population in June 2018," 2018). Herein, the roadway network is simplified from the road topology of Tucheng District; the electric power and telecommunication networks for Tucheng District are created based on the pipeline data ("NTPC iMAP,"), and the distribution of the pipeline is listed in Table 4.4.

The distribution of the nodes and links of the test infrastructure networks are shown in Figure 4.1, Figure 4.2, and Figure 4.3, where all the links are bidirectional; the topology of the test infrastructure networks are listed in Table 4.1. In the electric power network, the proposed cases only consider the power distribution network: one primary substation and two secondary substations are located in the study area. Thereby, this study assumes that there are two sub-areas of power distribution. Each of them has one backbone connected to the electric power supply node (the primary substation). In the telecommunication network, the links primarily follow the links of the roadway network, and it contains a single supply node.

In the test infrastructure networks, we assume that the demand nodes in each infrastructure network are located at the same places. That is, each demand node has the demand for services of all three infrastructure systems simultaneously. The demand of the necessities delivered through the roadway network, electricity in the electric power network and telecommunication service reflects the population in the vicinity of the demand nodes. The depots of restoration units are assumed to be located at the supply nodes of the associated networks.

For the probability distribution of the demand information, this study assumes that

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$d^r_{i,1} = 0.85\ d^r_{i,Actl}$, $d^r_{i,2} = 0.95\ d^r_{i,Actl}$, $d^r_{i,1} = 1.05\ d^r_{i,Actl}$, and $d^r_{i,1} = 1.15\ d^r_{i,Actl}$, where each section is with a width of $0.1\ d^r_{i,Actl}$. Moreover, this study assumes that the total probability for the low, medium, and high estimation is 0.25, 0.5, and 0.25, respectively. Hence, the expected value of the demand in the roadway network is equal to the actual value of the demand in the roadway network. The resulting demand probability distribution is shown in Table 4.3.

Table 4.1 Topology of the test infrastructure networks

Infrastructure	$\|\boldsymbol{N^g}\|$	$\|\boldsymbol{A^g}\|$	$\|\boldsymbol{N^g_S}\|$	$\|\boldsymbol{N^g_T}\|$	$\|\boldsymbol{N^g_D}\|$	$\|\boldsymbol{R^g}\|$
Roadway	68	104	1	44	23	1
Electric power	57	84	1	33	23	1
Telecommunication	60	91	1	36	23	1

Table 4.2 Supply in the test infrastructure networks

Node ID	$\boldsymbol{s^r_i}$	$\boldsymbol{s^p_i}$	$\boldsymbol{s^c_i}$
3	0	1,479	0
31	0	0	190
63	1,307	0	0

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Table 4.3 Demand in the test infrastructure networks

Node ID	$d^{r}_{i,Actl}$	d^{p}_{i}	d^{c}_{i}	$P^{r}_{i,1}$	$d^{r}_{i,1}$	$P^{r}_{i,2}$	$d^{r}_{i,2}$	$P^{r}_{i,3}$	$d^{r}_{i,3}$	$P^{r}_{i,4}$	$d^{r}_{i,4}$
4	76	129	17	0.000	64.6	0.033	72.2	0.066	79.8	0.033	87.4
6	42	72	10	0.000	35.7	0.060	39.9	0.119	44.1	0.06	48.3
7	52	89	11	0.000	44.2	0.048	49.4	0.096	54.6	0.048	59.8
9	44	74	10	0.000	37.4	0.057	41.8	0.114	46.2	0.057	50.6
11	70	118	16	0.000	59.5	0.036	66.5	0.071	73.5	0.036	80.5
13	28	48	7	0.000	23.8	0.089	26.6	0.179	29.4	0.089	32.2
16	29	48	7	0.000	24.6	0.086	27.6	0.172	30.4	0.086	33.4
18	69	118	15	0.000	58.6	0.036	65.5	0.072	72.5	0.036	79.3
20	66	112	15	0.000	56.1	0.038	62.7	0.076	69.3	0.038	75.9
23	29	50	6	0.000	24.6	0.086	27.6	0.172	30.4	0.086	33.4
27	29	50	6	0.000	24.6	0.086	27.6	0.172	30.4	0.086	33.4
28	41	70	9	0.000	34.9	0.061	39.0	0.122	43.0	0.061	47.1
35	40	67	9	0.000	34.0	0.063	38.0	0.125	42.0	0.063	46.0
37	53	90	11	0.000	45.0	0.047	50.4	0.094	55.6	0.047	61.0
42	25	43	5	0.000	21.3	0.100	23.8	0.200	26.3	0.100	28.8
43	28	48	4	0.000	23.8	0.089	26.6	0.179	29.4	0.089	32.2
44	20	34	4	0.000	17.0	0.125	19.0	0.250	21.0	0.125	23.0
46	20	34	5	0.000	17.0	0.125	19.0	0.250	21.0	0.125	23.0
51	32	54	7	0.000	27.2	0.078	30.4	0.156	33.6	0.078	36.8
54	19	31	4	0.000	16.1	0.132	18.1	0.263	19.9	0.132	21.9
57	20	34	4	0.000	17.0	0.125	19.0	0.250	21.0	0.125	23.0
59	21	35	4	0.000	17.9	0.119	19.9	0.238	22.1	0.119	24.1
60	18	31	4	0.000	15.3	0.139	17.1	0.278	18.9	0.139	20.7

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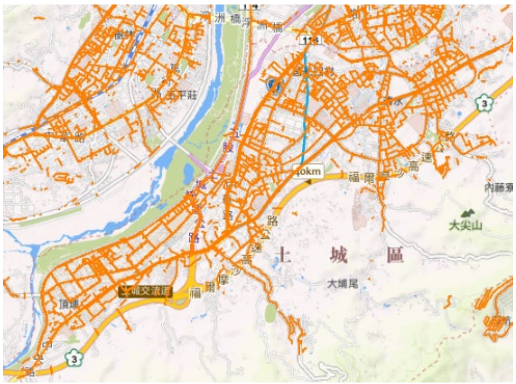
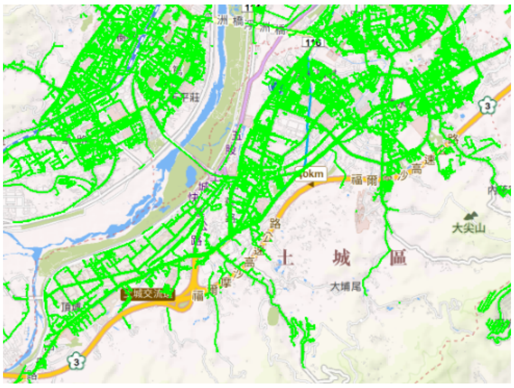
Table 4.4 Reference infrastructure networks

Infrastructure	Real world network
Roadway	
Electric power	
Telecommunication	

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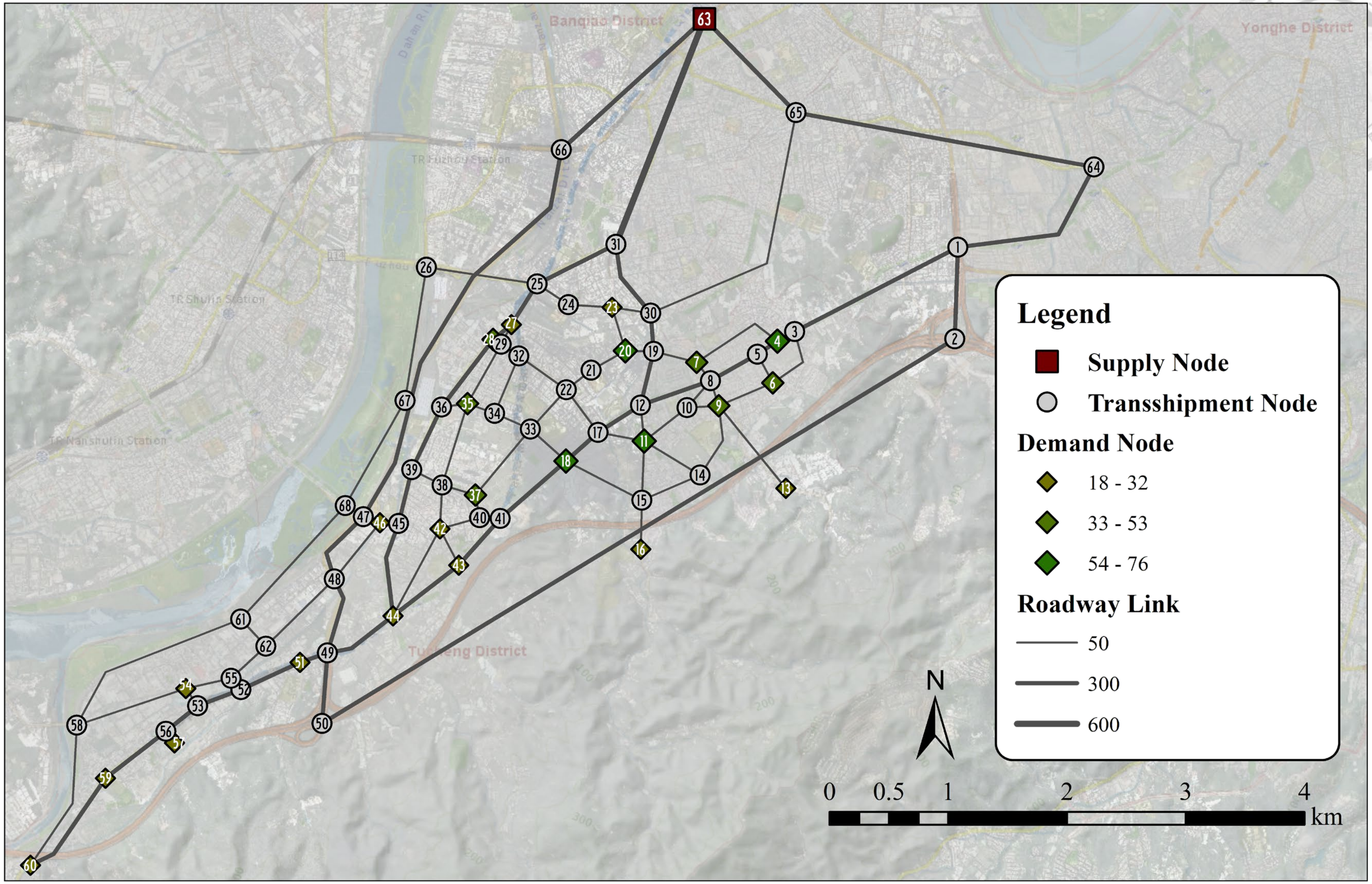

Figure 4.1 Test roadway network

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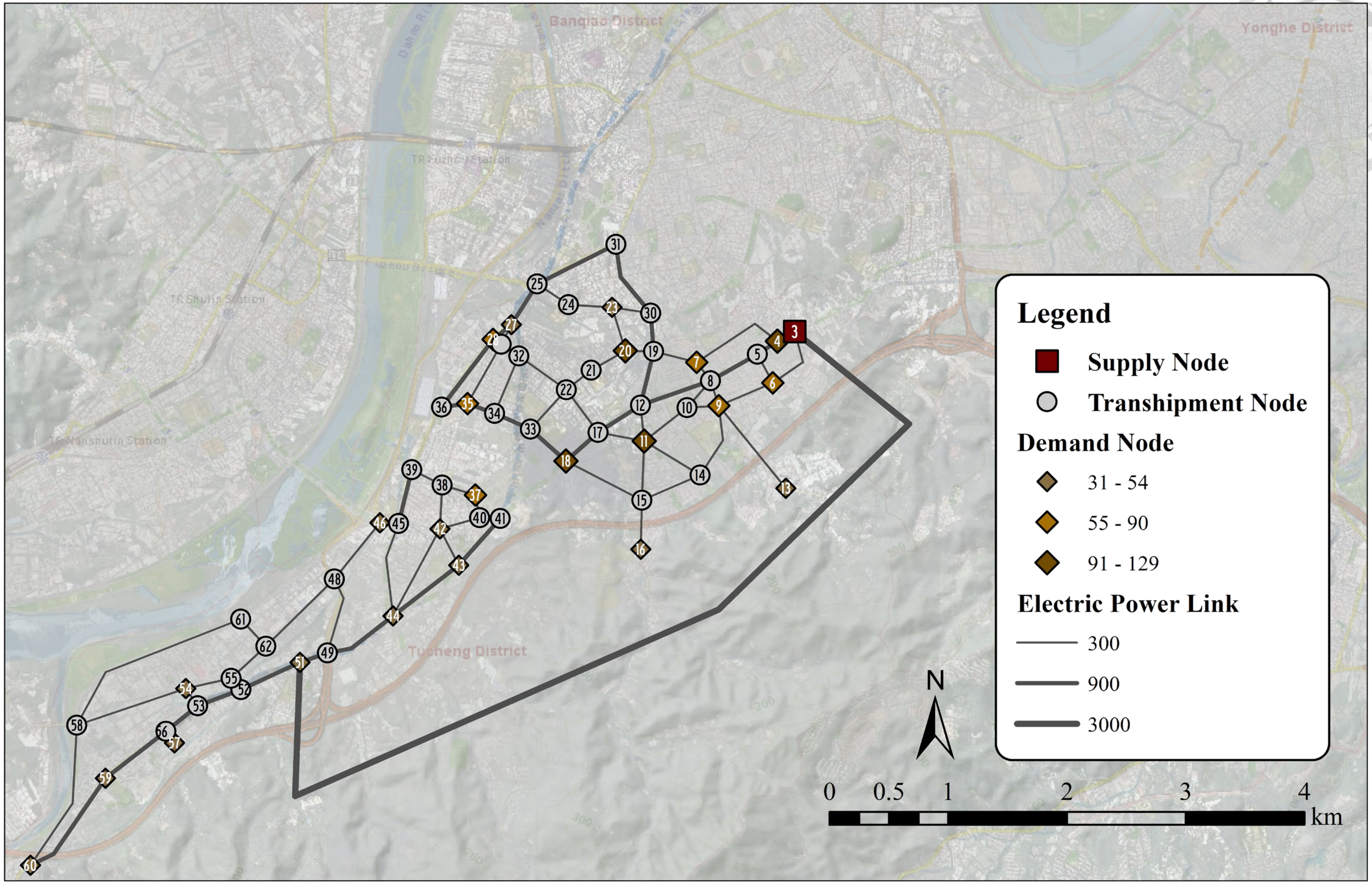

Figure 4.2 Test electric power network

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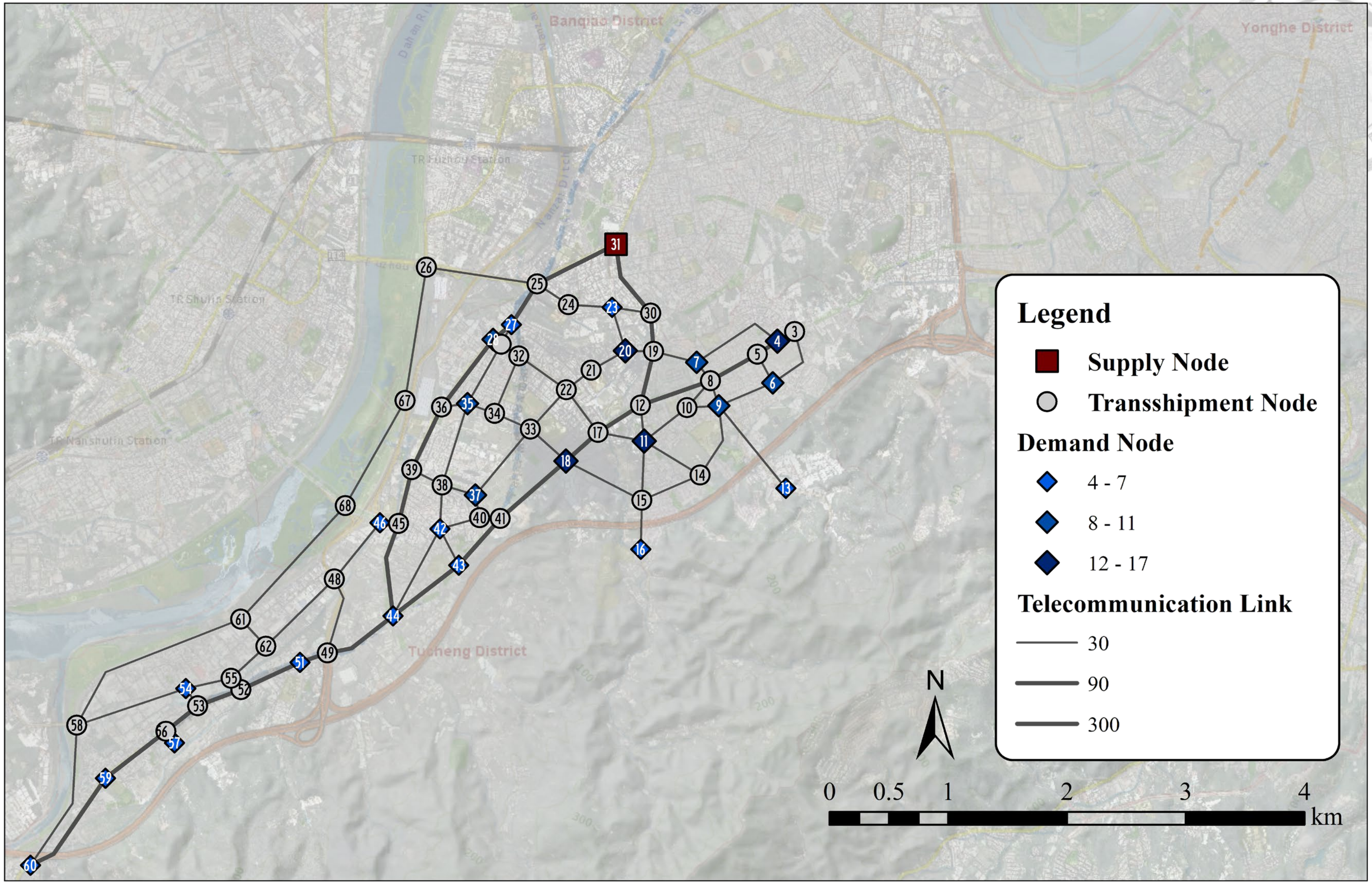

Figure 4.3 Test telecommunication network

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4.2 Case study: severe telecommunication disruption

From the perspective of the roadway network, the cyber interdependency indicates that the supply nodes cannot collect the information of the correct amount of demand at demand nodes without the functional telecommunication service. Hence, a severe telecommunication disruption, as presented in Figure 4.4, is formed to illustrate the cyber interdependency between the roadway and the telecommunication networks. Furthermore, in order to demonstrate the influence of the incomplete information to the restoration of the roadway network as the telecommunication network is severely damaged, this case adjusts the weight for the penalty for the incomplete information to showcase the different level of emphasis on demolishing the incompleteness of information regarding the amount of demand in the roadway network.

In this case, the south-western part of the telecommunication network is disconnected from the source node in the north-eastern part of the network, which is shown in Figure 4.3. That is, the south-western part of the demand nodes in the roadway network are lack of the correct demand information due to the failure and disconnection of the telecommunication service. However, the disruption in the roadway network is limited, and thus, this case primarily tests the influence of the incomplete information and how it affects the order of the restoration in the telecommunication network, rather than focusing on considering the reconnection of the roadway network.

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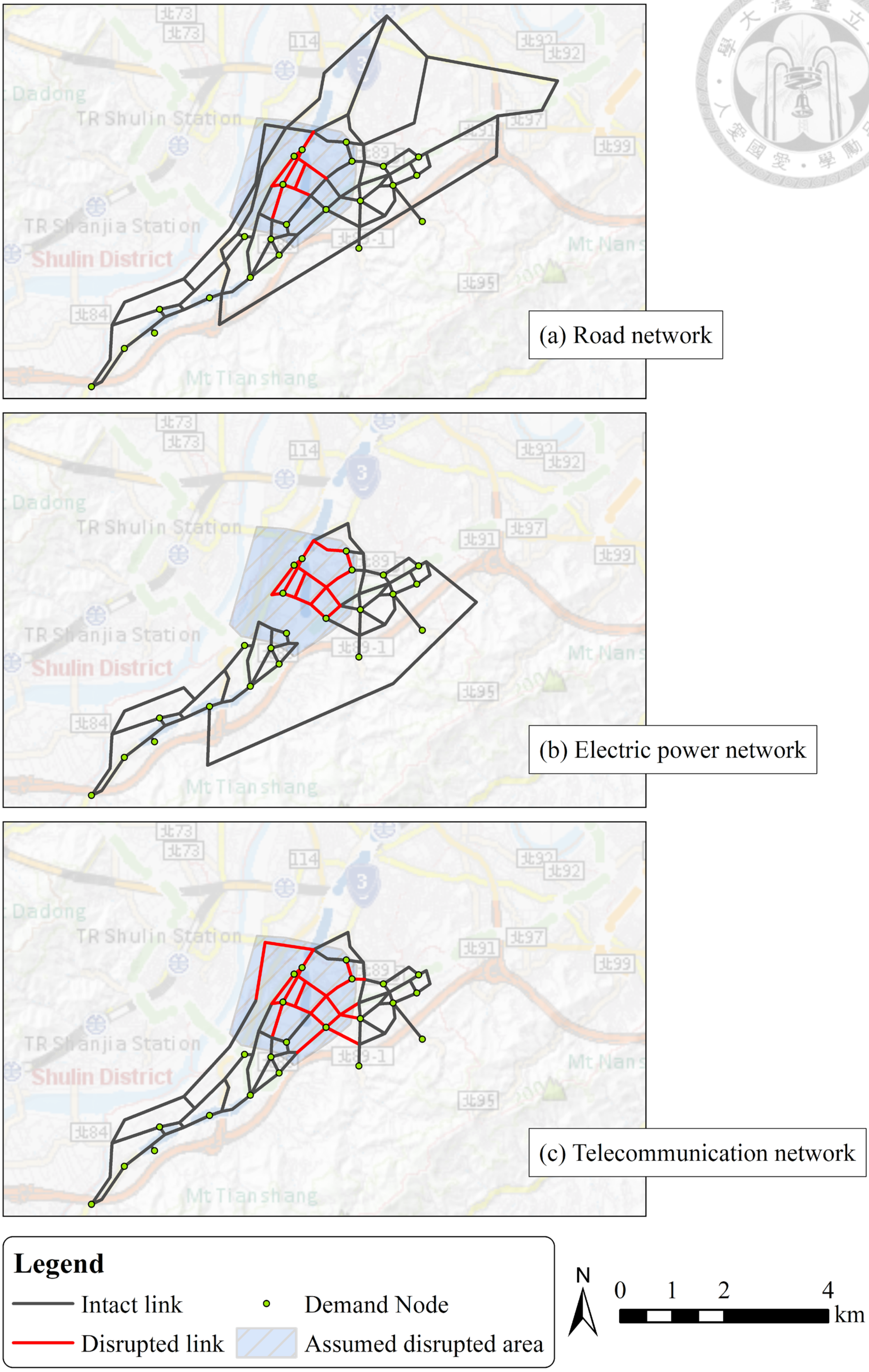

Figure 4.4 Disrupted links for severe telecommunication disruption

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4.2.1 Parameters

The weight of the penalty of the incomplete information is tested with a fixed interval of 0.1 from 0 to 4 to display the result from different emphasis level on the incomplete information. Moreover, the number of failed links in each network is allotted as follows: $\|R^r\| = 13, \|R^e\| = 21, \|R^c\| = 27$; then, other parameters for the model are listed in Table 4.5.

Table 4.5 Parameters for severe telecommunication disruption

Parameter	Value
Number of time stages	10
t_h	9
b_i	6
w_r	1
w_p	1
w_c	1
ω_{RL}	1
ω_{PI}	0~4 (with an interval of 0.1)

4.2.2 Tradeoff between incomplete information and resilience

The result of this case study shows the tradeoff between incomplete information and resilience under different level of emphasis on the incomplete information. The resulting tradeoff among different weights of the penalty for the incomplete information is presented in Figure 4.5, and the solution time for each scenario is displayed in Figure 4.6, which increases as the weight of the penalty for the incomplete information rises. The reason may be that the model with higher ω_{PI}, the solver needs to look for the compromise solution which incorporates the emphasis on eliminating the incompleteness of the demand information other than the model with lower ω_{PI}, which only needs to account for the optimal solution from the network flow approach. Herein, increasing the emphasis on eliminating the incompleteness of the demand information (increasing ω_{PI})

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would boost the recovery of the telecommunication services; however, due to the interdependencies among the infrastructure networks, the boosting might be achieved through sacrificing the performance recovery of other infrastructure networks, which decreases the resilience loss. In the following paragraphs, such relation similar to tradeoff is discussed in detail.

From Figure 4.5, the restoration schedules with different weight for the penalty for incomplete information lead to two distinct results: *low resilience loss with a high penalty for the incomplete information* or *high resilience loss with a low penalty for the incomplete information*. When ω_{PI} becomes greater than 2, the resulting restoration schedule shifts from low to high resilience loss. In order to observe the difference between two distinct kinds of results in detail, two specific weights ($\omega_{PI} = 0.5, 3.5$) are selected and analyzed. Herein, the restoration schedules for both weights are presented in Table 4.6 and Table 4.7, while the position of the restored links in each time stage is displayed in Figure 4.7, Figure 4.8, for $\omega_{PI} = 0.5$, Figure 4.9, and Figure 4.10, for $\omega_{PI} = 3.5$.

In the detailed maps for the resulting restoration schedules, the most distinct difference is the order of the restoration of the telecommunication network. In the scenario with low ω_{PI}, the model chooses to reconnect the western part of the disrupted area; however, in the scenario with high ω_{PI}, the model selects the eastern part of the disrupted area as the prioritized links for restoration.

In the western part of the disrupted area, it requires 3 time stages, which restores three telecommunication links, to reconnect the telecommunication service of the south-western part of the test infrastructure networks. Besides, in such a process, two demand nodes in the telecommunication network can also restore the telecommunication service.

On the other hand, in the eastern part of the disrupted area, it takes two links to

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reconnect the telecommunication service in the south-eastern part of the network. However, this process only restores one demand node in the telecommunication network.

Hence, the proposed model manages to tradeoff between the reconnection of the telecommunication network downstream and the restoration of some demand nodes in the telecommunication network. With low ω_{PI}, reconnecting the telecommunication network is not highly prioritized because it only influences the resilience loss of the telecommunication network and the calculation the expected unmet demand for the roadway network. However, with higher ω_{PI}, restoring the telecommunication service to receive correct demand information in the roadway network is more emphasized. Therefore, reconnecting the telecommunication service of the south-western part of the telecommunication network becomes more critical, and the model then chooses to accomplish this goal first.

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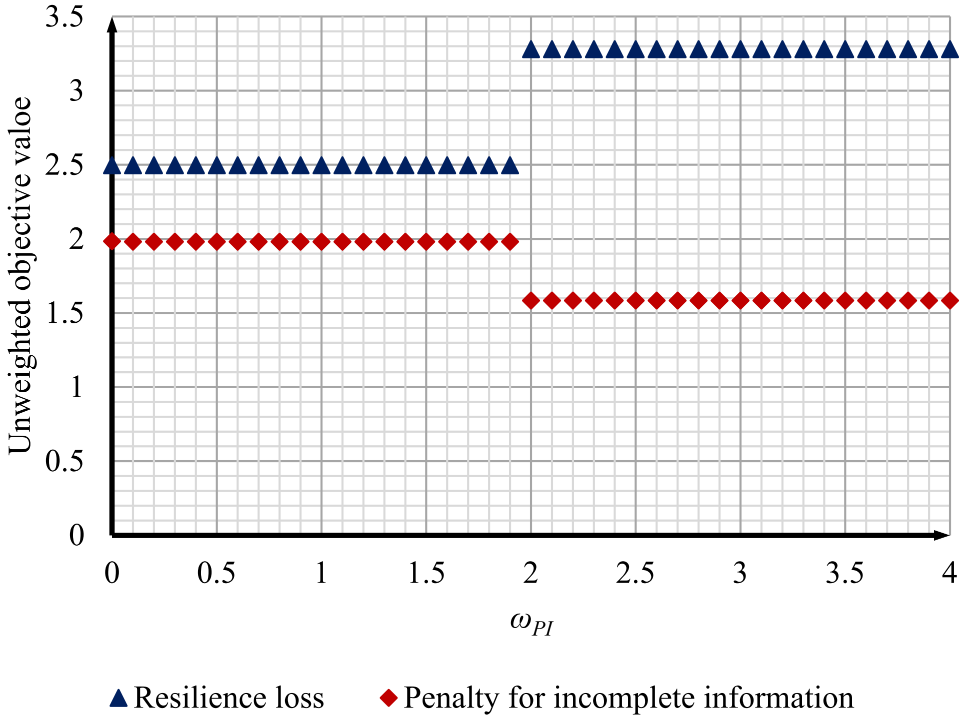

Figure 4.5 Unweighted objective value with different value of ω_{PI}

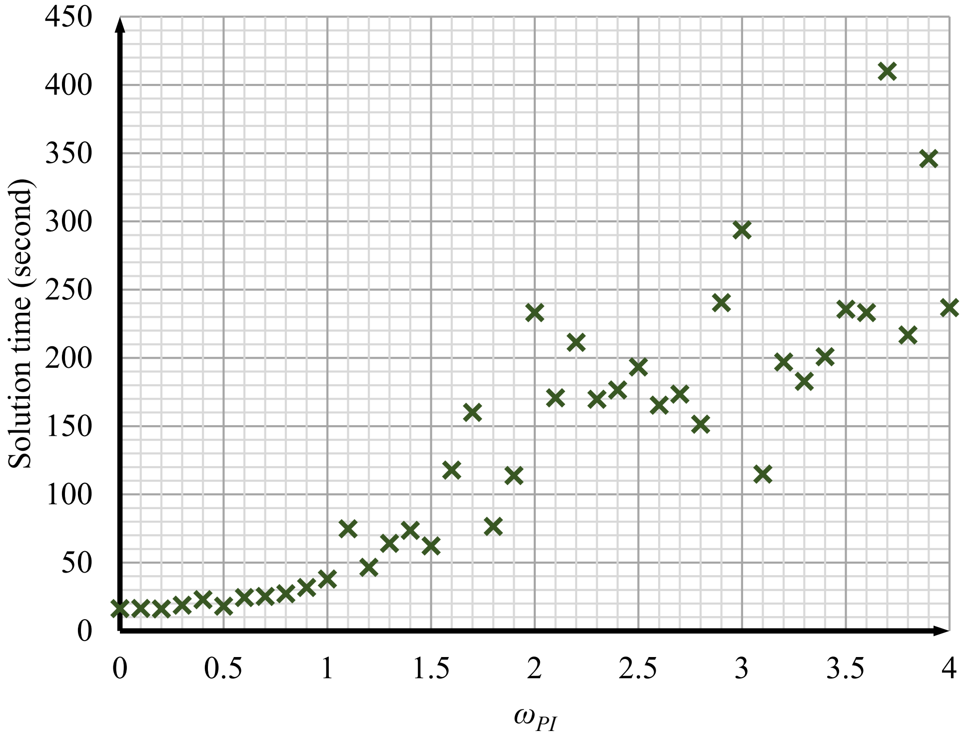

Figure 4.6 Solution time for severe telecommunication disruption

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Table 4.6 Restoration schedule for $\omega_{PI} = 0.5$

Time stage	Roadway	Electric power	Telecommunication
0→ 1	28 ⟷ 36	25 ⟷ 27	25 ⟷ 27
1→ 2	36 ⟷ 35	28 ⟷ 27	28 ⟷ 27
2→ 3	28 ⟷ 27	28 ⟷ 29	28 ⟷ 36
3→ 4	25 ⟷ 27	35 ⟷ 29	41 ⟷ 18
4→ 5	33 ⟷ 34		23 ⟷ 20
5→ 6	34 ⟷ 32	18 ⟷ 17	35 ⟷ 38
6→ 7			18 ⟷ 15
7→ 8			
8→ 9			

Table 4.7 Restoration schedule for $\omega_{PI} = 3.5$

Time stage	Roadway	Electric power	Telecommunication
0→ 1	28 ⟷ 36	25 ⟷ 27	18 ⟷ 15
1→ 2	35 ⟷ 38	28 ⟷ 27	18 ⟷ 33
2→ 3	28 ⟷ 27	35 ⟷ 29	23 ⟷ 20
3→ 4	25 ⟷ 27	28 ⟷ 29	25 ⟷ 27
4→ 5		23 ⟷ 20	28 ⟷ 27
5→ 6			28 ⟷ 36
6→ 7		27 ⟷ 29	35 ⟷ 38
7→ 8			
8→ 9			

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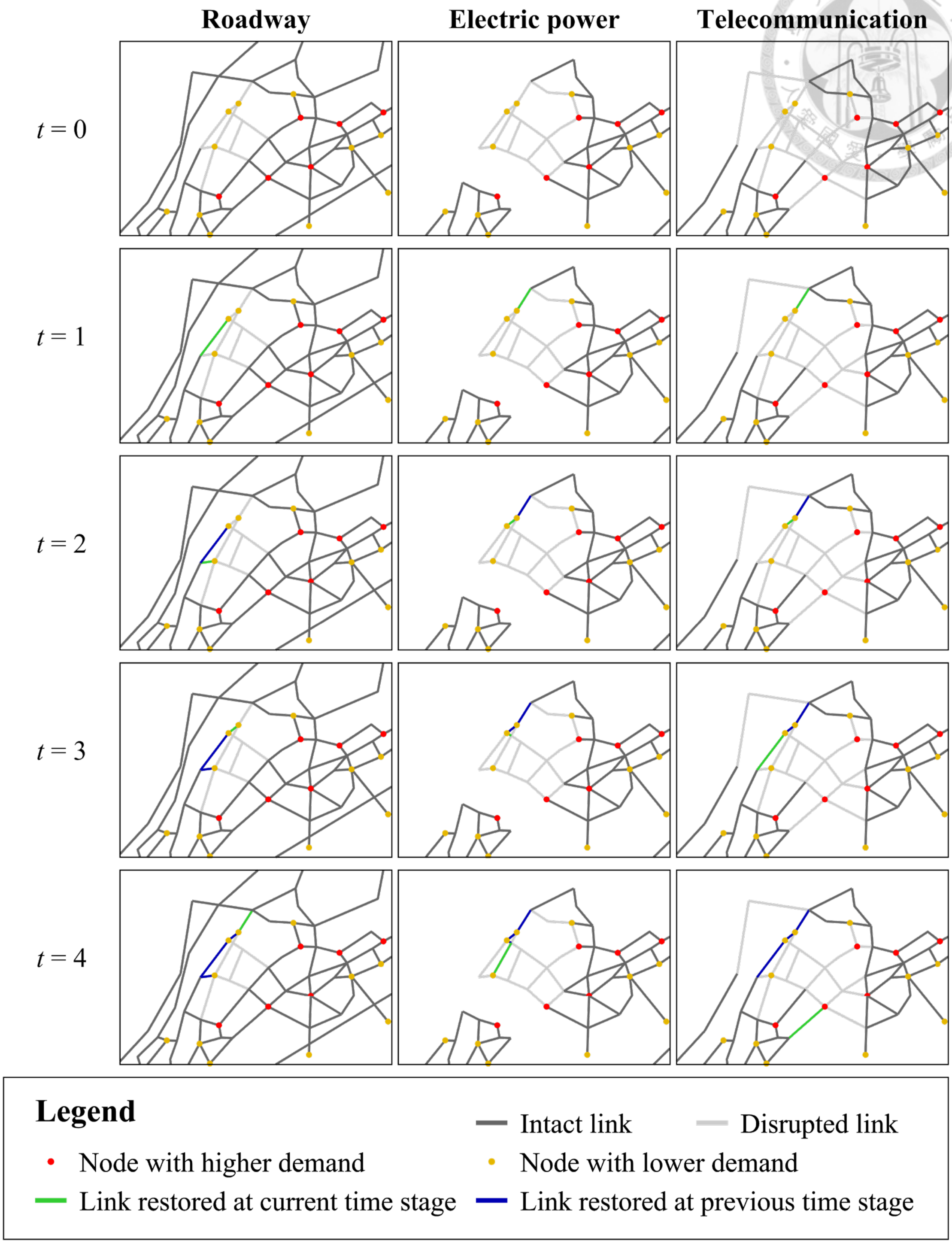

Figure 4.7 Restoration schedule for $\omega_{PI} = 0.5$ ($t = 0 \sim 4$)

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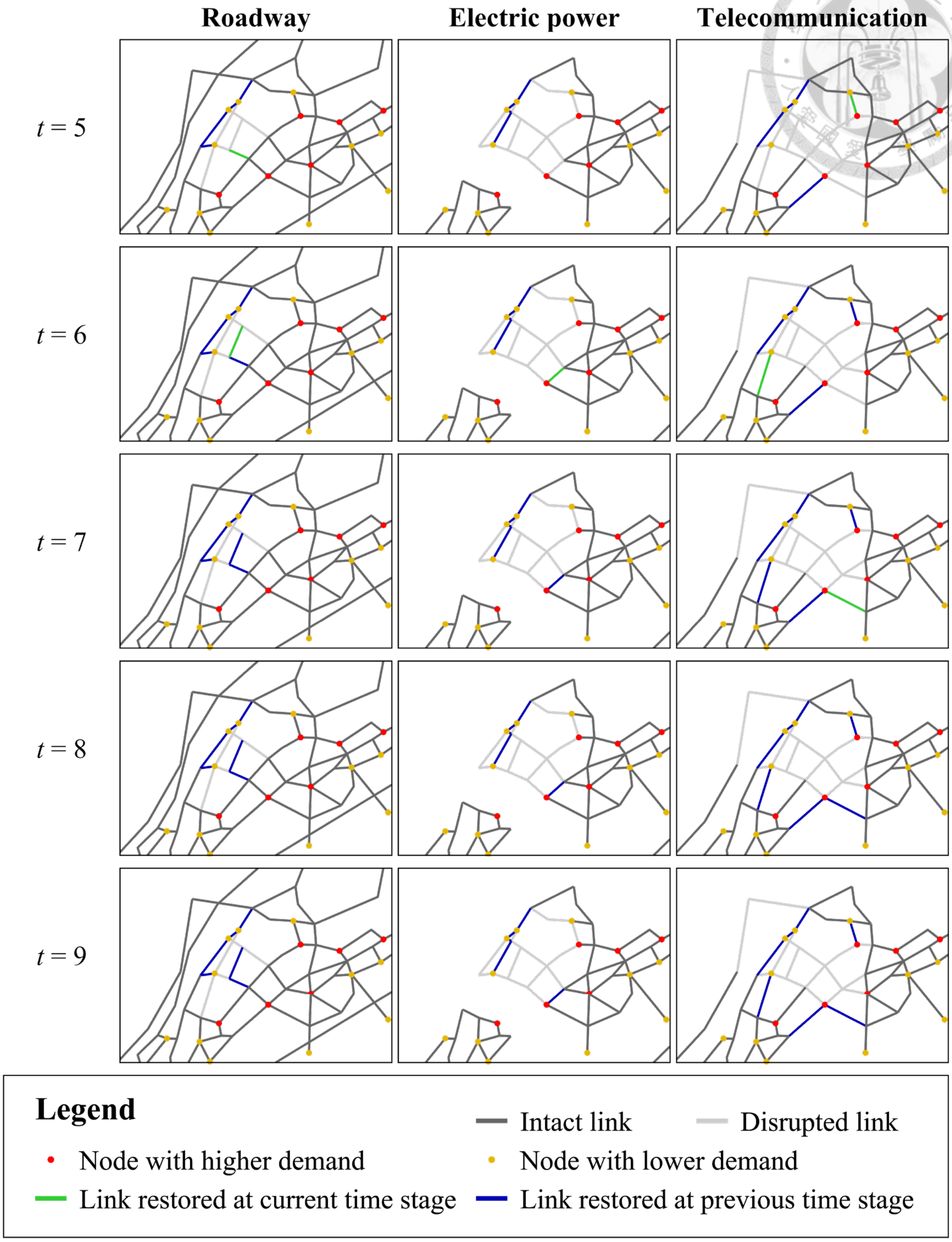

Figure 4.8 Restoration schedule for $\omega_{PI} = 0.5$ ($t = 5 \sim 9$)

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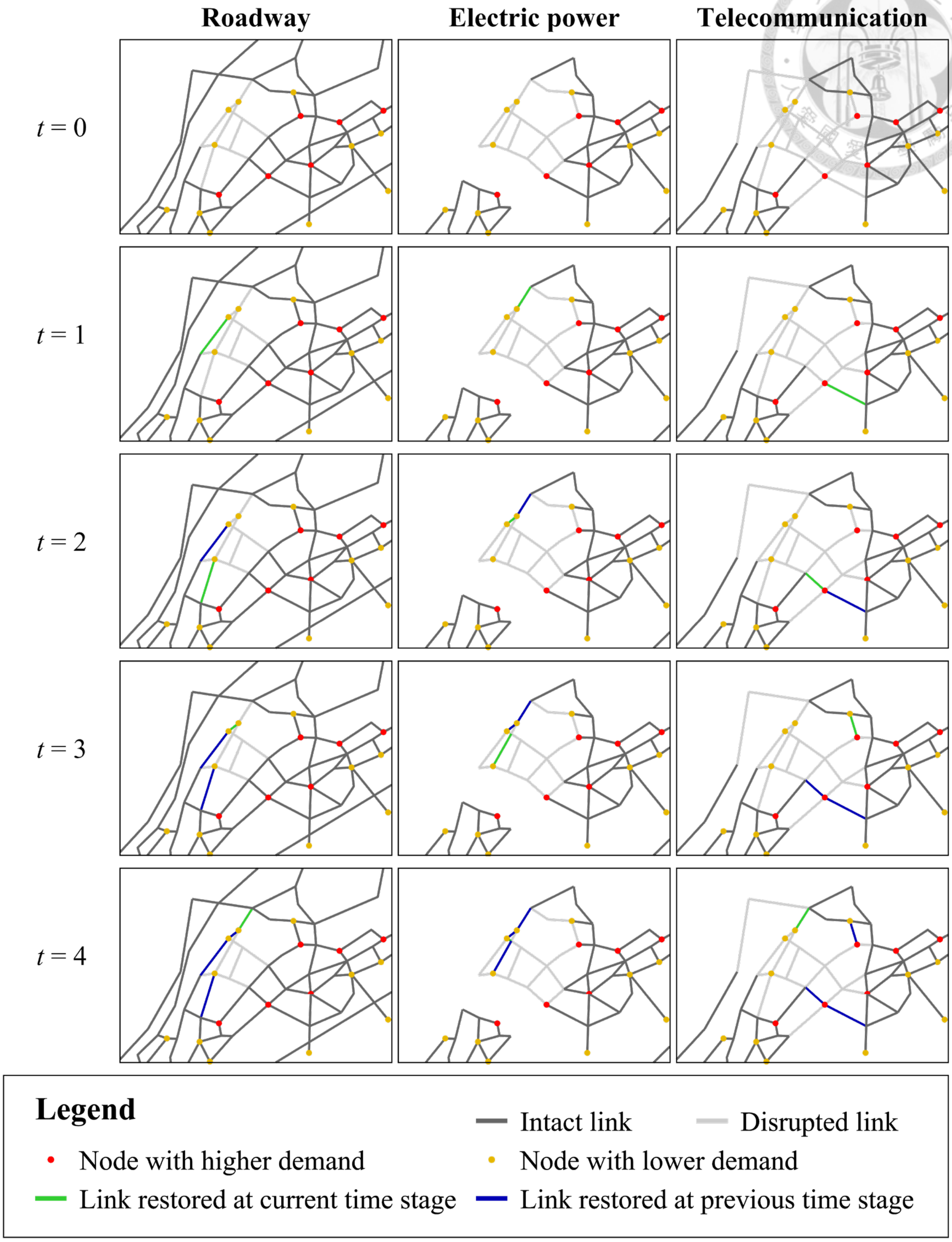

Figure 4.9 Restoration schedule for $\omega_{PI} = 3.5$ ($t = 0 \sim 4$)

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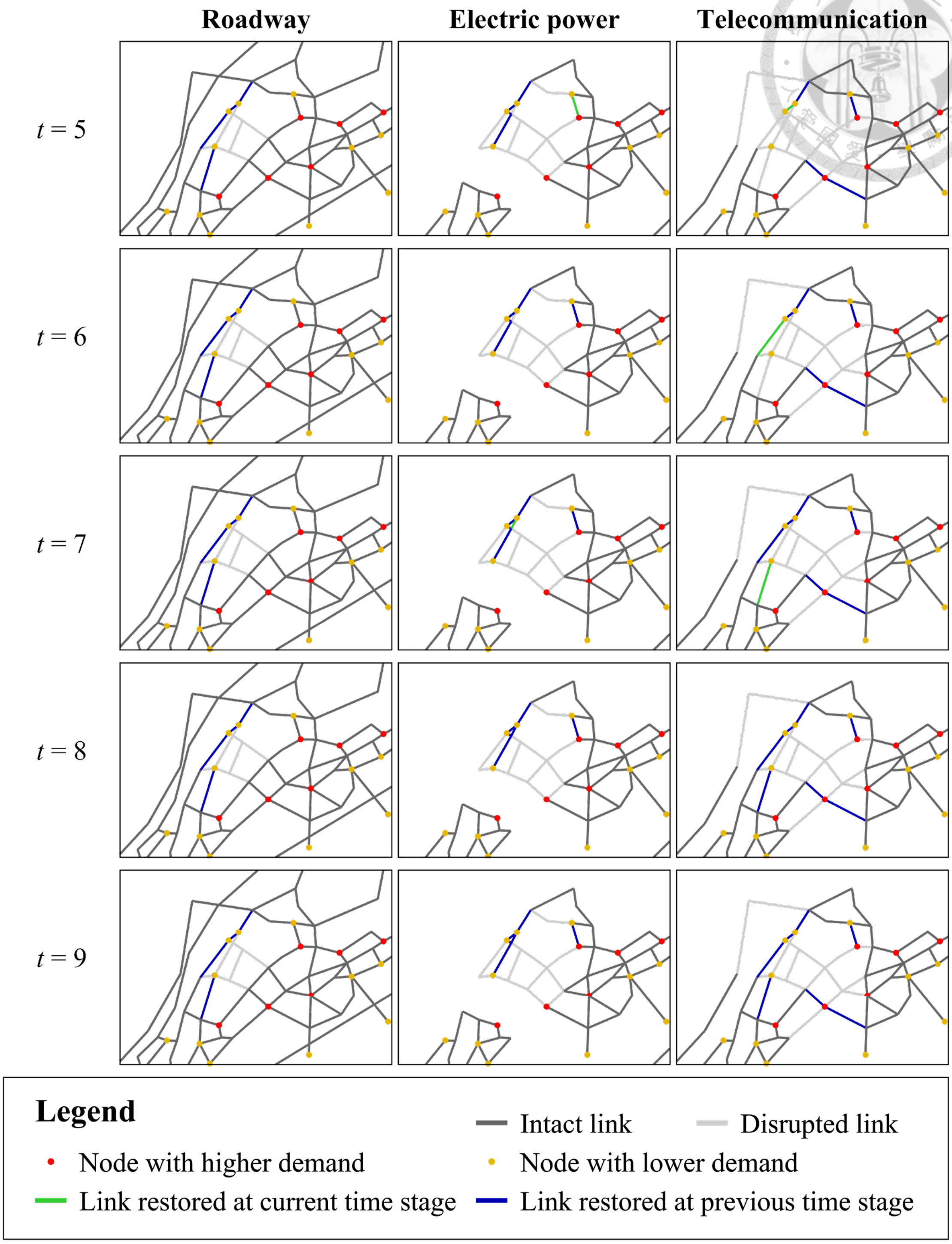

Figure 4.10 Restoration schedule for $\omega_{PI} = 3.5$ ($t = 5 \sim 9$)

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4.3 Case study: severe roadway disruption

When the roadway network is disrupted with severe damage, the manager of the restoration process has to tradeoff between the restoration of the roadway network and the connectivity of the restoration crews for other infrastructure networks. Hence, we assume a disruption with severe damage to the roadway network in order to emphasize the restoration interdependency between the roadway network and other networks.

In this case, the restoration interdependency is manifested through the comparison between the results from the inclusion and exclusion of the constraints regarding the restoration interdependency. For the scenario excluding the restoration interdependency, the constraints (14)-(16), (27), and (34)-(36) are omitted.

4.3.1 Parameters

The distribution of the disrupted links in each infrastructure network is displayed in Figure 4.11, while the number of the failed links in each network is designated as follows. $\|R^r\| = 43, \|R^e\| = 17, \|R^c\| = 20.$ Moreover, the penalty of the incomplete information is ignored in this case ($\omega_{PI} = 0$), and other parameters for the model are displayed in Table 4.8.

Table 4.8 Parameters for severe roadway disruption

Parameter	Value
Number of time stages	15
t_h	14
b_i	6
w_r	1
w_p	1
w_c	1
ω_{RL}	1
ω_{PI}	0

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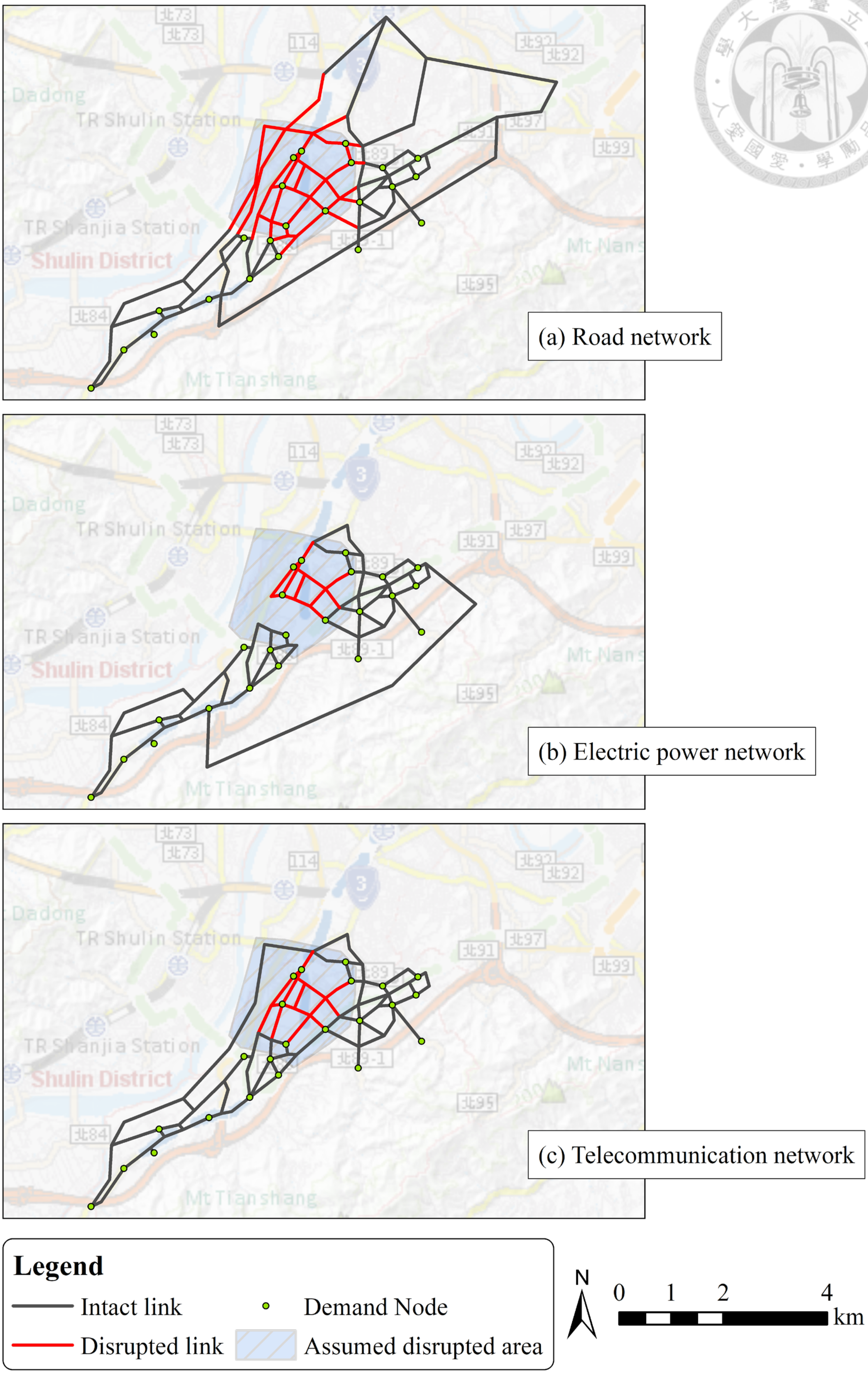

Figure 4.11 Disrupted links for severe roadway disruption

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4.3.2 Feasibility of restoration process

The result of this case study manifests the importance of the restoration interdependency when the restoration schedule includes the planning for restoring the roadway network while the restoration crews also use the roadway network as the routes toward the disrupted components. If we drop the constraints (14)-(16), (27), and (34)-(36) regarding the restoration interdependency, the optimal restoration schedules are summarized in Table 4.9, while the solution time for each scenario is 1,636.88 seconds for including the restoration interdependency and 12,575.05 seconds for excluding it. Moreover, Figure 4.12 shows that the scenario excluding the restoration interdependency mostly results in higher total performance in all time stages. Hence, the result seems to have higher system performance when excluding the restoration interdependency: that is, the resilience loss is lower, while the solution time is higher because of the looser feasibility from fewer constraints.

However, when we observe the restoration schedules in detail, which are listed in Table 4.10 and Table 4.11, and presented from Figure 4.13 to Figure 4.18, the amount of the unmet demand is underestimated when excluding the restoration interdependency. From Figure 4.13, it can be observed that the electric power restoration crew does not restore any failed links when t = 1 because they are unreachable through the roadway network. In contrast, from Figure 4.16 to Figure 4.18, the model excluding the restoration interdependency schedules the infeasible restoration for the electric power links and the telecommunication links which are inaccessible for the restoration crews through the roadway network. Comparing the results of restoration schedules including and excluding the restoration interdependencies, the proposed model regarding the restoration interdependency outputs a more realistic restoration schedule to provide a more accurate

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assessment of the resilience of the multiple infrastructure networks.

Table 4.9 Summary of two scenarios

	Resilience loss (unweighted)	**Total performance loss (unweighted)**		
		Roadway	**Electric power**	**Telecommunication**
Include restoration interdependency	3.9585	2.7645	0.4361	0.7579
Exclude restoration interdependency	3.4232	2.5399	0.3097	0.5737

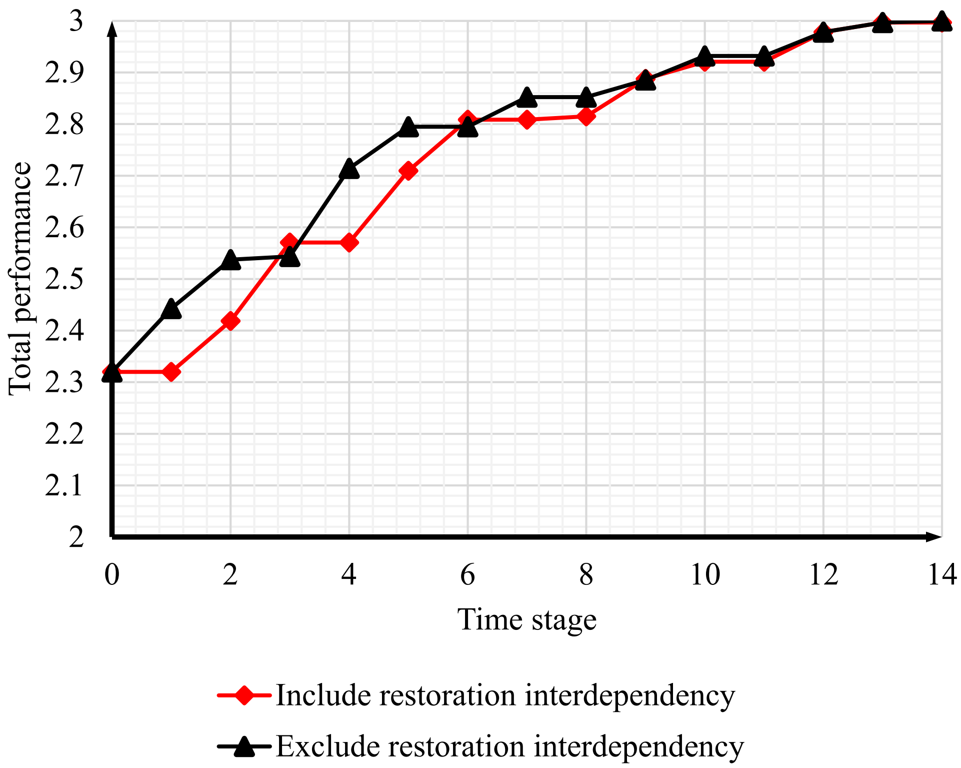

Figure 4.12 Performance change throughout time stages

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Table 4.10 Restoration schedule with restoration interdependency

Time stage	Roadway	Electric power	Telecommunication
0→ 1	31 ⟷ 25		
1→ 2	25 ⟷ 27	25 ⟷ 27	25 ⟷ 27
2→ 3	19 ⟷ 20	28 ⟷ 27	28 ⟷ 27
3→ 4	27 ⟷ 29	27 ⟷ 29	27 ⟷ 29
4→ 5	35 ⟷ 29	35 ⟷ 29	35 ⟷ 29
5→ 6	28 ⟷ 27		35 ⟷ 38
6→ 7	43 ⟷ 41		20 ⟷ 21
7→ 8	41 ⟷ 18		36 ⟷ 35
8→ 9	66 ⟷ 47		18 ⟷ 33
9→10	23 ⟷ 30	29 ⟷ 32	35 ⟷ 34
10→11	42 ⟷ 40		
11→12	40 ⟷ 37		
12→13	23 ⟷ 20		
13→14	35 ⟷ 38		

Table 4.11 Restoration schedule without restoration interdependency

Time stage	Roadway	Electric power	Telecommunication
0→ 1	19 ⟷ 20	25 ⟷ 27	25 ⟷ 27
1→ 2	18 ⟷ 17	28 ⟷ 27	28 ⟷ 27
2→ 3	17 ⟷ 12	36 ⟷ 35	36 ⟷ 39
3→ 4	66 ⟷ 47	28 ⟷ 36	28 ⟷ 36
4→ 5	23 ⟷ 30	35 ⟷ 34	36 ⟷ 35
5→ 6	37 ⟷ 33		35 ⟷ 29
6→ 7	18 ⟷ 33		
7→ 8	25 ⟷ 27		29 ⟷ 32
8→ 9	31 ⟷ 25		34 ⟷ 32
9→10	28 ⟷ 27		
10→11	38 ⟷ 42	33 ⟷ 34	
11→12	35 ⟷ 38		27 ⟷ 29
12→13	23 ⟷ 20		
13→14	38 ⟷ 37		

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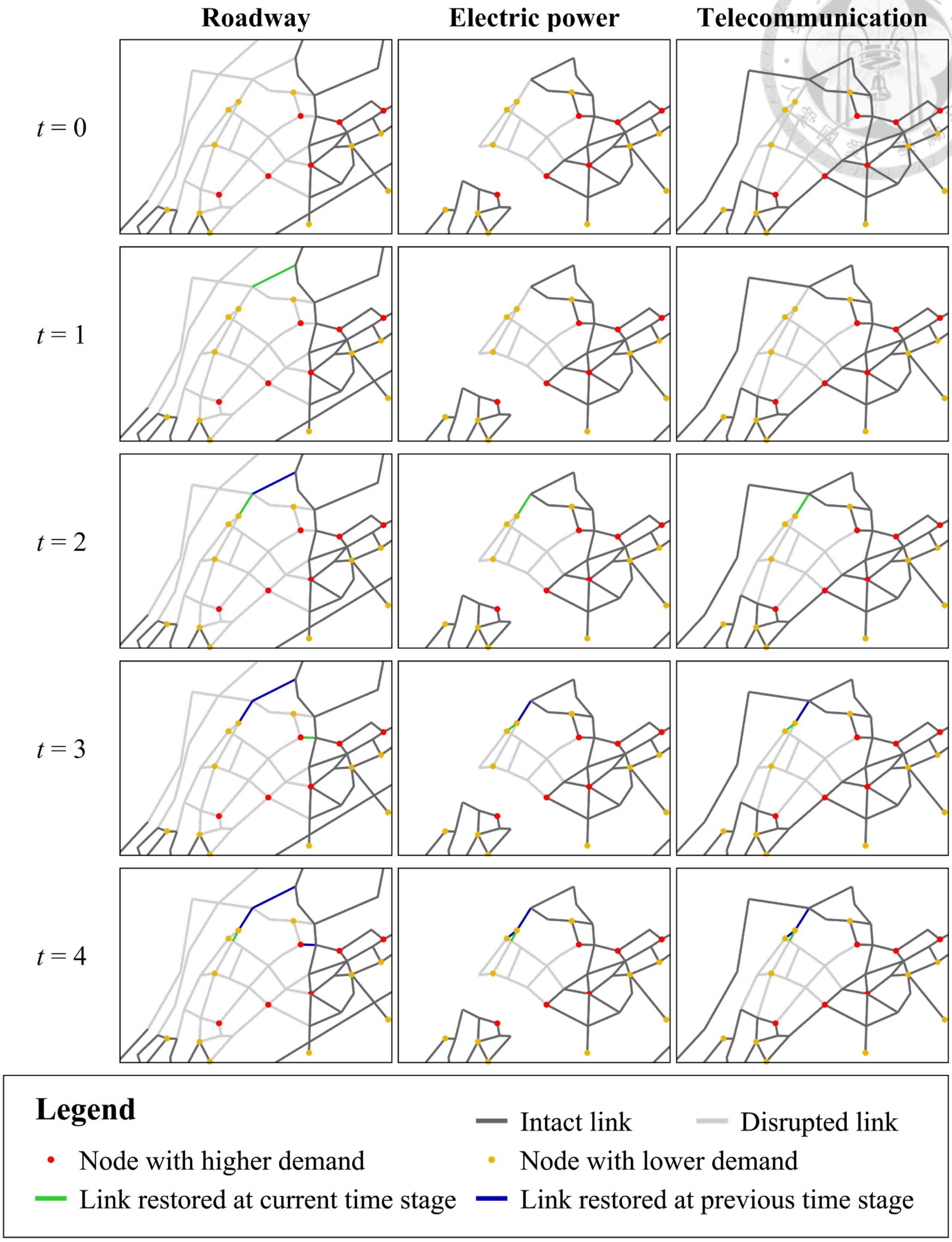

Figure 4.13 Restoration schedule with restoration interdependency ($t = 0 \sim 4$)

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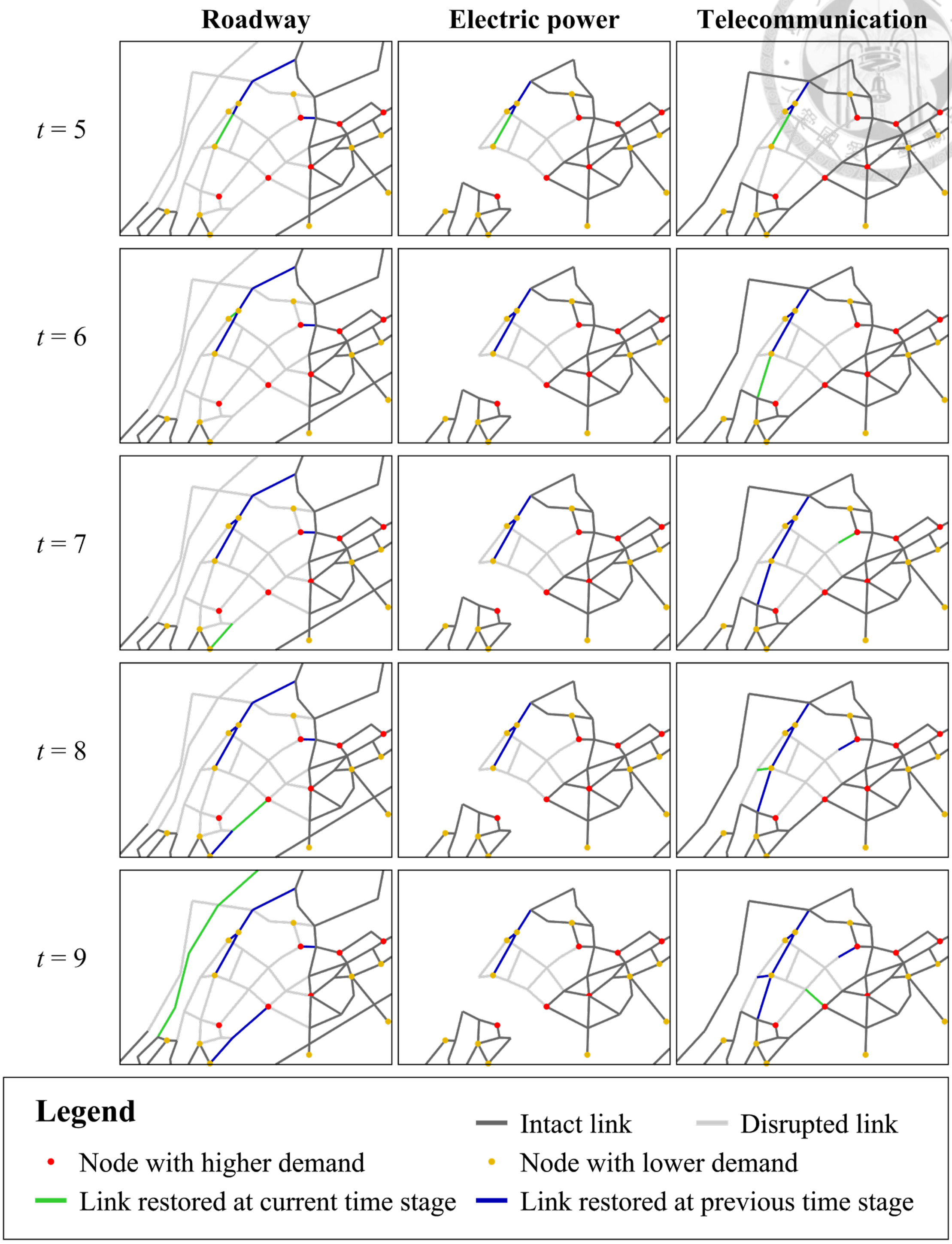

Figure 4.14 Restoration schedule with restoration interdependency ($t = 5 \sim 9$)

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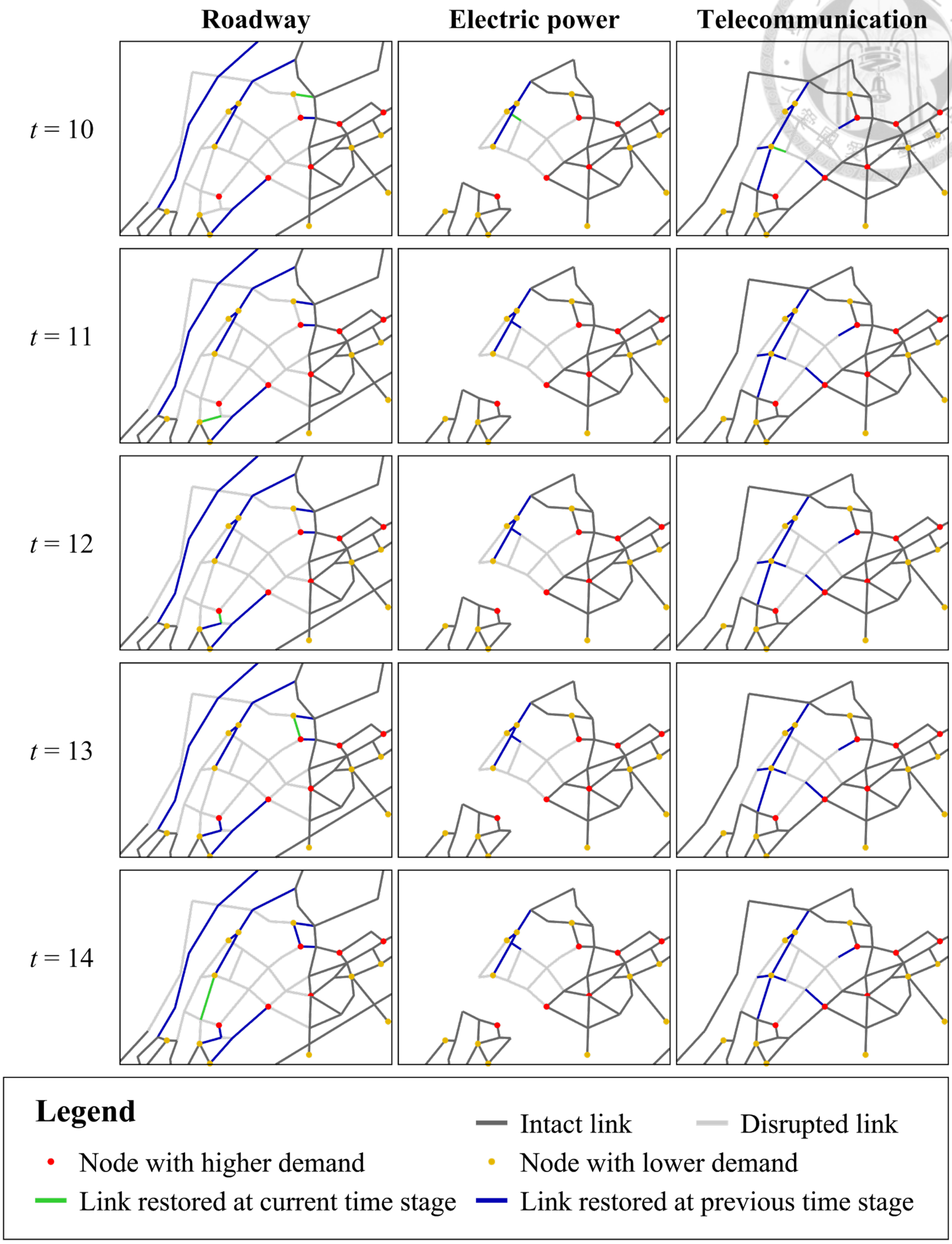

Figure 4.15 Restoration schedule with restoration interdependency ($t = 10 \sim 14$)

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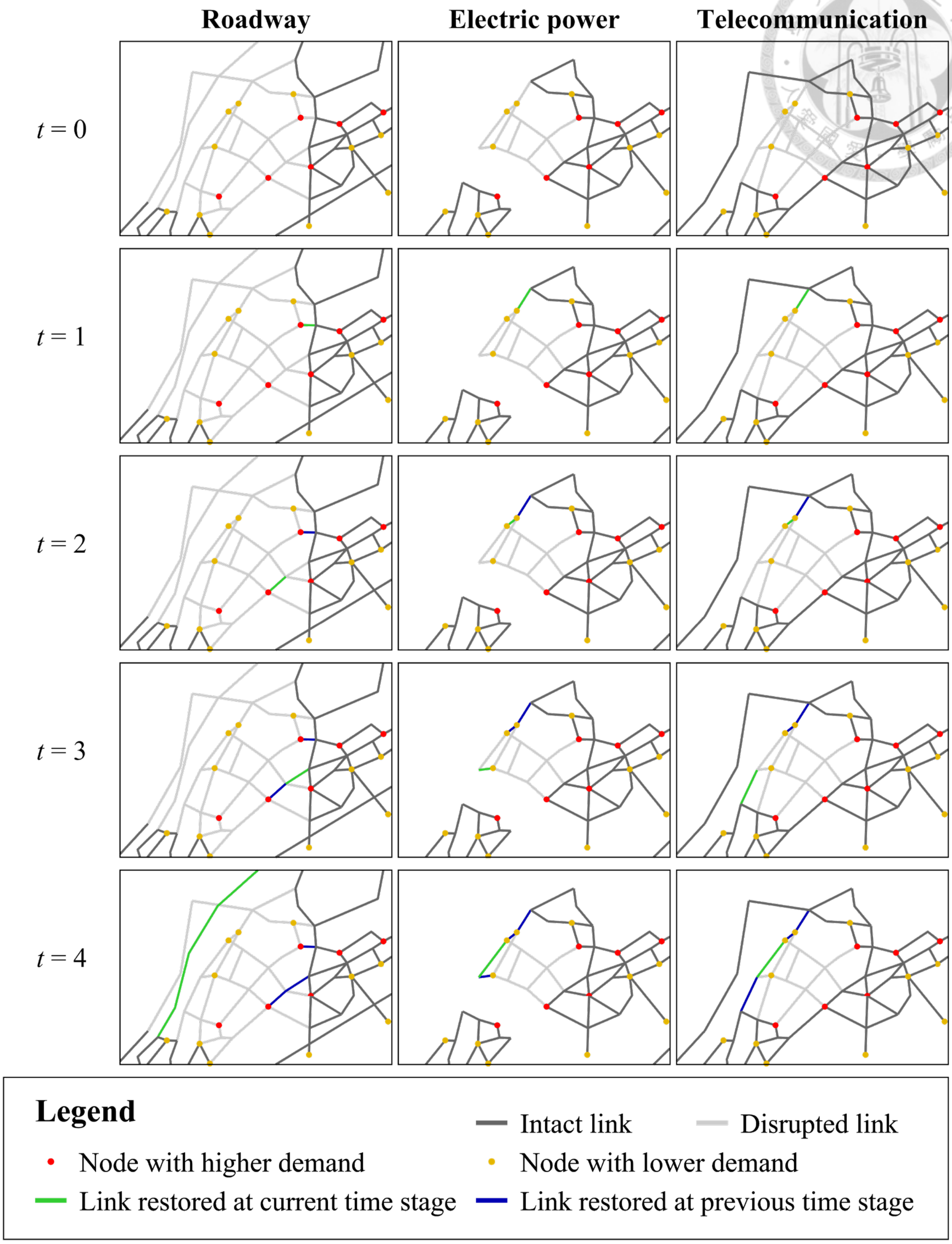

Figure 4.16 Restoration schedule without restoration interdependency ($t = 0 \sim 4$)

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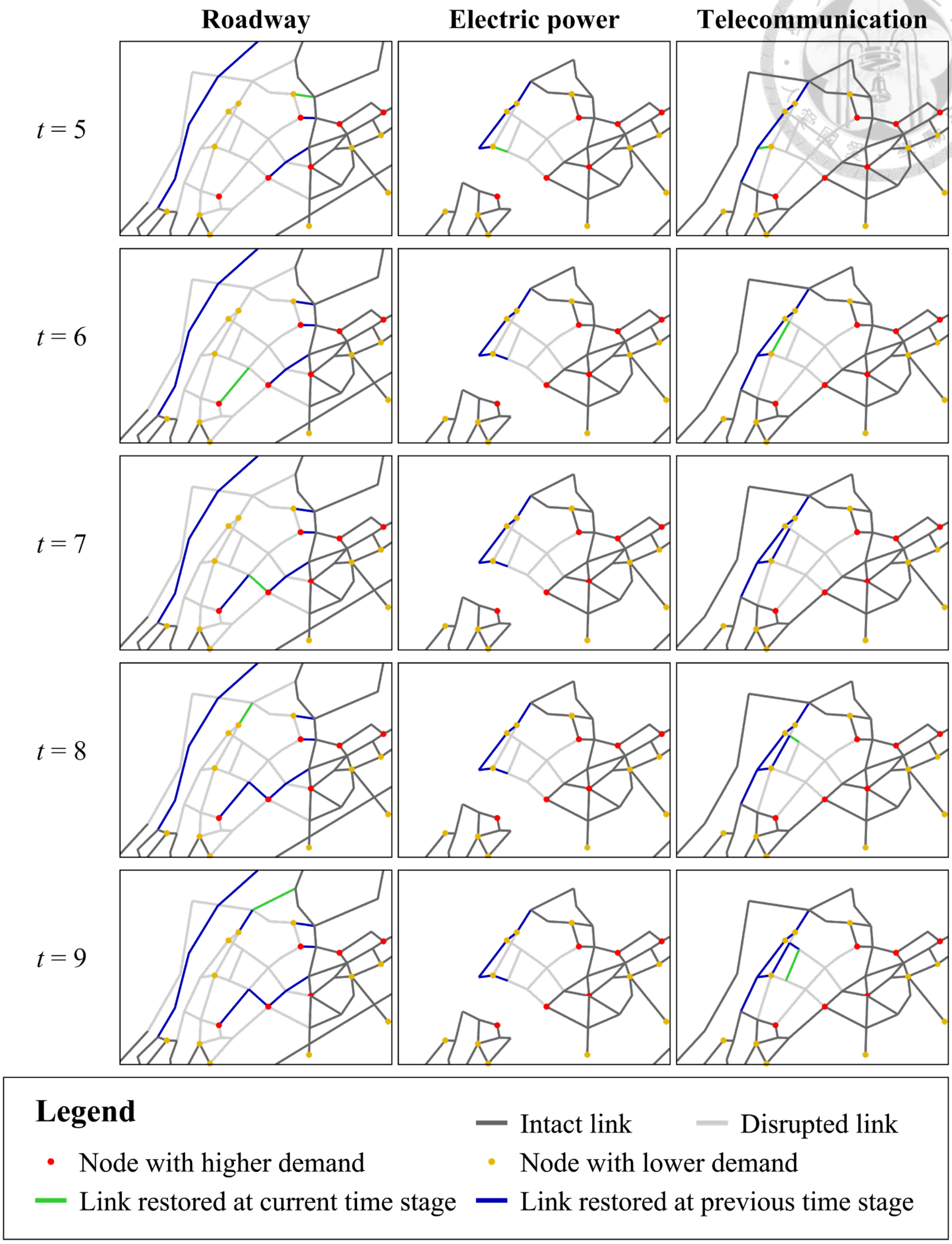

Figure 4.17 Restoration schedule without restoration interdependency ($t = 5 \sim 9$)

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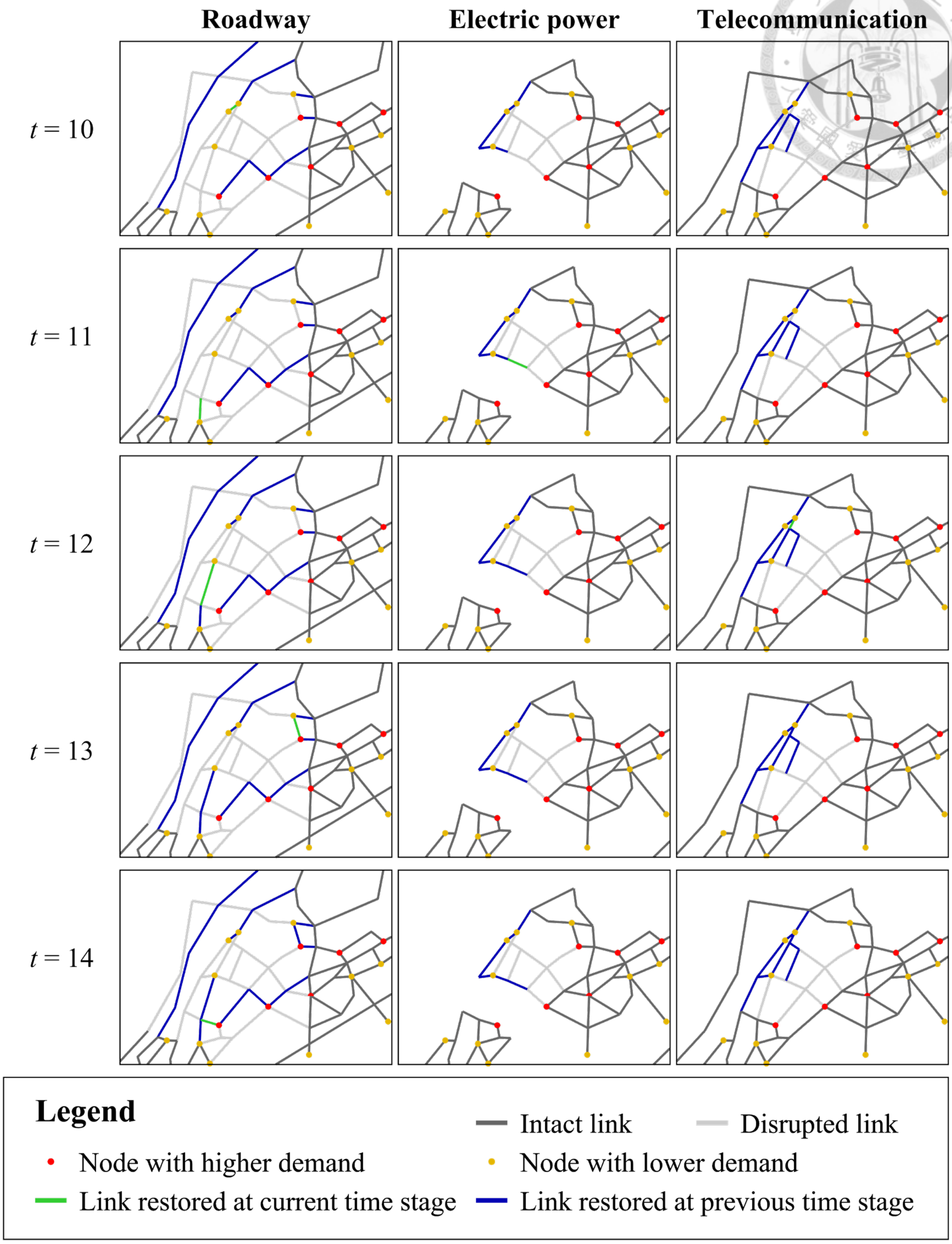

Figure 4.18 Restoration schedule without restoration interdependency ($t = 10 \sim 14$)

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CHAPTER 5

CONCLUSIONS

5.1 Research Summary

Due to the rising concern of disaster response and the assessment of infrastructure resilience, it is essential to holistically model the performance change of interdependent infrastructure systems throughout the restoration phase after a disruption resulting from disaster impact. In order to analyze the performance of such complicated infrastructure systems, the interdependencies embedded among infrastructure systems has to be described explicitly. Previous studies have been analyzing the interdependencies regarding the functional relationship among system components. This study focuses on restoration interdependencies concerning the accessibility through the roadway network for restoration units of each infrastructure network. Additionally, the cyber interdependencies between electric power and telecommunication networks are also discussed in the numerical experiments. Then, the expected unmet demand and the probability distribution of the demand in the roadway network are presented to address the incomplete information of the amount of demand when the telecommunication services are failed.

In order to combine the abovementioned concerns, this study develops the mixed integer quadratic programming model to optimize the restoration schedule for improved system resilience based on the network flow method. In the developed model, the objective function with the resilience loss and the penalty for the incomplete information is introduced, while the part of resilience loss includes quadratic terms due to the calculation of the expected unmet demand. Moreover, the developed model applied the

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network flow method not only to solve the delivery of the commodity in each infrastructure network but also calculate the connectivity between the disrupted links and the depot of the restoration crews in each stage. Therefore, the feasibility of the restoration acts can be evaluated in the stage bases using the network flow method. Besides, the other kinds of interdependencies are described through the constraints in the model. Then, the restoration schedule of the disrupted interdependent infrastructure networks can be modeled, and four types of interdependencies are all covered in the model.

Using the developed model and the test infrastructure networks of Tucheng District, we analyze the resilience of the interdependent infrastructure systems with two cases of service disruption. The analysis results show that the developed model is capable of describing the cyber interdependency between the telecommunication and the roadway networks. In this case, we conceive that the correct amount of demand in the roadway network is unavailable if the telecommunication service is disrupted and failed. The experiment of the cases shows the tradeoff between minimizing resilience loss and eliminating the incomplete information. Then, this study implemented another case to demonstrate the capability of describing the restoration interdependency explicitly. By contrast, if the optimization of the restoration schedule does not include the restoration interdependencies, it can overestimate the resilience of the infrastructure systems because some parts of the derived restoration schedule are not attainable.

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5.2 Future Study

In the future study, the discussion of the influence of the cyber interdependency to the supervisory control and data acquisition for the infrastructure systems can extend to the infrastructure other than roadway network. For example, the demand in the electric power network might be variable to the number of electric power users, while such information requires the telecommunication service to transmit efficiently.

Then, more types of interdependencies may need to be comprehensively factored, and the performance function evaluating each infrastructure system may need to be adjusted to reflect their functional and network characteristics better. For instance, the factor of the traffic signal control and the police directing traffic can differ the capacity and link travel time of the roadway links. However, the traffic signals require the electric power to be functional, or it would cause a delay when passing the intersection and increase the link travel time. Herein, this type of physical interdependency is not covered in this study, and it can be discussed in the future study. Moreover, the performance function for the roadway network should also include link travel time other than connection merely because the capacity and the efficiency of the roadway network are also indicated the performance and the functionality of the network. However, the inclusion of the travel time may let the mathematical model become highly non-linear.

Furthermore, the performance measured in this study is only confined to the ability to deliver emergency logistics. In the future study, the performance of the infrastructure systems can extend to the normal functionality, such as the normal traffic in the roadway network, including the OD pattern for the nodes in the disrupted area. Hence, the consideration of the capacity becomes essential, and the inclusion of the link travel time for the roadway network becomes necessary.

doi:10.6342/NTU201904193

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REFERENCE

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning, 100*, 341-343. doi:10.1016/J.LANDURBPLAN.2011.02.021

Almoghathawi, Y., Barker, K., and Albert, L. A. (2019). Resilience-driven restoration model for interdependent infrastructure networks. *Reliability Engineering & System Safety, 185*, 12-23. doi:10.1016/J.RESS.2018.12.006

Batabyal, A. A., Gunderson, L. H., and Pritchard, L. (2007). Resilience and the Behavior of Large-Scale Systems. *Journal of Range Management, 56*, 301. doi:10.2307/4003824

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra, 19*, 733-752. doi:10.1193/1.1623497

Cavdaroglu, B., Hammel, E., Mitchell, J. E., Sharkey, T. C., and Wallace, W. A. (2013). Integrating restoration and scheduling decisions for disrupted interdependent infrastructure systems. *Annals of Operations Research, 203*, 279-294. doi:10.1007/s10479-011-0959-3

Çelik, M., Ergun, Ö., and Keskinocak, P. (2015). The Post-Disaster Debris Clearance Problem Under Incomplete Information. *Operations Research, 63*, 65-85. doi:10.1287/opre.2014.1342

doi:10.6342/NTU201904193

Fang, Y.-P. and Sansavini, G. (2019). Optimum post-disruption restoration under uncertainty for enhancing critical infrastructure resilience. *Reliability Engineering and System Safety, 185*, 1-11. doi:10.1016/j.ress.2018.12.002

Fang, Y.-P. and Zio, E. (2019). An adaptive robust framework for the optimization of the resilience of interdependent infrastructures under natural hazards. *European Journal of Operational Research, 276*, 1119-1136. doi:10.1016/J.EJOR.2019.01.052

Fiksel, J. (2003). Designing Resilient, Sustainable Systems. *Environmental Science and Technology, 37*, 5330-5339. doi:10.1021/es0344819

Ghosn, M., Dueñas-Osorio, L., Frangopol, D. M., McAllister, T. P., Bocchini, P., Manuel, L., Ellingwood, B. R., Arangio, S., Bontempi, F., Shah, M., Akiyama, M., Biondini, F., Hernandez, S., and Tsiatas, G. (2016). Performance Indicators for Structural Systems and Infrastructure Networks. *Journal of Structural Engineering, 142*, F4016003. doi:10.1061/(ASCE)ST.1943-541X.0001542

González, A. D., Dueñas-Osorio, L., Sánchez-Silva, M., and Medaglia, A. L. (2016). The Interdependent Network Design Problem for Optimal Infrastructure System Restoration. *Computer-Aided Civil and Infrastructure Engineering, 31*, 334-350. doi:10.1111/mice.12171

Henry, D. and Emmanuel Ramirez-Marquez, J. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering & System Safety, 99*, 114-122. doi:10.1016/J.RESS.2011.09.002

doi:10.6342/NTU201904193

Hosseini, S., Barker, K., and Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety, 145*, 47-61. doi:10.1016/j.ress.2015.08.006

Karakoc, D. B., Almoghathawi, Y., Barker, K., González, A. D., and Mohebbi, S. (2019). Community resilience-driven restoration model for interdependent infrastructure networks. *International Journal of Disaster Risk Reduction*, 101228. doi:10.1016/j.ijdrr.2019.101228

Lee, E. E., Mitchell, J. E., and Wallace, W. A. (2007). Restoration of services in interdependent infrastructure systems: A network flows approach. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews, 37*, 1303-1317. doi:10.1109/TSMCC.2007.905859

Nan, C. and Sansavini, G. (2017). A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering & System Safety, 157*, 35-53. doi:10.1016/J.RESS.2016.08.013

NTPC iMAP. Retrieved from https://map.ntpc.gov.tw/

Nurre, S. G., Cavdaroglu, B., Mitchell, J. E., Sharkey, T. C., and Wallace, W. A. (2012). Restoring infrastructure systems: An integrated network design and scheduling (INDS) problem. *European Journal of Operational Research, 223*, 794-806. doi:10.1016/J.EJOR.2012.07.010

doi:10.6342/NTU201904193

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety, 121*, 43-60. doi:10.1016/J.RESS.2013.06.040

Rinaldi, S. M., Peerenboom, J. P., and Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine, 21*, 11-25. doi:10.1109/37.969131

Shan, S. (2015). Rescuers search for missing in Wulai. *Taipei Times*.

Sharkey, T. C., Nurre, S. G., Nguyen, H., Chow, J. H., Mitchell, J. E., and Wallace, W. A. (2016). Identification and Classification of Restoration Interdependencies in the Wake of Hurricane Sandy. *Journal of Infrastructure Systems, 22*, 04015007. doi:10.1061/(ASCE)IS.1943-555X.0000262

Statistic on population in June 2018**. (2018).** from Department of Civil Affairs, New Taipei City Government

Vugrin, E. D., Warren, D. E., Ehlen, M. A., and Camphouse, R. C. (2010). A Framework for Assessing the Resilience of Infrastructure and Economic Systems. *Sustainable and Resilient Critical Infrastructure Systems*, 77-116. doi:10.1007/978-3-642-11405-2_3

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety, 141*, 5-9. doi:10.1016/J.RESS.2015.03.018

doi:10.6342/NTU201904193

Zhang, P. and Peeta, S. (2011). A generalized modeling framework to analyze interdependencies among infrastructure systems. *Transportation Research Part B: Methodological, 45*, 553-579. doi:10.1016/J.TRB.2010.10.001

Zhang, X., Mahadevan, S., Sankararaman, S., and Goebel, K. (2018). Resilience-based network design under uncertainty. *Reliability Engineering & System Safety, 169*, 364-379. doi:10.1016/J.RESS.2017.09.009

doi:10.6342/NTU201904193