Quantifying the Resilience of Emergency Response Networks to Infrastructure Interruptions through an Enhanced Meta-Network Based Framework

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ABSTRACT

Building effective and resilient emergency response networks (ERN) is essential for the rapid recovery of interrupted infrastructure during extreme events. Aiming at providing a critical benchmarking and implementable strategies for improving ERN resilience, this study proposes a novel framework to systematically quantify ERN resilience through an enhanced Meta-Network Analysis (MNA)-based approach. This framework firstly applies the MNA approach to conceptualize the complex emergency response as three-stage “Agent-Task-Resource-Knowledge” (A-T-R-K) meta-networks, representing connections among stakeholders, response tasks, emergency resources, and professional knowledge. Then, suitable meta-network measures (i.e., natural connectivity, average speed, overall task completion, and the integrative metric of task resource/knowledge needs and task resource/knowledge waste) generated accordingly are used to quantify ERN resilience capacities—robustness, rapidity, resourcefulness, and redundancy. This proposed framework is validated through a case study of the emergency response to the Manchester Arena attack in the United Kingdom. The dynamic change of ERN resilience over time as well as possible causes within the case scenario are analyzed. Additionally, its resilience improvement strategies and the advantages of the MNA approach are discussed. Overall, this enhanced MNA-based framework promotes an understanding of emergency response performance through systematically conceptualizing the complex ERN structure and dynamically quantifying ERN resilience capacities. Lessons learned from historical disasters provide decision-makers with implementable support to advance their collaboration and knowledge sharing, and optimize resources and tasks for enhancing resilience in future infrastructure operation and emergency response activities.

Keywords: Emergency response; Network modeling; Network resilience; Infrastructure; Manchester Arena attack

INTRODUCTION

Infrastructure—the backbone of our society (Nan and Sansavini 2017; Vaughan–Morris 2012)—provides lifeline services (e.g., power, water, gas, communication, and transportation) as well as maintains social services (e.g., public health, education, entertainment, and finance) (Aldrich 2017; Jacobson 2017; Klinenberg 2018; Montgomery 2013). Following disasters, effective response actions are critical for the rapid recovery of interrupted infrastructure systems, thereby sustaining their functionality (Abbasi and Kapucu 2012; Comfort and Haase 2006). Notably, effective emergency responses require that all stakeholders coordinate and collaborate effectively in performing well-assigned response tasks, obtaining and allocating emergency resources, and learning and exchanging professional knowledge (Li and Ji 2021; Zhu and Mostafavi 2018; Kapucu and Hu 2016). From the managerial perspective, all these involved critical entities (i.e., stakeholder, task, resource, and knowledge), as well as their interactions form an emergency response network (ERN) to carry out emergency response actions. Given the uncertainties (e.g., infrastructure vulnerability, weather conditions, and response strategies) in disasters, it is imperative to enhance the resilience of the ERN to infrastructure interruptions (Black and Spowage 2018; Comfort and Haase 2006; Dong et al. 2020).

Building upon the theories of resilience and networks, ERN resilience is defined as an emergency response network's capacity to provide required resources and knowledge support for planning, resisting, and absorbing the initial damage as well as rapidly recovering from the unexpected change (Hosseini et al. 2016; Lai and Hsu 2019). Quantitative measurement of network resilience provides a critical benchmarking for evaluating the performance of ERNs over the disaster prevention, disaster response, and function recovery stages (Bruneau et al. 2003; Ouyang et al. 2012), coupled with necessary remedies for resilience improvement (Vlacheas et al. 2013; Hu et al. 2022; Cutter 2003). Although previous research has focused on stakeholder/organization coordination of ERNs (Li and Ji 2021; Lai and Hsu 2019; Abbasi and Kapucu 2012; Kapucu 2006), few of them have clarified and visualized the complex interactions among all types of critical entities—stakeholders, response tasks, emergency resources, and professional knowledge (Choi et al. 2019; Zhu and Mostafavi 2018). In the theory of resilience, the resilience capacities of emergency response are usually manifested through four dimensions (referred to as 4Rs): *robustness, rapidity, resourcefulness, and redundancy* (Bruneau et al., 2003). Despite the efforts in investigating network metrics of ERNs, such as natural connectivity (Li and Ji 2021), the relative size of giant component (Osei-Asamoah and Lownes 2014), clustering coefficient (Kim et al. 2017), and overall task completion rate (Zhu and Mostafavi 2018), most of the studies still possess their limitation in systematically revealing the 4Rs. Taking a holistic view of network resilience and emergency response actions, there is a need to design quantitative network metrics suitable for combining complex interactions among stakeholders, tasks, resources, and knowledge as well as revealing 4Rs across the three-stage emergency response.

To bridge the aforementioned research gaps, this study aims to propose a novel framework for quantifying ERN resilience capacities, thereby enhancing emergency response performance and maintaining infrastructure functionality. This framework: (1) develops an enhanced meta-network analysis (MNA) approach for conceptualizing an actual ERN with the interactions among the entities (i.e., stakeholder, task, resource, and knowledge) and (2) quantifies the 4Rs utilizing suitable meta-network measures (i.e., natural connectivity, average speed, overall task completion, and the integrative metric of task resource/knowledge need and task resource/knowledge waste). The proposed framework is then fully applied to examine the Manchester Arena attack in the United Kingdom (UK). Following that, the derived meta-network resilience metrics are analyzed, and the strategies for ERN resilience improvement are identified. The proposed framework allows us to quantitatively assess the ERN resilience by compiling the 4Rs. Novel network metrics are developed analytically to represent the 4Rs capacities accordingly. The proposed framework together with the resilience measures can be customized for quantifying the ERN resilience under other emergency response scenarios for infrastructure interruptions, such as repair crew allocation for power outage restoration and hospital emergency management during the COVID-19 pandemic. In this sense, the systematically learned experience and knowledge are transferrable for future emergency response to infrastructure disruptions, thereby maintaining the functionality of infrastructure systems.

LITERATURE REVIEW

Emergency Response Networks for Infrastructure Disruptions, and Resilience Capacity

In case of disasters, effective and timely emergency responses are critical for infrastructure systems to sustain lifeline services and reduce damage loss (Abbasi and Kapucu 2012). Emergency response actions consist of various tasks, such as preparedness and emergency training (Kapucu 2008; Sermet and Demir 2019), evacuation (Huang et al. 2017; Georgiadou et al. 2010), healthcare provision (Zakrison et al.2020; Xiang et al. 2020), damage and risk assessment (Ghobarah et al. 1999; Shah et al. 2020; Bernal et al 2017), and restoration of infrastructure functionality (Chen and Ji 2021; Bai et al. 2021). Effectively performing complex response tasks usually requires that stakeholders with various roles and responsibilities collaborate for obtaining and allocating required emergency resources as well as learning and exchanging professional knowledge (Li et al. 2020b; Li and Ji 2021). From the managerial perspective, complex emergency response actions exhibit networked characteristics that involve various entities (i.e., stakeholder, task, resource, and knowledge) as well as their interactions (Comfort 2007; Zhu and Mostafavi 2018; Kapucu and Hu 2016)

In light of these complex networked characteristics, many efforts have been devoted to emergency response networks (ERNs) for protecting infrastructure systems. Specifically, most of these efforts have been focused on stakeholder/organization collaboration, in which representative studies include: (1) clarifying and modeling the stakeholder response network structures and revealing their basic characteristics (Hossain and Kuti 2010; Kim et al. 2017; Kapucu 2006); (2) examining the evolution of interorganizational response network structures and investigating high-performance network structures (Abbasi and Kapucu 2012; Comfort 2007; Nowell et al. 2018); and (3) investigating the network performance via network measures and exploring factors that influence network performance (Vasavada 2013; Li and Ji 2021; Lai and Hsu 2019). Despite the useful insights, these studies only deal with the one-dimension relationship of *"who interacts with whom, or what interacts with what"*. It's still difficult to reveal what resources or/and information are required by tasks and what resources or/and knowledge are captured by stakeholders. This modeling limitation prevents scholars from accurately conceptualizing ERN structure as well as measuring their performance (Zhu and Mostafavi 2018). Thus, multiple entities (i.e., stakeholder, task, resource, and knowledge), as well as their complex interactions, are desired to be integrated into ERNs.

The uncertain disaster environment (e.g., extreme weather, terrorist attack, and infectious disease) highlighted the importance of resilient ERNs to infrastructure interruptions. Accordingly, the public sector and academia have paid increasing attention to ERN resilience (Lai and Hsu 2019; Berkeley et al. 2010; Li and Ji 2021). As a typical social-ecological system, ERN operations not only depend upon their physical components (e.g., emergency resources) but also require social units (e.g., government agencies, private sectors, media, and communities) to take response actions (Comfort 2007; Eakin et al. 2017; Yu et al. 2016). The widely-accepted social-ecological system thinking emphasized the ability to absorb damages and to return to normal function levels as the resilience of a system (Folke 2006; Ouyang et al. 2012) and highlighted the system's self-organization and adaptive capacity (Folke 2006). Given the time-dependent system functionality, Ouyang et al. (2012) further divided the emergency response cycle into three stages—disaster prevention stage, damage propagation, and function recovery stage. Building upon these conceptual resilience insights and ERN structures, this study defines the concept of ERN resilience as an emergency response network's capacity to provide required resources and knowledge support for planning, resisting, and absorbing the initial damage as well as rapidly recovering from the unexpected change (Hosseini et al. 2016; Lai and Hsu 2019). Notably, Bruneau et al. (2003) interpreted robustness, rapidity, resourcefulness, and redundancy (4Rs) as a proxy for resilience capacity.

Resilience Measurement for Infrastructure Networks and ERN

Guided by the classic 4Rs framework (Bruneau et al. 2003), numerous studies have endeavored to quantify system resilience for supporting resilience-based improvements in response to infrastructure interruptions (Balakrishnan and Zhang 2020; Hu et al. 2022; Cutter et al. 2008). Focusing on infrastructure systems, many studies modeled the performance response curves following disastrous events and applied the “resilience triangle” paradigm to extract metrics (e.g., the system’s lowest performance level and the recovery time) for quantifying robustness and rapidity capacities (Ouyang et al. 2012; Gu et al 2020; Rod et al 2020; Choi et al. 2019; Li et al. 2020b). Additionally, several studies have modeled the physical infrastructure networks as complex graphs and adopted topological-based indicators to assess network vulnerability (Deng et al. 2017; Mortula et al. 2020), robustness (Osei-Asamoah and Lownes 2014; Yazdani et al. 2011), and redundancy (Kim et al. 2017). However, these studies did not uncover all resilience capacities (4Rs) of infrastructure systems.

Concentrating on ERN resilience for infrastructure interruptions, existing literature widely used conventional network metrics for measuring the performance of ERNs, such as natural connectivity (Li and Ji 2021; Wu et al. 2011), network density (Abbasi and Kapucu 2012; Lai and Hsu 2019), cliques (Comfort and Haase 2006), and centrality metrics (Eisenberg et al. 2020). In specific, Lai and Hsu (2019) developed the organization response networks being activated for earthquakes and calculated the measures of centralization, clustering, and density for analyzing the response networks’ redundancy, robustness, and resourcefulness. Similarly, Li and Ji (2021) used the “natural connectivity” metric to evaluate stakeholder collaboration robustness for infrastructure system protection. In response to cascading failures in the power grid networks, Eisenberg et al. (2020) developed the social networks of organizations and used the centrality metrics to identify critical power grid infrastructure and response organizations for facilitating the resilience of blackout management systems. However, these studies simply considered connectivity patterns of homogeneous organization networks (e.g., one or at most two types of node), and they were ill-suited for heterogeneous ERN networks formed by multiple types of entities (e.g., stakeholder, task, resource, and knowledge). Correspondingly, those network metrics also failed to represent resilience capacities (4Rs) in a systematic way (Li and Ji 2021; Nowell et al. 2017; Eisenberg et al. 2020).

Going beyond the conventional approaches, the meta-networks analysis (MNA) provides a promising approach to model the ERN by accounting for multiple-type entities and their various interactions (Carley 2003; Li et al. 2015). Namely, rather than purely representing "*who interacts with whom, or what interacts with what*", MNA supports representing additional interactions such as: *"What you do? How does who you know impact what you know"* simultaneously (Carley 2003). Specifically, previous social scientists proposed ten entity classes for developing a multi-dimensional MNA model: *Agent, Resources, Knowledge, Tasks, Organizations, Locations, Events, Actions, Beliefs, and Roles* (Carley 2003; Li et al., 2015). Based on their generated node-level measures and network-level measures, some studies tried to analyze resilience capacities from the perspective of emergency response (Martin et al. 2013; Zhu and Mostafavi 2018). For example, Zhu and Mostafavi (2018) conceptualized the emergency response infrastructure system as the meta-network consisting of organizations, information, resources, and tasks nodes as well as their links, and used the "overall task completion" metric to express its resilience capacity. Li et al. (2020a) modeled the urban infrastructure systems as the meta-network composed of actor, plan, task, and infrastructure, in which they used the "Consistency Rate" to examine the coordination among actors and the integration among plans in resilience planning. Currently, the derivation of meta-network metrics for systematically quantifying 4Rs of ERN is still a major challenge. However, the multi-type logical interactions among various stakeholders, response tasks, emergency resources and professional knowledge in the meta-networks, and the network-level metrics generated accordingly related to connectivity, performance, needs, and waste provide a promising way to systematically characterize the 4Rs of ERN (Carley 2003; Altman et al 2020). With a holistic view of complex multi-dimensional ERN structures and 4Rs, this study will propose a novel framework to advance the MNA-based ERN model for infrastructure interruptions and derivate meta-network measures suitable for systematically quantifying ERN resilience capacities.

Research Gaps

A thorough review of the literature identifies two research gaps that need to be addressed. First, existing ERN studies on emergency response performance and resilience for infrastructure interruptions mostly concentrated on stakeholder/organization coordination (Fontainha et al 2020; Abbasi and Kapucu 2012; Li and Ji 2021), while few studies have successfully clarified and visualized the complex ERN structure consisting of multiple-type entities (i.e., stakeholders, response tasks, emergency resources, and professional knowledge) and their interactions. Second, most of the existing network metrics failed to quantify ERN resilience capacities (4Rs) in a systematic way, which leads to a segmented indication of the ERN resilience against infrastructure interruptions.

RESEARCH FRAMEWORK

To bridge the aforementioned knowledge gaps, this research used an enhanced MNA approach to develop the multi-dimensional ERN model that accounts for the interactions of stakeholders, response tasks, emergency resources, and professional knowledge. Furthermore, a series of suitable meta-networks measures were extracted to individually quantify resilience capacities (4Rs). The details of the enhanced MNA-based framework for quantifying ERN resilience are shown in **Fig. 1.**

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Step 1. Develop the Three-stage Emergency Response Meta-networks

Given the three-stage resilience analysis framework (Ouyang et al. 2012), the emergency response to infrastructure interruptions is conceptualized as three meta-networks (i.e., the disaster prevention meta-network, disaster response meta-network, and function recovery meta-network) with various nodes and links. Specifically, four types of entities are selected to represent the nodes in each stage, including *task (T), agent (A), resource (R),* and *knowledge (K)*. In a given emergency response, ***tasks*** are the emergency response activities performed, i.e., the emergency preparedness work and a series of emergency response actions and recovery activities. Then, any stakeholders (e.g., government authorities, emergency service agencies, agencies/teams responsible for operationally managing the event, infrastructure owners and operators, disaster-affected individual people and organizations, social media, and certain non-profit organizations) who perform emergency response tasks are identified as the ***agents***. These agents deploy and control their available ***resources*** (e.g., equipment and rescue service) to complete the emergency response tasks. Moreover, the ***knowledge*** nodes represent skills or information (e.g., leadership and governance and the risk status at the scene) mastered by agents for completing emergency response tasks.

The next step for developing emergency response meta-networks is to establish the links between the nodes. To conceptualize the complex emergency response actions, seven types of links (i.e., the links of **AA, AT, AR, AK, KT, RT, and TT**) between nodes are established. This conceptualization is based on the following assumptions: (1) the completion of each task requires specific resources and knowledge which are maintained and controlled by its assigned agents; and (2) each task could only be completed when its assigned agents capture all task-required resources and knowledge.

Accordingly, seven sub-networks (i.e., the network of **AA, AT, AR, AK, RT, KT, and TT**) are integrated as “A-T-R-K” meta-networks, as shown in **Fig.2.** To be specific, the bidirected AA network connects the agent nodes, which reflects the interactions (e.g., collaboration, and resources exchange) among agents during the emergency response actions (Li and Ji 2021; Carley and Reminga 2004). The directed AT network connecting the nodes of agents and their assigned tasks can be described as *who is assigned to which task*. The directed AR and AK networks link the nodes of agents and their available resources and knowledge, respectively. While the former depicts *who knows what knowledge*, the latter represents *who owns what resource*. In addition, the directed RT and KT network connect the tasks and their necessary resources and knowledge, respectively. While the RT network depicts *what resource is required for which task*, the KT network means *what knowledge is required for which task*. The TT network clarifies *which task is relied on which task.* This meta-network structure retains similar elements from the classic meta-network theory (Carley 2003; Carley and Reminga 2004), allowing it to vividly depict the emergency response actions for protecting and recovering infrastructure functionality over time. Notably, the AA network is a single-mode and bidirected network, while the networks of AR, AK, AT, RT, and KT are two-mode and directed networks, and the TT network is a single-mode and directed network.

Fig. 2. should be inserted here

Mathematically, each sub-network is defined as a binary meta-matrix, and seven different types of meta-matrix (e. i., [AA], [AT], [AK], [AR], [KT], [RT], and [TT]) are developed in each emergency response stage, where the element marked as "1" represents a link between two nodes, and the element marked as "0" represents no link between two nodes. The meaning of different types of links is shown in **Fig. 2.** After all the meta-matrixes in each emergency response stage are determined based on all nodes and their links from the given disaster, this study adopts the Organization Risk Analysis (ORA) software program to develop the three-stage emergency response meta-networks. ORA is a statistical toolkit for analyzing network data (Carley 2003; Altman et al. 2020), which has been validated in other studies (Zhu and Mostafavi 2018; Li et al. 2015).

Step 2. Quantify ERN Resilience Capacities

In addition to conventional network measures, such as network density, centrality, and cliques count (Wasserman and Faust 1994; Freeman 1979; Scott 1988), Carley (2003) explored a series of meta-network measures from the meta-network analysis, some of which [e.g., overall task completion (Zhu and Mostafavi 2018), and consistency rate of missing links (Li et al. 2020a)] have been applied in prior ERN resilience studies related to infrastructure systems. To uncover all resilience capacities (4Rs), namely *robustness, rapidity, resourcefulness, and redundancy,* this study selected suitable meta-network metrics (i.e., natural connectivity, average speed, overall task completion, and the integrative metric of task resource/knowledge needs and task resource/knowledge waste) to derivate 4Rs measures respectively.

(1) *Robustness*

Robustness is the "ability of elements and systems to withstand a given level of disturbances without suffering function loss" (Albert et al. 2000; Bruneau et al. 2003). Mathematically it represents the structural robustness in networks by measuring the redundancy of alternative routes, namely natural connectivity (Wu et al. 2011; Li and Ji 2021). Here, alternative routes indicate the available choices for agents to collaborate with other agents to capture available resources and knowledge. As the number of alternative routes increases, the ERNs become more robust, specifically, the agents would discover more solutions to complete response tasks particularly when they have unavailable necessary resources or insufficient knowledge.

"Natural connectivity" is selected to represent the *robustness* (R_{Rob}) of each-stage ERN by the following **Eq. (1)**

$$Robustness = R_{Rob}(G_{AA}) = ln(\frac{1}{m}\sum_{j=1}^{m} e^{\lambda_j}) \quad (1)$$

Where G_{AA} is the emergency response AA network; AA = the binary matrix of the AA network; $\lambda_j(j = 1, \ldots, m)$ = the eigenvalues of $[AA]$; and m = the total number of eigenvalues. The maximum robustness represents that G_{AA} achieves the highest natural connectivity when all agents are fully connected, while the minimum robustness represents that G_{AA} achieves the lowest natural connectivity when all agents are disconnected.

(2) *Rapidity*

Rapidity is the "system's capacity to prevent, resist and function recover from the disruptions in a timely manner" (Bruneau et al. 2003). At the network level, *rapidity* is operationalized as the "average speed" measure, which characterizes the communication speed with which any two agent nodes can interact (Carley 2003). Mathematically, the average speed is "the inverse of the average shortest path length between agent node pairs", being standardized on a 0-1 scale (Carley 2003). Naturally, a higher average speed in the AA network leads to faster communication among agents and hence promotes resources sharing and knowledge exchange (Marion et al. 2016).

As one of the performance measures in meta-networks, "average speed" is selected to express the *rapidity* (R_{Rap}) of each-stage ERN by the following **Eq. (2)**

$$Rapidity = R_{Rap}\ (G_{AA}) = \frac{1}{n}\sum_{i=1}^{n}\frac{(n-1)}{d_i} \tag{2}$$

Where G_{AA} is the unimodal input AA network in this stage; n = the total number of agent nodes in this stage; d_i = the sum of the inverse of shortest path lengths from agent node i to other agent nodes if a path exists, and it is specialized as **Eq. (3)**

$$d_i = \sum_{u=1, u\neq i, D(i,u) > 0}^{n}\frac{1}{D(i,u)} \tag{3}$$

Where D is defined as the distance matrix of G_{AA}; $D(i,u)$ = shortest path length from node i to node u, if a path exists.

(3) *Resourcefulness*

Resourcefulness is conceptualized as the “ability to apply resources to response to disasters and achieve goals” (Bruneau et al. 2003; MacKinnon and Derickson 2013). Here, resourcefulness is the ERN’s ability to complete emergency response tasks with resources and knowledge. Accordingly, the “overall task completion” metric referring to the percentage of tasks that can be completed by the designated agents with the required resources and knowledge, is the best performance-related indicator for representing *resourcefulness* from the network level (Razzoli et al. 2014; Zhu and Mostafavi 2018).

Considering the research assumption (2) set in the Step 1, we enhance the equation to measure “overall task completion” for representing the *resourcefulness* (R_{Res}) of each-stage ERN, as shown in following **Eq. (4)**

$$Resourcefulness = R_{Res} = \frac{|T| - |S_{RK}|}{|T|} \tag{4}$$

Where $|T|$ = the number of tasks that need to be completed; $|S_{RK}|$= the number of tasks that cannot be completed based on whether the agents have the required resources and knowledge to perform tasks, which is calculated by the following **Eq. (5)** and **Eq. (6)**:

$$S_{RK} = \{i | 1 \leq i \leq |T|, \ \exists j: \ N_{RK}(i,j) < 0\} \tag{5}$$

$$\mathrm{N_{RK}} = \left(\mathrm{AT^T} \times \begin{bmatrix}\mathrm{AR} \\ \mathrm{AK}\end{bmatrix}\right) - [\mathrm{RT\ KT}]^{\mathrm{T}} \tag{6}$$

Where N_{RK} =the Knowledge/Resources gap matrix, which represents the gap between the required resources/knowledge for tasks and the available resources/knowledge for agents; $N_{RK}(i,j)$ is the element of the N_{RK} at the i^{th} row and j^{th} column; AT = the binary matrix of the AT network; AT^T = the transpose matrix of AT; AR = the binary matrix of the AR network; AK = the binary matrix of AK network; RT = the binary matrix of the RT network; and KT = the binary matrix of the KT network;

$[RT\ KT]^T$=the transpose matrix of $[RT\ KT]$.

(4) *Redundancy*

Redundancy is "the capability to access alternative resources to maintain the system's normal functionality in disasters" (Bruneau et al. 2003; Nowell et al. 2017). At the network level, redundancy can be conceptualized as "each task has multiple accesses to resources/knowledge via agents assigned to it." This viewpoint is inspired by the general meta-network measures: "task resource/knowledge needs" and "task resource/knowledge waste" (Li et al. 2015; Altman et al. 2020). Mathematically, the *redundancy* (R_{Red}) of each-stage ERN is calculated by the following **Eq. (7)** and **Eq. (8)**:

$$\text{Redundancy} = R_{Red} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} Rd_{RK}(i,j)}{\sum_{i=1}^{m}\sum_{j=1}^{n}\ [RT\ KT]^{\mathrm{T}}(i,j)} \qquad (7)$$

$$Rd_{RK}(i.j) = \begin{cases} 0 \quad , & if\ [RT\ KT]^{\mathrm{T}}(i,j) = 0 \\ \dfrac{N_{RK}(i,j)}{[RT\ KT]^{T}(i,j)}\ , & if\ [RT\ KT]^{\mathrm{T}}(i,j) \neq 0 \end{cases} \qquad (8)$$

Where $Rd_{RK}(i,j)$ is the element of the matrix Rd_{RK} at the i^{th} row and j^{th} column; $[RT\ KT]^{\mathrm{T}}(i,j)$ is the element of the transpose matrix of $[RT\ KT]$ at the i^{th} row and j^{th} column; $N_{RK}(i,j)$ is the element of the N_{RK} matrix **in Eq.(6)** at the i^{th} row and j^{th} column. Notably, in the N_{RK} matrix, $N_{RK}(i,j) > 0$ represents that the resource/knowledge j is redundant for completing the task i (i.e., at least the task i possesses one more route to access the required resources/knowledge).

CASE STUDY: THE MANCHESTER ARENA ATTACK

To verify the feasibility of the proposed MNA-based framework in quantifying ERN resilience for infrastructure interruptions, the emergency response actions in the well-known Manchester Arena Attack in the UK were analyzed in detail as a case study. For brevity purpose, a detailed content of the 'A-T-R-K' meta-networks of this case can be found in the Appendix.

Case Introduction

The Manchester Arena is an indoor arena that links to Manchester Victoria Train Station through a "foyer", in Manchester, England (**Fig. 3.**) On May 22, 2017, approximately 14,000 people, mostly teenagers with their families, attended the concert of American singer Ariana Grande. At the end of the concert, a suicide bomber detonated a shrapnel-laden homemade bomb in the foyer, when the foyer was crowded with concert-goers leaving the concert, people waiting for their families, and merchandise sellers. In this incident, 22 people were unfortunately killed, over 100 sustained physical injuries, and many more suffered from psychological traumas. The Manchester Arena attack was the deadliest terrorist attack in the UK since the 2005 London Train Bombings.

Fig. 3. should be inserted here

Following the actual response actions in Manchester Arena, this paper clarified this terrorist event using the storyline in **Fig. 4.** Also, based on the three-stage resilience analysis framework (Ouyang et al. 2012), the emergency response process was divided into three stages: disaster prevention stage, disaster response stage, and function recovery stage. The following three-stage resilience analysis can explicitly reflect the dynamic change of resilience capacities over time.

Fig. 4. should be inserted here

Data Collection and Meta-Network Development

The prerequisites for developing precise emergency response meta-networks include collecting detailed and accurate data about the actual responses to the Arena attack and extracting reliable nodes and links. The process of data collection and meta-network development is shown below and an illustrative example is provided in **Fig. 5.**

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First, as summarized in **Table 1.**, the original and authoritative data, including guideline information and actual information, were collected from national and local government profiles, professional associations' reports, and academic publications. Specifically, the guideline information is predefined by national or local government agencies. For example, the Joint Emergency Services Interoperability Principles (JESIP) (i.e., co-locate, communication, coordination, a joint understanding of risk, and shared situational awareness), which was established in 2012 by the UK government, has become the national standard for multi-agency response to major or complex incidents (JESIP 2016). Guided by this JESIP framework, the local multi-agency partnership Great Manchester Resilience Forum (GMRF) constructed emergency exercises more than once in advance of the Arena event, and most GMRF members performed significant roles in response to the Arena attack (Greater Manchester Resilience Forum 2021). For the actual information, the Kerslake Report (2018) described the actual emergency response actions in detail.

Table. 1. should be inserted here

Second, the extracted data was stored in two structured datasets including entities and relationships. Notably, the stage of emergency response where the entity or relationship presented is marked in each piece of data. The data for each entity or relationship was extracted based on the description of nodes and links in the Research Framework section. The extracted nodes of the agent, task, resource, and knowledge are provided in the Appendix.

Third, the structured datasets were classified based on different relationships among nodes over the three-stage emergency response process. For each stage, the constructed seven relationship datasets (i.e., AA, AR, AK, AT, RT, KT, and TT connections) were transferred separately into meta-matrices based on the mathematical definitions in the Research Framework section.

Lastly, all meta-matrices were imported into the ORA software for visualizing the three-stage ERNs.

In each stage, seven sub-networks (i.e., AA, AR, AK, AT, RT, KT, and TT networks) were integrated as one meta-network, and the 4Rs measures were obtained via matrix calculations.

Topological Characteristics of Three-stage Meta-Networks

The three-stage "A-T-R-K" response meta-networks for the Arena attack are visualized in **Fig. 6.** Overall, the topology of the meta-networks becomes denser across the three emergency response stages, indicating the continuous appearance of entities and their connections. In detail, a huge cluster in the three meta-networks is formed around GMRF members (e.g., NR-A11, BTP-A01, GMHSCP-A06, GMP-A07, NWAS-A12, and HSE Eng.-A20). Through reviewing data sources, it has been identified that these GMRF members' pre-disaster multi-agency exercises (PT07) significantly facilitate stakeholder communication to perform emergency response tasks. Specifically, NR (A11, the owner of Manchester Arena and its connected Victoria station) and SMG (A15, the operator of the Manchester Arena) have acted as the central role to perform disaster prevention and response tasks, while GMP (A07, Greater Manchester Police) has actively collaborated with other agents to perform function recovery tasks such as scene control, the crowd evacuation, and accident investigation. Additionally, it's found that the services of security (R02), first aid (R03), and medical care (R05) are the fundamental resources needed for disaster preparedness and response tasks, and a specialized set of resources for patient treatment (R12) and financial support (R11) is mostly required by the long-term function recovery tasks. For the required knowledge nodes, disaster prevention and response tasks have more links with K19 (the contingency planning and joint operating procedures), K20 (multi-agency coordination structure), and K02 (hazards assessment), while function recovery tasks are frequently connected to K04 node (emergency resources.

Fig. 6. should be inserted here

The total number of four-type nodes and their seven-type links in the three-stage meta-networks are summarized in **Fig. 7.** The number of stakeholders/agents involved, professional knowledge, and the tasks required to be done all increase over the three-stage emergency response process, while the number of resources captured by agents decreases in the function recovery stage. This mainly results from the fact that the tasks of disaster prevention and response are more complex with required various resources, while most recovery tasks need a specialized set of resources merely for patient treatment and financial support for a long time (Kerslake 2018). Accordingly, the AR links representing the agents' available recovery resources show similar downward trends, and the RT links representing the resources required for tasks achieve the maximum (links=39) in the disaster response stage and then gradually decrease to 9 links in the function recovery stage. The remarkable increase of other links, particularly AA and AK links, could be explained largely by the increasing interactions among stakeholders as well as their increasing response tasks.

Fig. 7. should be inserted here

Generally, the network density metric is used to analyze the connectedness of the networks (Wasserman and Faust 1994; Li and Ji 2021). In the AA networks, the value of network density decreases significantly from 0.62 to 0.37 and then gradually increases to 0.4 over the three emergency response stages. Overall, the connectedness level of AA networks is not high. Although the number of agents and their interactions have a considerable increase (**Fig.7.**), the gradually decrease of network density is largely due to the increasing emerging stakeholders as well as their extensive interactions in disaster response and function recovery stages (Kerslake 2018; Li and Ji 2021).

Resilience Capacities of Three-stage ERNs

The resilience capacities (4Rs) of three-stage ERNs in the Manchester Arena attack were calculated according to **Eq. (1–8),** and the results in **Fig. 8.** were analyzed as follows.

Fig. 8. should be inserted here

(1) Robustness

As shown in **Fig.9.**, the robustness increases gradually from 3.51 to 17.37 over the three-stage emergency response, and the relatively high robustness indicates that the agents have many alternative routes to connect (Li and Ji 2021). Notably, before the Arena event, many planning exercises for emergencies across the Manchester city region had been done by GMFR members guided by the JESIP framework (JESIP 2016). Founded on these already established relationships among stakeholders, the subsequent emergency responses to the Arena attack fully applied the JESIP principles, which enabled stakeholders to tightly collaborate (Carley 2003; JESIP 2016; UNISDR 2015). Overall, the pre-disaster joint response practices, as well as JESIP applications, significantly contribute to the ERE robustness, and this real-world test demonstrates the feasibility of "natural connectivity" to depict the ERN robustness.

(2) Rapidity

Fig. 8. depicts that the network rapidity slightly decreases from 0.78 to 0.64 before it increases to 0.69 (on a 0-1 scale) over the three-stage emergency response process. In disaster preparedness, the number of stakeholders involved is relatively small (agent count =12), and most of them are GMFR members who had participated in the multi-agency planning and exercising activities more than once (Kerslake 2018). With those numerous existing directed links in the relative-small disaster prevention network, the stakeholders' communication speed is high for transmitting information quickly (Marion et al. 2016). As represented in **Fig.7.**, the count of agents increases during the subsequent disaster response stage, while some AA links were lost due to the lack of an inter-agency radio link (R01) (Kerslake 2018). Moreover, the large number of emerging agents who newly appeared in the disaster response stage could not develop a direct connection with other agents in this short phase. Consequently, the communication speed among agents is negatively affected during the disaster response stage. Although more agents join in the function recovery stage, the

overall interactions among agents are more stabilized and hence the communication speed gradually increases.

(3) Resourcefulness

The resourcefulness peaks (resourcefulness=1) in the disaster prevention stage (**Fig.9.**), indicating that all disaster preparedness tasks are completed in line with adequate resources and knowledge (Bruneau et al. 2003). Going back to the Arena attack, this high resourcefulness was mostly contributed by the multi-agency planning and exercising activities led by *GMFR* before the attack and the risk assessment performed by *SMG (A15)* to inform multi-agency partners about completing preparedness tasks (Kerslake 2018). Strikingly, a significant decrease to 0.74 is observed in the disaster response stage (**Fig. 8.**). Through detailed investigation, the absence of the *"Greater Manchester Fire and Rescue Service" (GMFRS, A05)* failed some disaster response tasks (Kerslake 2018). In specific, within 15 minutes of answering the first call reporting explosion at the Arena, the *Force Duty Officer in GMP (A07)* declared the Operation PLATO contingency for the suspected Marauding Terrorist Firearms Attack, and meanwhile, the Force Duty Officers were required to notify other partners for joint-working response (JESIP 2016; Kerslake 2018). However, due to the lack of an inter-agency radio link (R01), *GMFRS* was not informed immediately (i.e., uncompleted RT07) and failed to arrive at the scene until two hours (the previous average response time is less than six minutes) after the explosion (Kerslake 2018; UNISDR 2015). Accordingly, GMFRS fire service resources (e.g., stretchers and ballistic protection equipment) and its Special Rescue Teams could not be deployed to the immediate scene, resulting in the failure or inefficiency of some response actions such as customers and staff evacuation (RT08), casualty portage (RT11), rescue resources deployment (RT14), and casualty data collection and report (RT17). Additionally, certain inappropriate press approaches (i.e., a lack of respect and photographing the anguished families without permission) and the government's limited financial support directly hindered the recovery of the bereaved families (FT02) in the function recovery stage, leading to its lower resourcefulness (0.95) compared to the disaster prevention stage.

(4) Redundancy

Across the three-stage emergency response process, the network redundancy considerably decreases from 3.02 to 0.80 before it then slightly increases to 1.05 (**Fig. 8.**). The high redundancy in the disaster prevention stage depicts that most prevention tasks have multiple routes to access required resources/knowledge via stakeholders (Bruneau et al. 2003). Learning from repetitive planning exercises around GMFR members, SMG (A15) carried out the risk assessment, including risk factors, the level of security, and medical cover required, then forwarded the risk assessment directly to the Arena's multi-agency partners before the event started (Kerslake 2018). Accordingly, there was a shared communication across the stakeholders in disaster preparedness, which contributed significantly to a high redundancy value. Notably, the redundancy is relatively lower for disaster response and function recovery tasks. Through reviewing the emergency response process, the following facts could explain the relatively low redundancy. For one thing, a combination of poor communication and poor procedures in the initial explosion rendered some agents (such as *GMFRS*) to lose their connections (Kerslake 2018), thus the routes for some specific response tasks (i.e., RT07, RT08, and RT11) to obtain their required resources/knowledge via agents were limited or even lost. For the other thing, as the number of emergency response tasks increased, the variety of resources and knowledge required for these tasks increased, while the number of agents who had the required resources/knowledge for various tasks did not increase significantly. Notably, this unsynchronized increase relatively decreased the number of routes for tasks to capture their required resources/knowledge via agents, and thus resulted in low redundancy.

DISCUSSION

The proposed MNA-based framework for quantifying ERN resilience to infrastructure interruptions was verified in the presented case study. Several key findings related to resilience improvement strategies and the advantages of adopting the MNA approach were discussed below.

Strategies to Improve ERN Resilience Capacities

Based on the association between the calculated 4Rs and their corresponding meta-network measures, a series of strategies can be formulated to enhance each resilience capacity specific to the case scenario. Having in place the ERN resilience improvement strategies is essential as the stakeholders need to learn from this attack and fully prepare for future emergency response (Choi et al. 2019; Balakrishnan and Zhang 2020). Such strategies in resilience planning can have wider implications for other emergency response scenarios as natural and human disasters are emergent and infrastructure systems are vulnerable (for example, the current threat level is substantial in the UK, implying that an attack is likely) (Security Service MI5 2022).

In terms of maintaining high *robustness*, such strategies as strengthening the multi-agency planning and exercises before the event are effective to increase the routes of stakeholder connectivity during emergency response. In particular, *GMRF* should continue to lead the multi-agency planning program across the city-region level, and all stakeholders (e.g., GMRF members) should apply the JESIP principles not just for emergency preparation but also for multi-agency communication in disaster responding (JESIP 2016). This case scenario as well as prior studies showed the value of already established partnerships among stakeholders in facilitating ERN robustness (Kapucu and Hu, 2016), and well-developed pre-disaster training programs are essential to strengthen the partnerships (Li and Ji 2021).

For enhancing the network *rapidity*, the key to increasing the communication speed of the ERN is to expand the direct links among agents (Carley 2003; Kapucu and Hu 2016). In this case scenario, the specific lessons for enhancing ERN rapidity include adding an appropriate number of central stakeholders (e.g., NR, GMP, and other government authorities) with extensive links and maintaining the availability and functionality of communication channels/tools. (Kerslake 2018; JESIP 2016). These strategies establish more direct relationships among agents based on a clear multi-agency coordination structure as well as reliable technical support. Remarkably, the multi-agency coordination structure should clarify the leading roles in response actions across the strategic, tactical, and operational levels, address cross-level issues, and allow certain flexibility of changing roles in emergencies (Dong et al. 2020; Bhakta Bhandari 2014).

According to network analysis, the level of *resourcefulness* depends on the completion rate of emergency response tasks with the support of resources and knowledge (Altman et al 2020). It's worth noting that the significant decrease in resourcefulness in the disaster response stage is a consequence of insufficient resources and knowledge. All the uncompleted response tasks as well as the missing resources and knowledge across the emergency response are listed in Table 2. Learning from these failures in the case scenario, more attention should be paid to prevent potential weaknesses in resources supplying and knowledge training, such as the failure of communication channels, the lack of rescue services and post-event mental treatment, inefficient response procedures, inexperienced risk/facility condition assessment, and the poor skills in media handling. Other ERN studies also emphasized the value of amassing sufficient emergency resources (Choi et al. 2019) and training crisis management knowledge (Comfort 2007) in resilience planning.

Table 2. should be inserted here

As depicted by meta-network measures, increasing the routes for tasks to obtain required resources/knowledge via various agents is the key point to strengthening the capacity of *redundancy*.

Specific strategies could be observed from the case scenario, including ensuring the immediate response of stakeholders and facilitating the share of rescue resources and response knowledge (i.e., risk status, and situational awareness). The promotion of applying the JESIP principles in the Greater Manchester Resilience Strategy 2020-2030 also highlighted the interoperability practice (Greater Manchester Resilience Forum 2021). Notably, in terms of the response task of RT11 (casualty portage), the *NWAS, BTP, GMP, and Arena staff*, and surprisingly the public used the improvised stretchers to evacuate casualties, even in the absence of *GMFRS* resources and its special rescue teams. This emerging coordination action also promoted the evacuation tasks to proceed efficiently. Namely, building redundancy routes for tasks to capture their required resources could enhance the resourcefulness of ERN to a certain extent (Lai and Hsu 2019).

Advantages of Adopting the MNA Approach

As depicted in the case study, the emergency response actions can be conceptualized as "a series of stakeholder capture the necessary resources and knowledge to complete their assigned response tasks". Thus, the structure of ERN is a complex consisting of multiple-type nodes (e.g., agent, task, resource, and knowledge) and diverse links (i.e., AA, AT, AR, AK, KT, RT, and TT links). In marked contrast to the conventional studies that usually focus on limited types of node (e.g., one or at most two types of node), the MNA provides a promising approach to model the complex ERN with multi-type nodes and diverse connections (Carley 2003; Altman et al. 2020). Equipped with multi-dimensional topologies, the developed "A-T-R-K" meta-network can precisely conceptualize the emergency response actions by clarifying and visualizing the interactions of agent, task, resource, and knowledge nodes (Kapucu and Hu 2016; Zhu and Mostafavi 2018). Critically, compared to prior ERN resilience metrics (Li and Ji 2021; Lai and Hsu 2019), the generated meta-network measures provide a more systematic way of characterizing ERN resilience capacities (4Rs). In addition to analyzing stakeholder collaboration in terms of the response robustness and communication rapidity, the enhanced MNA model can reveal the gap between the actual captured resources/knowledge by agents and the desired resources/knowledge required by tasks, which realizes the accurate measure of resourcefulness and redundancy. Accordingly, the proposed MNA-based framework for quantifying ERN resilience is capable of detecting the factors that change the degree of resilience capacities, and thus corresponding resilience strategies have been identified for future infrastructure systems protection and other emergency response scenarios.

CONCLUSIONS

By combining the enhanced MNA-based approach with resilience theories, this study proposes a novel framework to quantify resilience capacities (4Rs) of ERN in response to infrastructure interruptions. Specifically, the developed "A-T-R-K" meta-networks precisely conceptualize and visualize the complex ERN structure consisting of four-type nodes (i.e., agent, task, resource, and knowledge) and seven types of links (i.e., AA, AT, AR, AK, KT, RT, and TT). Accordingly, the generated meta-network measures (i.e., natural connectivity, average speed, overall task completion, and the integrative metric of task resource/knowledge needs and task resource/knowledge waste) are used to systematically quantify ERN 4Rs, i.e., robustness, rapidity, resourcefulness, and redundancy.

The emergency response to the Manchester Arena attack was analyzed as a case study to validate the proposed MNA-based framework in evaluating ERN resilience to infrastructure interruptions. This technique allows us to systematically classify which types of actors/resources/knowledge are most active and interconnected during the disaster prevention, response, and recovery stages of the Manchester Arena attack. It reveals that stakeholder interactions gradually become intense, and culminate in the recovery stage. It implies that greater efforts should be made to encourage the pre-disaster multi-agency exercises led by

GMFR, and clarify the central roles in the multi-agency coordination structure, so that when crisis strikes, the ERN will respond with high robustness and rapidity. Moreover, amassing sufficient emergency resources, training crisis management knowledge, and promoting resources/knowledge sharing will fairly contribute to resourcefulness and redundancy of the ERN. Additionally, the resources related to security services, first aid, medical care, and communication systems are essential for disaster preparedness and response, while the resources related to post-event mental treatment and financial support are critical in function recovery. The knowledge regarding contingency planning and joint operating procedures, multi-agency coordination structure, hazards assessment, and emergency resources information is critically required by specific stakeholders to effectively perform response tasks.

This study has made some contributions to the body of knowledge on ERN resilience and infrastructure operation. Theoretically, this study proposes an enhanced MNA-based framework to systematically quantify ERN resilience capacities in consideration of the complex ERN structure. This novel framework can potentially be applied to other infrastructure operation and emergency response scenarios. In practice, the practices and lessons learned from historical disasters via examining their emergency response resilience can help stakeholders foster collaboration, plan resources, assign tasks and learn knowledge for improving resilience in future infrastructure operation and emergency response.

As an exploratory study, this research has limitations that, however, could form the basis for future studies. First, the developed three-stage emergency response meta-networks could not precisely reflect the dynamic status of nodes and their links in each stage. It is suggested that future studies implement data-mining methods to collect details about recent emergency responses for infrastructure failures, and precisely capture the time evolution of ERN resilience across the emergency response process. Second, the agents' capacity for self-organization and adaptation in emergency response has not been seriously considered in this study due to limited accident details. Given this limitation, future studies can integrate the agent-based approaches into the MNA modeling process to better simulate the actual emergency response actions (Macal and North 2010; Bonabeau 2002). Last but not least, multiple future case studies on historical disastrous events can investigate the factors that influence the ERN resilience, thereby the proposed resilience strategies can be safely extrapolated to other infrastructure protection and emergency response scenarios.

APPENDIX. NODES IN THE THREE-STAGE EMERGENCY RESPONSE META-NETWORKS FOR THE MANCHESTER ARENA ATTACK

Node types	Nodes
Agent nodes	A01: BTP (British Transport Police); A02: CO (Coroner's Office); A03: ET-UK (Emergency Training UK - Arena medical and first aid providers); A04: GMCA (Greater Manchester Combined Authority); A05: GMFRS (Greater Manchester Fire and Rescue Service); A06: GMHSCP (Greater Manchester Health and Social Care Partnership); A07: GMP (Greater Manchester Police); A08: GMPF (Greater Manchester Police Federation); A09: MCC (Manchester City Council); A10: MD (Ministry of Defence); A11: NR (Network Rail); A12: NWAS (North West Ambulance Service); A13: NWFC (North West Fire Control); A14: N (Northern); A15: SMG (SMG-Manchester Arena operating company); A16: TGM (Transport for Greater Manchester); A17: MH, C&LG (Ministry of Housing, Communities & Local Government); A18: EO (Expert Organizations); A19: C&P (Charities& Public); A20: NHS-E (National Health Service England); A21: V (Vodafone); A22: M (Media).
Resource nodes	R01: An inter-agency radio link; R02: Security services; R03: First aid service; R04: Fire and rescue service; R05: Medical care service;

	R06: Casualty portage and stretchers; R07: Specialist medical equipment; R08: Authorized firearms officers and weaponry; R09: Military resources; R10: Transport vehicle and drivers; R11: The Fund and financial assistance; R12: Mental health and emotional wellbeing support; R13: Bereavement service. R14: National mutual aid telephone system
Knowledge nodes	K01: The level of security and medical cover required; K02: Hazards present or suspected; K03: Emergency services present and those required; K04: Emergency resources present and those required; K05: Structural and functional condition of physical and hardware facilities; K06: Status of emergency personnel; K07: The nature and scale of the mass casualty incident.; K08: Exact location of the disturbance; K09: Safe condition of the site; K10: Whether evacuation routes are safe to use; K11: Number, type, and severity of casualties; K12: Other information of each casualty and their family; K13: Skills in media handling; K14: Leadership and governance; K15: Finance and resource capacity; K16: Media standards and ethics; K17: Basic casualty portage capabilities; K18: Experience of shrapnel and blast injuries; K19: Contingency planning and standard operating procedures; K20: Multi-agency coordination structure; K21: The large-scale intensive deployment of firearms capability; K22: Situational awareness and the joint understanding of risk.
Task nodes in disaster prevention stage	PT01: Formulate resilience-oriented Joint Emergency Services Interoperability Programme; PT02: Conduct emergency training and undertake regular simulation exercises; PT03: Run briefing, training, and awareness sessions in individual boroughs; PT04: Risk and threat assessment before the activity to inform preparedness; PT05: Decide the level of security and medical cover required and arrange field personnel for the event; PT06: Send these risk assessments directly to the multi-agency partners in advance; PT07: Participate in multi-agency exercises.
Task nodes in disaster	RT01: Manage or directly control crowd behaviors; RT02: Evacuate the crowds; RT03: Provide care and first aid to casualties;

response stage	RT04: Assess the safety status of the incident scene; RT05: Close nearby road; RT06: Warning and informing the public; RT07: Communicate the declaration of Operation PLATO; RT08: Evacuate the general staff; RT09: Triage casualties; RT10: Set up a casualty clearing station close to the scene of the emergency; RT11: Move casualties in the correct order of priority to the Casualty Clearing Station; RT12: Evacuate casualties to the most appropriate hospital; RT13: Assess the risk of sending firefighters toward such an incident without sufficient protection; RT14: Clarify details of the incident, obtain a secure forward control point, deploy resources to it; RT15: Draw in firearm from across the country rapidly; RT16: Use the armed police to search the arena, pacify and create a safer working environment; RT17: Activate the necessary telephony and computer systems to receive and collate casualty data; RT18: Assess the structural safety of the foyer area and provide crucial support; RT19: Assist the ongoing multi-agency searches, arrests, and operations.
Task nodes in function recovery stage	FT01: Match missing person reports with known casualty information; FT02: Provide support to bereaved families; FT03: Check and replace used healthcare equipment; FT04: Move victims' bodies to a temporary body storage facility; FT05: Move deceased victims from the scene to the mortuary; FT06: Identify the Victims; FT07: Allocate Family Liaison Officer to those directly affected; FT08: Establish an official fund to receive donations from the public, and make payments; FT09: Hold a series of activities around the Manchester arena; FT10: Investigate the cause of the incident and any criminal culpability arising from it; FT11: Deploy a Trauma Risk Management Team to identify support for the mental health of officers alongside the active; FT12: Collate casualty information from the hospital; FT13: Enact their crisis management protocols; FT14: Join a survey of Victoria train station to assess its potential to be re-opened; FT15: Format a Transport Cell to ensure impacted transport links return to operation; FT16: Assess the condition of the station including the roof and the block separating the Arena from the platforms; FT17: Examine the damage to the Arena's glazed atrium roof; FT18: Mobilize the necessary specialists to carry out a series of maintenance and recovery work; FT19: Reopen Victoria train station to train and tram services;

	FT20: Reopen Manchester Arena; FT21: Investigate, report, and learn from the incident.

DATA AVAILABILITY STATEMENT

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGMENT

This research is sponsored by the National Natural Science Foundation of China (Grant number: 71901120 and - 72072031), Humanities and Social Science Youth Foundation, Ministry of Education of the People's Republic of China (Grant number: 19YJCZH080), and supported by Qing Lan Project of Jiangsu, China.

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TABLES

Table 1. Representative data sources

Types	Data title	Sources
Guideline information	The National Security Strategy of the United Kingdom Security in an interdependent world	National government file
	JESIP (2016) Joint Doctrine - the Interoperability Framework (Edition 2 - July 2016)	National government file
	National Risk Register of Civil Emergencies 2017 edition	National government file
	Operation PLATO Initial Response Contingency Planning Guidance to Police Forces	National government file
	Greater Manchester emergency management plans	Local government file
	Greater Manchester Resilience Forum websites	Local government websites
	Greater Manchester Resilience Strategy 2020 – 2030	Local government file
Actual information	The Kerslake Report: An independent review into the preparedness for, and emergency response to, the Manchester Arena attack on 22nd May 2017	Non-statutory review
	The psychosocial response to a terrorist attack at Manchester Arena, 2017: a process evaluation	Academic publication

Table 2. Uncompleted tasks, missing resources, and missing knowledge

Emergency response stage	Uncompleted tasks	Missing resources	Missing knowledge
Disaster prevention	/	/	/
Disaster response	RT07: Communicate the declaration of Operation PLATO RT08: Evacuate the general staff RT11: Move casualties in the correct order of priority to the Casualty Clearing Station RT14: Clarify details of the incident, obtain a secure forward control point, and deploy resources to it RT17: Activate the necessary telephony and computer systems to receive and collate casualty data	R01: An inter-agency radio link R06: Casualty portage and stretchers R07: Specialist medical equipment R08: Authorized firearms officers and weaponry R09: Military resources R14: National mutual aid telephone system	K05: Structural and functional condition of physical and hardware facilities K13: Skills in media handling K19: Contingency planning and standard operating procedures K22: Situational awareness and the joint understanding of risk
Disaster recovery	FT02: Provide support to bereaved families	/	K16：Media standards and ethics

FIGURE CAPTIONS

Fig. 1. Research framework

Fig. 2. Conceptual “A-T-R-K” meta-network

Fig. 3. Manchester Arena and evacuation routes after the attack

Fig. 4. Three-stage response process of the Manchester Arena attack

Fig. 5. Illustrative example of data collection and meta-network development

Fig. 6. “A-T-R-K” response meta-networks for Arena attack across the three stages: (a) Disaster prevention stage; (b) Disaster response stage; and (c) Function recovery stage.

Fig. 7. Summary of three-stage meta-networks: (a) Number of nodes; and (b) Number of links

Fig. 8. Dynamic change of 4Rs across three emergency response stages

Fig.1

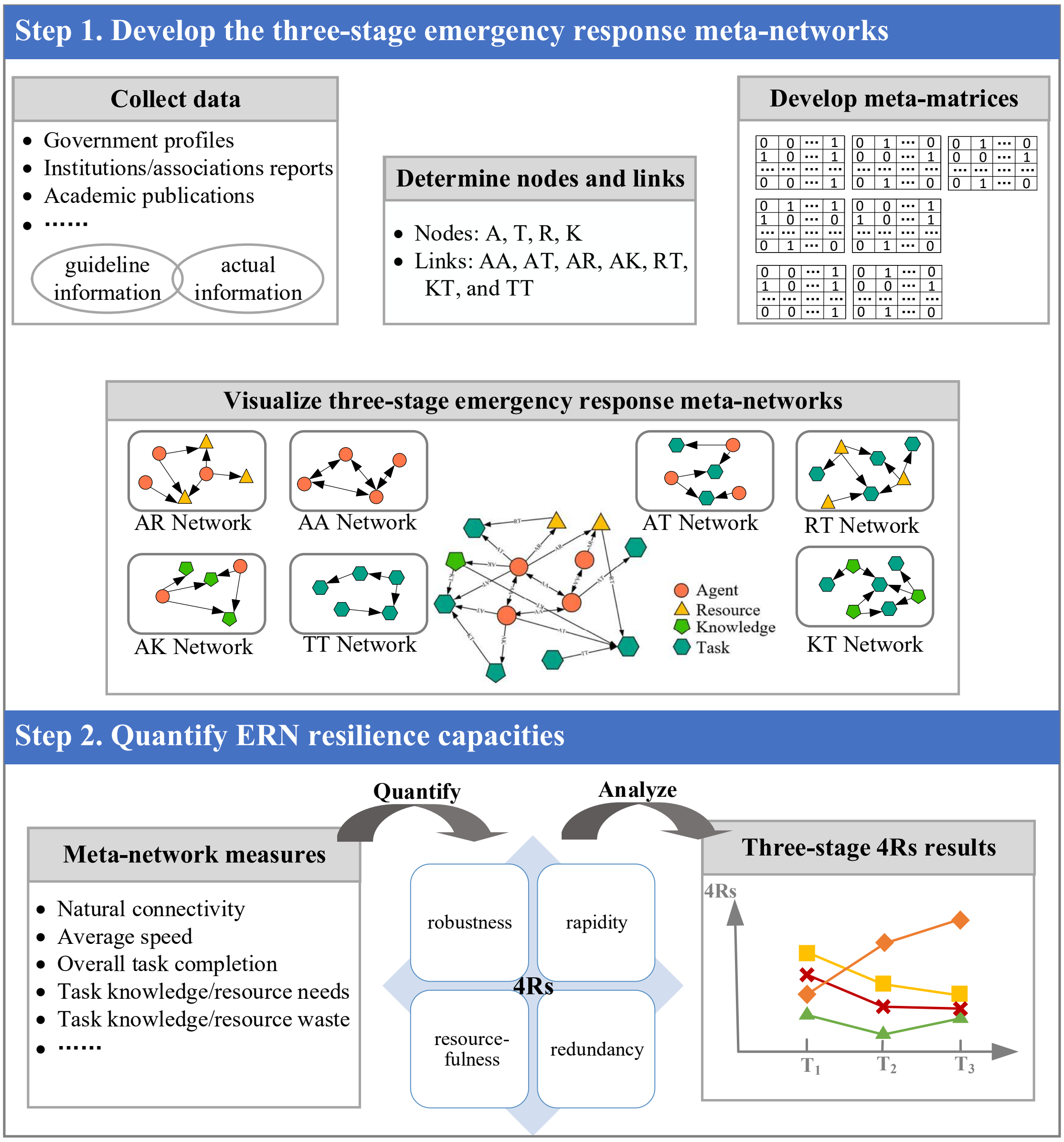


Fig. 1. Research framework

Fig.2

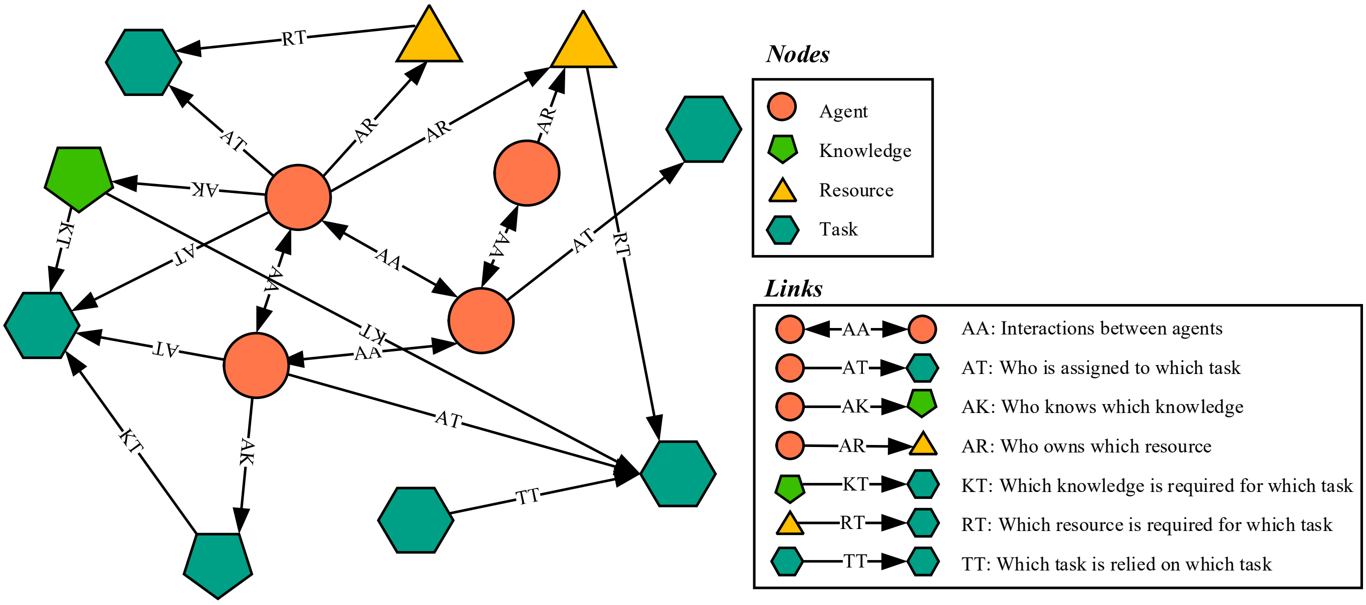


Fig. 2. Conceptual "A-T-R-K" meta-network

Fig.3

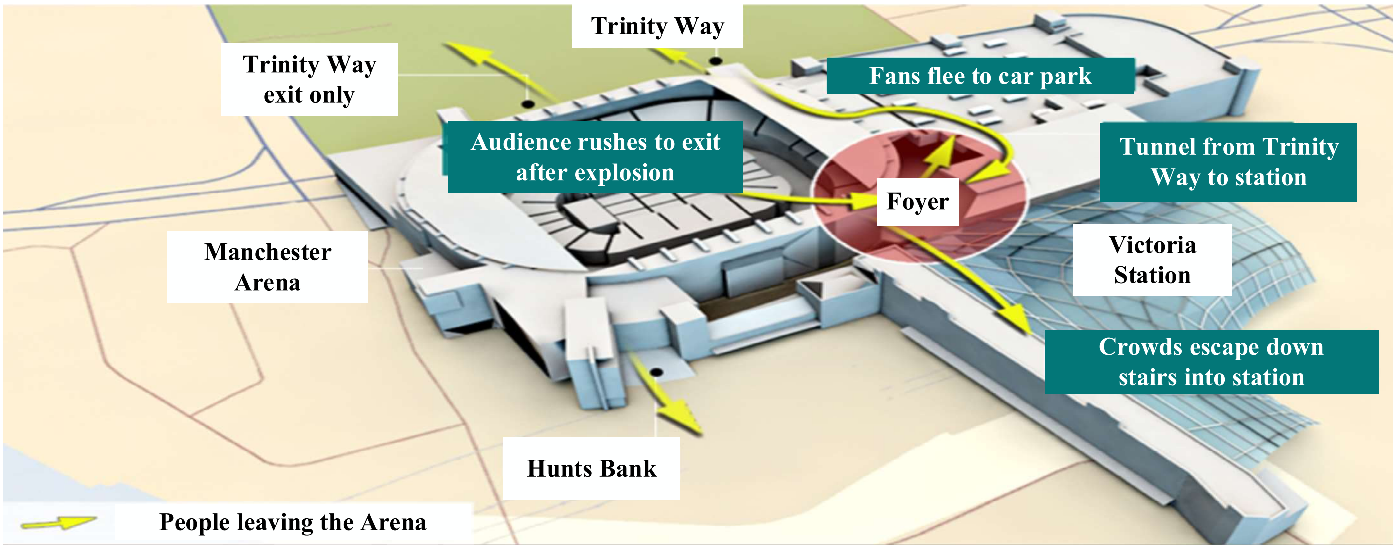


Fig. 3. Manchester Arena and evacuation routes after the attack

Source: The Kerslake Report (Kerslake 2018)

Fig.4

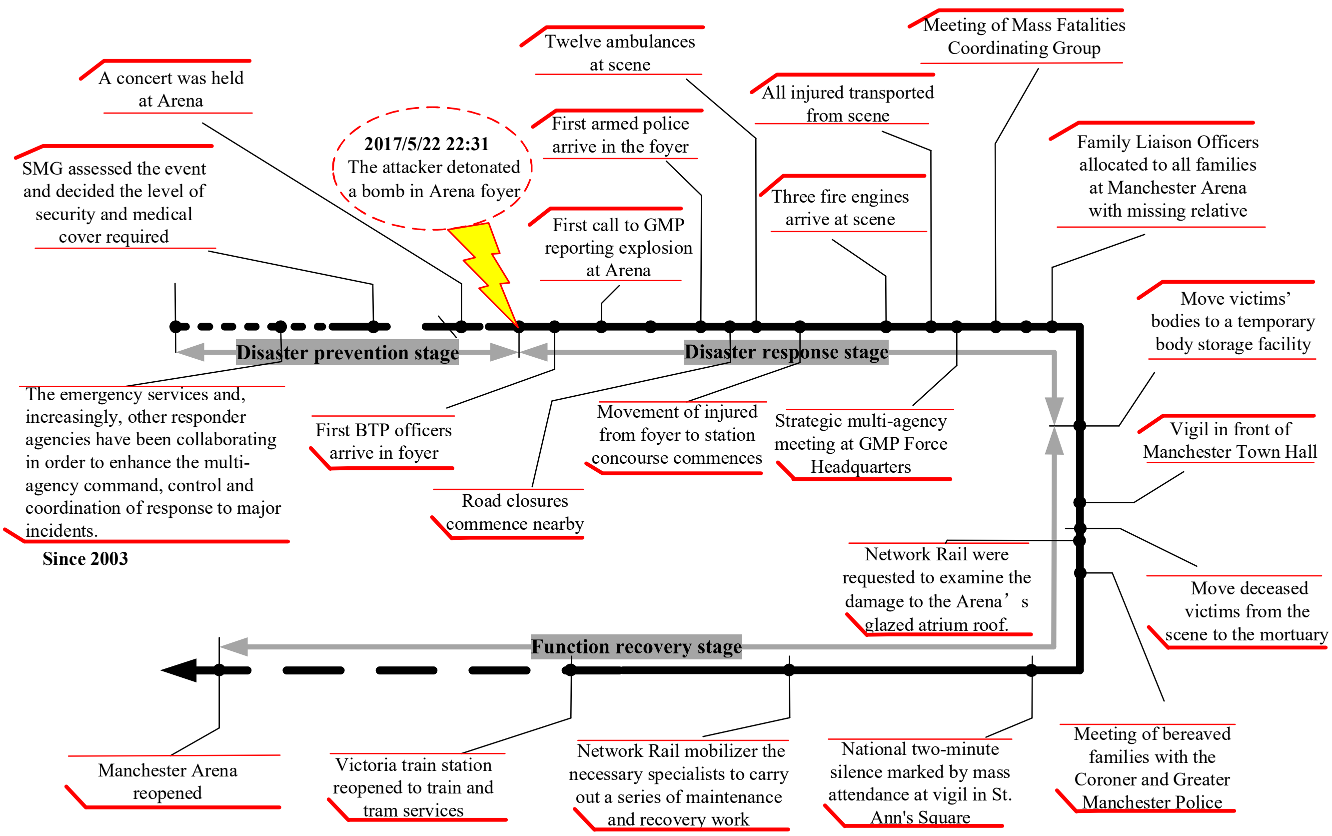


Fig. 4. Three-stage response process of the Manchester Arena attack

Fig.5

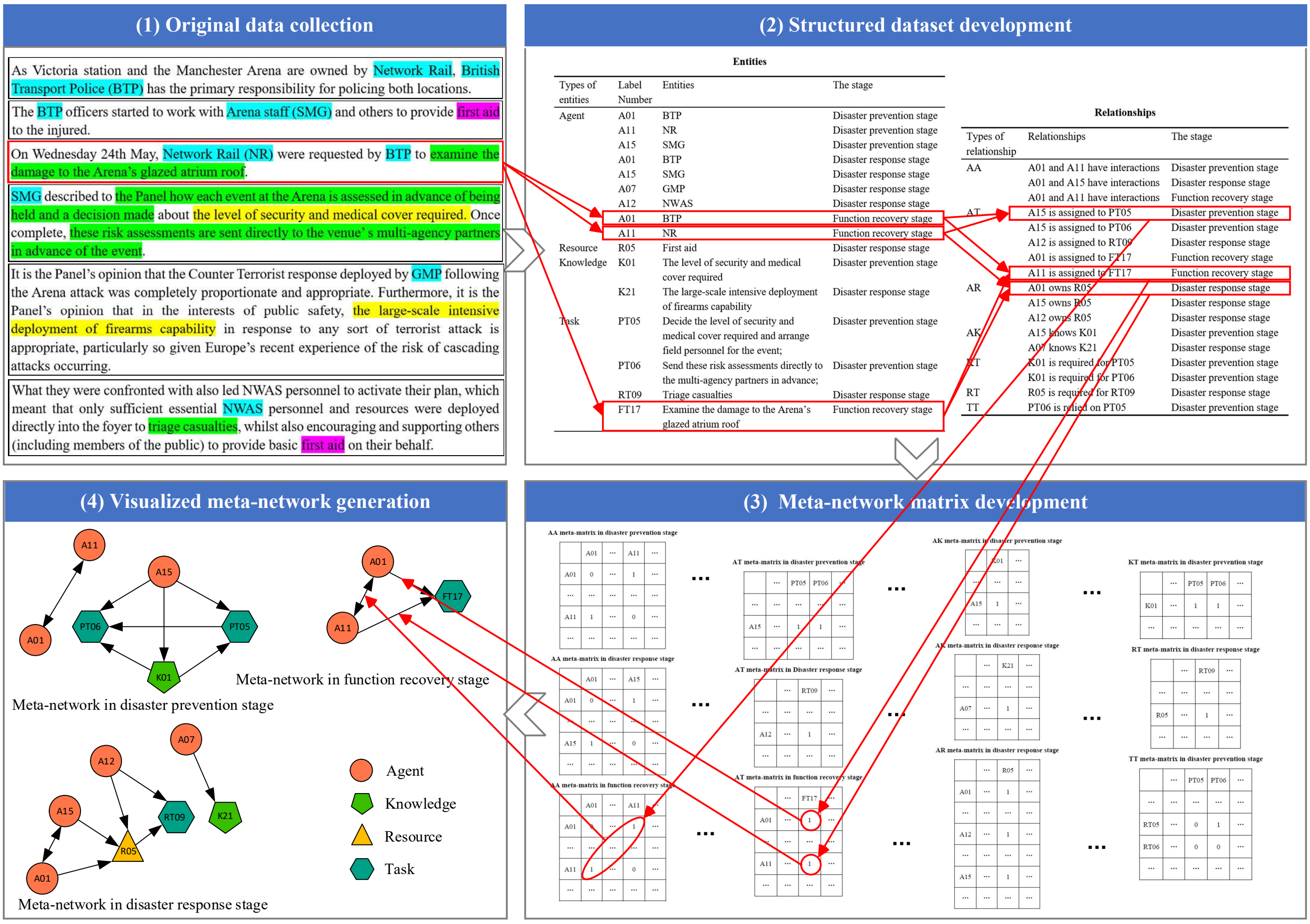


Fig. 5. Illustrative example of data collection and meta-network development

Fig.6

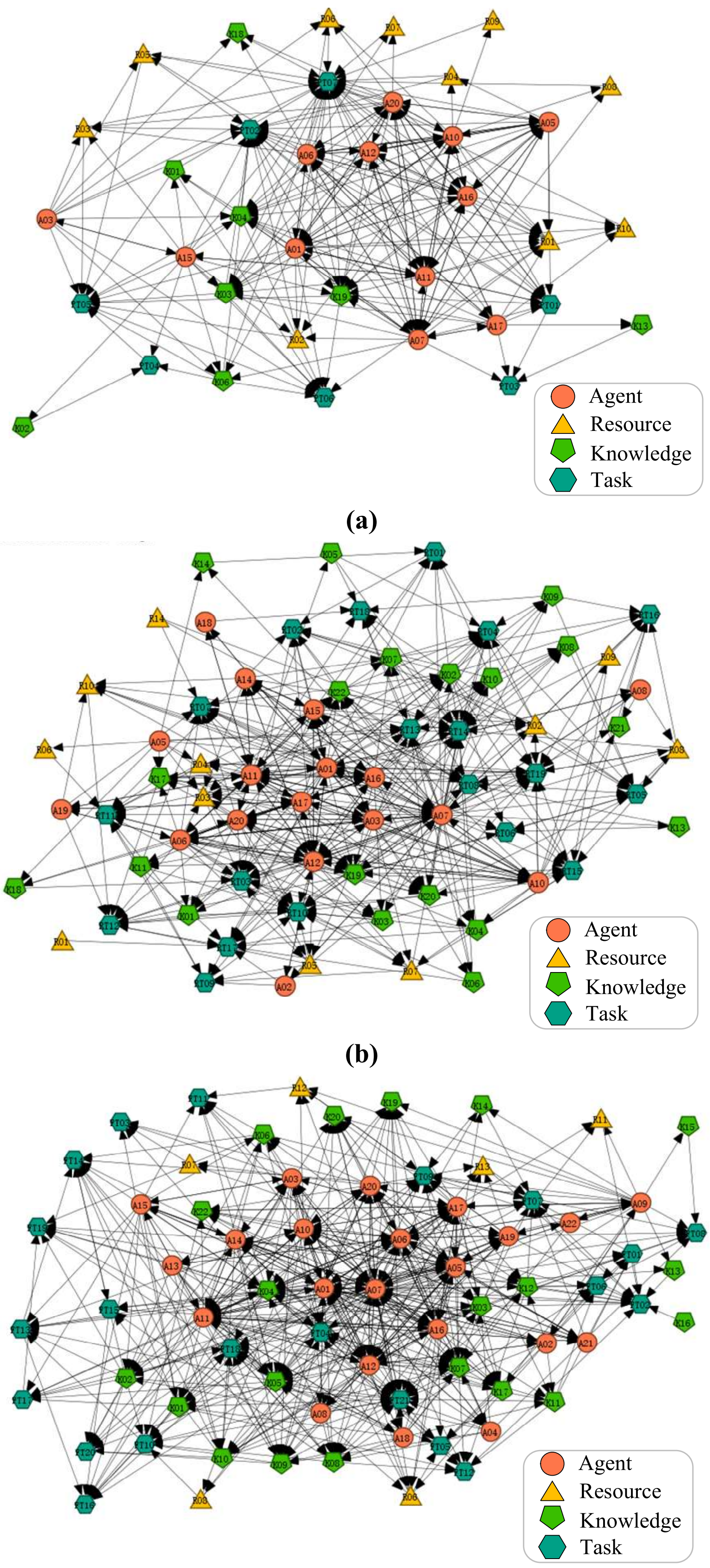
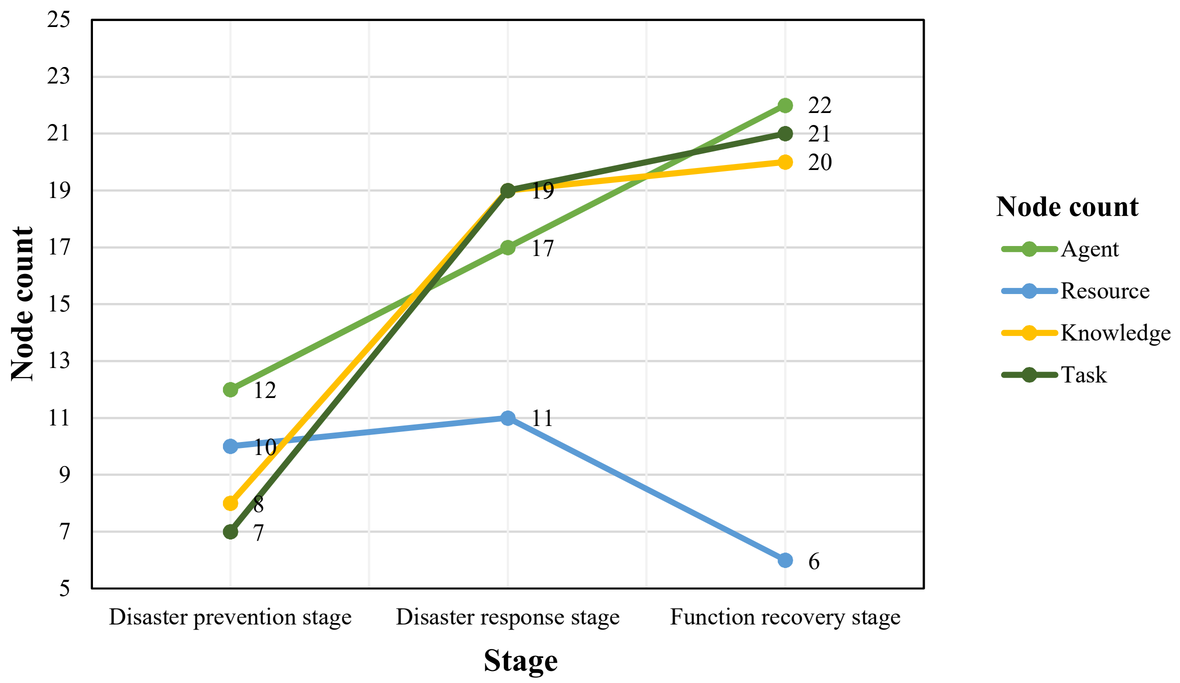
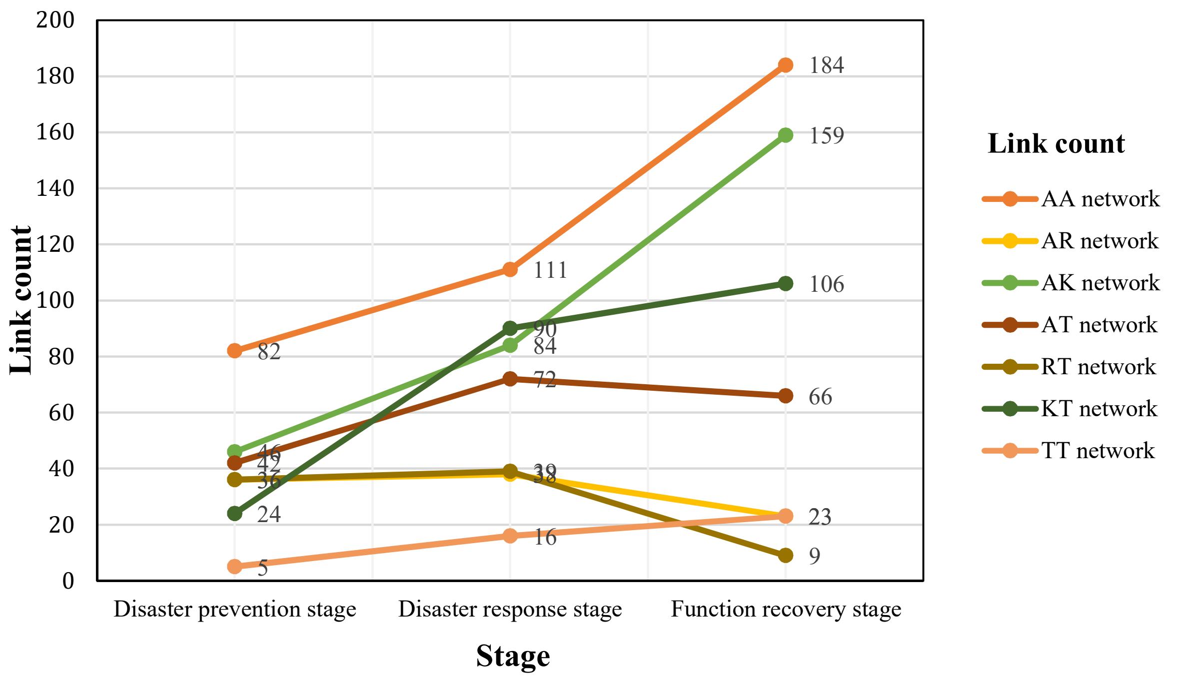


Fig. 6. "A-T-R-K" response meta-networks for Arena attack across the three stages: (a) Disaster prevention stage; (b) Disaster response stage; and (c) Function recovery stage

Fig.7



(a)



(b)

Fig. 7. Summary of three-stage meta-networks: (a) Number of nodes; and (b) Number of links

Fig.8

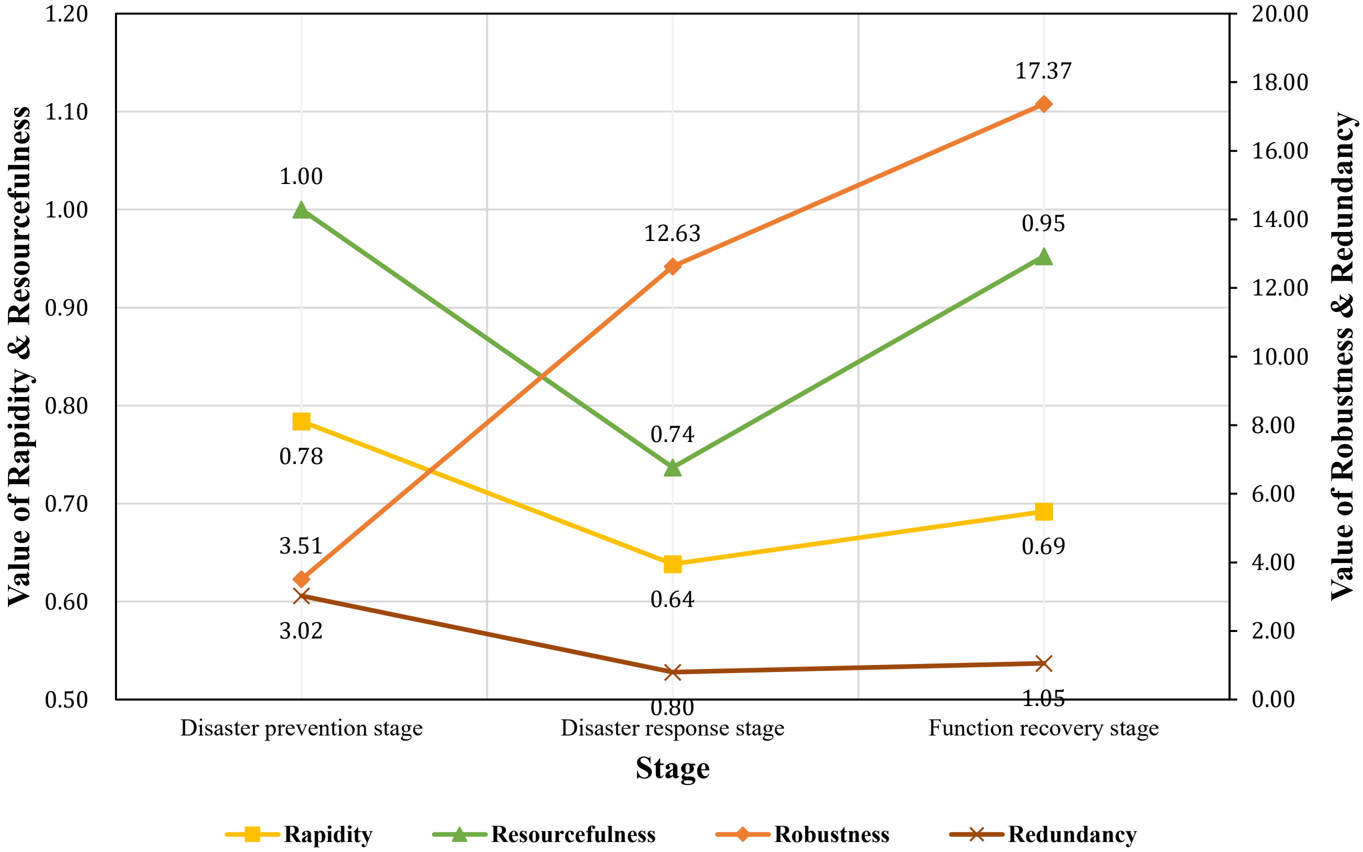


Fig. 8. Dynamic change of 4Rs across three emergency response stages