Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26077-cd

Critical infrastructure dependencies: A network analysis based on expert knowledge

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Critical Infrastructures do not operate in isolation. On the contrary, the failure of one infrastructure can result in the impairment of many others, potentially amplifying the consequences of disruptive events such as extreme weather. A first step towards limiting such cascading effects is to improve our understanding of the dynamic dependencies within the network of socio-technical infrastructures. We contribute to this issue by presenting an analysis of infrastructure dependencies based on expert knowledge. To this end, thirteen experts from ten distinct infrastructure sectors within a city were interviewed to identify dependencies among them. The interviews were conducted based on an interview guideline that was arranged in accordance with the four phases of the resilience cycle. This division allows us to derive an individual network for each phase, ultimately providing a way to visualize and analyze the dynamical evolution of dependencies over the course of a crisis scenario. Overall, the paper presents a methodology for gaining valuable insights into the dynamics of infrastructure dependencies that can inform future disaster resilience analyses. Our approach emphasizes the importance of considering the interplay between different actors and that this interplay is not static but evolves in response to a changing crisis situation.

Keywords: Critical Infrastructure, infrastructure dependencies, network analysis, expert interviews, resilience cycle, crisis management.

1. Introduction

Critical infrastructures (CI) provide essential services, such as food, water and energy to society (Mentges et al., 2023). As such services are required at all times, CI must always maintain a certain degree of functionality, even under the most unfavorable conditions (Gordan et al., 2024). Conversely, failure or malfunction of a CI can have severe consequences for society.

It is therefore of uttermost importance to consider the consequences of CI failures when analyzing the impact of disruptive events such as extreme weather events. In this context, it is important to notify that CIs provide services not only directly to society, but also to other infrastructures (Rinaldi and Peerenbom J.P., 2001) – a prime example being the electricity supply which is required by society as well as by many other CIs. Accordingly, a failure in one infrastructure can cause the impairment of the functionality of other infrastructures (Gordan et al., 2024). Ultimately, such cascading events can severely amplify the consequences of the initiating disruptive event (Tsavdaroglou et al., 2018).

The progression of a cascading failure event does not follow a simple if-then logic (if CI A fails then CI B fails) but is the result of a dynamic interplay between the initiating disruptive event, the affected technical systems and the reaction of human actors (e.g. infrastructure operators and emergency responders) (Kachali et al., 2018). In addition to these factors, time play a decisive role. For example, the duration of a power outage can have a significant impact. Short outages can often be bridged with emergency generators, while longer outages can be severely problematic (Arvidsson et al., 2023; Witte et al., 2021). Therefore, the time dimension must be considered as a key aspect when analyzing cascading effects (Gong et al., 2023). Accordingly, a first step to minimize the impact of cascading events is to better understand the dynamic inter-dependencies within the network of socio-technical infrastructures, which explicitly includes those actors responsible for the protection and restoration of CI.

The aim of the work is to present process-based, dynamic interdependencies between CI during extreme weather events. To this end, guideline based expert interviews where conducted to capture relevant processes, dependencies and actors. The material was systematically analyzed using Mayring´s qualitative content analysis (Mayring, 2015; Wagemann et al., 2020), enabling the identification of key processes in each phase. The results were visualized using network graphs to illustrate the temporal change in dependencies during a extreme weather event. The application aims to test the procedure´s functionality rather than to provide a complete picture of all interdependencies in the study area.

2. Background

2.1. *Infrastructure dependencies*

A CI is said to depend on another if its state is influenced by the state of the other (Rinaldi and Peerenbom J.P., 2001). Such dependencies or links between CI can take on various forms. For instance, a link between two CI can represent a one way connection, if only one depends on the other, or a two way connection, if the two are interdependent (Ouyang, 2014). Furthermore, the source of an interdependency between two CIs can be quite different. In this regard, Rinaldi and Peerenbom J.P. (2001) introduced physical, cyber, geographical and logical dependencies as the four main categories of CI dependencies (see e.g. Ouyang (2014) for alternative classifications). Overall, CIs are interlinked by a dense, complex network of different types of dependencies and should therefore be seen as a system of systems (Rinaldi and Peerenbom J.P., 2001; Ouyang, 2014; Hokstad et al., 2012).

2.2. *Resilience Cycle*

Resilience is the capacity of a system to deal with disruptive events. This capacity encompasses multiple sub-capacities that become active at different phases during a disruption. A common way to illustrate this is the resilience cycle that comprises four successive phases (Rehak et al., 2019) (Fig. 1). In this illustration, the preparation phase is initiated by the warning of an impending disruptive event. The occurrence of this event marks the start of the absorption phase and the recovery phase captures the rather long-term regeneration from the impacts of the event. When there are no pending events, the system can adapt to better deal with future challenges. As this adaption phase describes normal operation of a CI, we refer to this phase as normal operation in the following.

Fig. 1. Illustration of the resilience cycle according to Rehak et al. (2019)

3. Methodology

Approaches for analyzing CI interdependencies and associated cascading effects can be categorized as expert-based, empirical, or simulation-based (Arvidsson, 2024). In this work, an expert-based approach is used to obtain a deeper understanding of the interdependencies between CI. To this end, semi-standardized interviews with thirteen representatives from ten different infrastructures are conducted, each following a predefined interview guideline.

3.1. *Interview Guideline*

The aim of the expert interviews is twofold. First, the interviews serve to gather information about the dependencies and interactions between different CIs. And secondly, the interviews should allow to display the dynamics of these dependencies over the course of an extreme event. To this end, a scenario-based semi-standardized interview guideline is used (Liebold and Trinczek, 2009) that is structured in accordance with the resilience cycle (Fig. 1) and is therefore divided into the following four sections:

(1) Normal Operation
(2) Preparation
(3) Absorption
(4) Recovery

In the section on preparation, absorption and recovery, an extreme weather event was introduced to help experts place themselves in a concrete scenario and thereby reflect on dependencies more precisely. In each phase, interviewees are asked about the primary tasks and main processes that need to be carried out, the conditions that need to be met in order to do so (e.g. which infrastructure services are required) and the actors with whom they need to cooperate. Each section of the guideline consists of a combination of open and closed questions (von dem Berge, 2020) which allows participants to set their own priorities (open questions frame the exploratory part of the interview, e.g. ”What do you need to be able to offer your service?”) but at the same time ensures that all of the most important dependencies are addressed (closed questions serve as backup questions, e.g. ”To what extent are you dependent on the public telephone network?”).

3.2. *Content Analysis*

To derive the network of dependencies and interactions between the different CIs and associated actors, the transcribed interviews were analyzed using Mayring’s qualitative content analysis approach (Mayring, 2015; Wagemann et al., 2020). To this end, we followed a deductive approach in which dependencies between two actors/infrastructures were categorized with regard to the phase (normal operation, preparation, absorption and recovery) in which they are important (main-categories) and with regard to the underlying process that causes the dependency (subcategories). In this way, we created a list of dependencies, where each dependency is characterized by a start node (the dependent actor), an end node (the actor which is relied on), a classification of the dependency (the underlying process) and a time stamp that indicates in which phase(s) the corresponding process is active.

3.3. *Network Analysis*

The list of dependencies can easily be transferred into a directed network, in which each dependency (entry of the list) corresponds to a directed edge of the network. Furthermore, the time stamps allow to derive individual networks for each phase of the resilience cycle, which ultimately provides a way to visualize the dynamics of dependencies over the course of an extreme event. Another advantage of the representation as a network, in addition to the concise visualization, is that it allows examine the dependencies between infrastructures and associated actors using networks analysis tools.

In this work, we use simple metrics like the total number of edges within the network to examine the dynamic evolution of infrastructure dependencies over the course of a disruption. Furthermore, we use the *degree centrality* to identify nodes that could be particularly significant in a crisis situation. The degree centrality quantifies the centrality of a node based on the number of connections/edges it has. In directed networks, a distinction can be made between *in-degree centrality* and *out-degree centrality* (Newman, 2018), where the former measures how many incoming edges a node has and the latter how many outgoing edges a node has. As we assume that an edge pointing towards a node means that this node is relied upon, the in-degree centrality captures how many other nodes depend on the services, support or information provided by this actor. Accordingly, a high in-degree can be associated with a high importance in the network. Conversely, the out-degree centrality can be used to estimate the most dependent actors within a network as it highlights those nodes which require input from many other actors.

4. Results

The methodology was tested in a city at the German North Sea Coast. As the German North Sea coast has always been exposed to the risk of storm surges (Tinz and Müller-Navarra, 2014; Kox Thomas, 2015), the scenario of an extreme storm surge event has been integrated into the guideline. In order to illustrate the dependencies of the CI within a sufficiently bad scenario, it was also assumed that coastal protection fails. Ten interviews were conducted with thirteen representatives from CI in the areas of utility services and civil protection. In addition to the interviewed CI, infrastructures that were mentioned particularly frequently in the interviews were also included in the network graphs.

4.1. *Nodes and edges*

In order to transfer the list of dependencies obtained from the expert interviews (see Section 3.2) into infrastructure dependency networks, the infrastructures/actors in the list were summarized into ten infrastructure sectors, each representing an individual node in the dependency network. The nodes are Emergency Services (ES), Civil Security Services (CSS), Warning Services (WS), Food Supply (FS), Coastal Protection (CP), Municipal Facilities (MF), Healthcare Facilities (HF), Power Supply (PS), Information and Communication Technology (ICT) and Transportation and Traffic (TT).

The dependencies (or edges) between nodes were categorized into four general types in accordance with the underlying process that forms the dependency (e.g. one actor warning another of a pending storm surge corresponds to an instance of 'communication'):

- Service supply
- Bridge infrastructure
- Communication
- Cooperation

This categorization is intended to allow a deeper insight into the source of the changes of the dependency network over the course of the four phases of the resilience cycle. To this end, a specific color is assigned to each process category.

4.2. *Phase-specific network graphs*

To illustrate the temporal dynamics in the dependencies between infrastructures, an individual network graph for each phase of the resilience cycle was created (Fig. 2). Already the visual inspection of these phase-specific graphs reveals the significant change of dependencies over the course of a disruption. This impression is backed up by the evolution of the total number of edges in the network, which increases significantly from the normal operation (46 edges) to the preparation phase (72 edges) and then remains at a high but slightly lower level (69 edges in the absorption phase, 68 edges in the recovery phase).

To better understand the change in the number of dependencies, the consideration of the number of edges in each dependency category is insightful (Fig. 3). As soon as an impending storm surge becomes apparent, actors are warned (directly by WS and indirectly by other actors). Subsequently, various actors must discuss and inform each other about measures that need to be taken to protect their own and other infrastructures from potential damage. Furthermore, to make decisions on necessary measures, decisions makers require information from different infrastructure sectors which is passed on by the corresponding actors. Accordingly, the amount of communication dependencies increases significantly in the preparation phase. In addition, the number of cooperation dependencies and the number of service supply dependencies increase as protective measures are already taken at this stage (requires cooperation) and different actors prepare for the pending crisis (e.g. increase on service supply by FS as actors prepare to supply their emergency personnel).

In the following phases of the resilience cycle (absorption and recovery), the number of communication dependencies decreases as all actors have been warned and many of the measures to be taken have already been coordinated. In contrast, the number of cooperation dependencies increase further as protective measures are main-

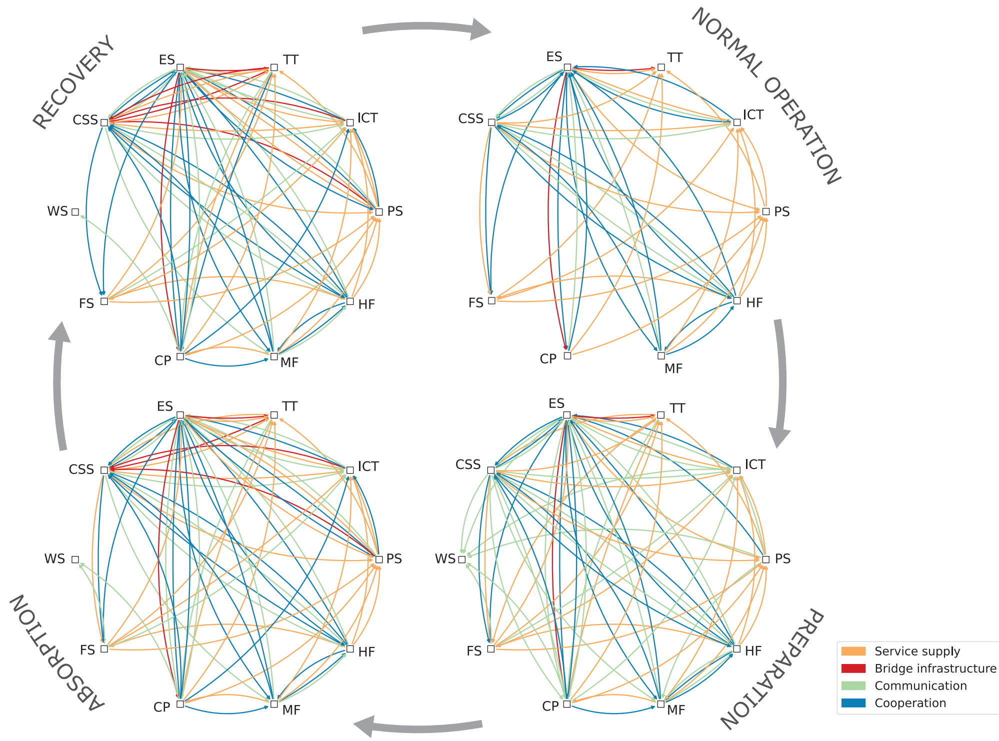

Fig. 2. Dependencies between CI in the normal operation, preparation, absorption and regeneration phase based on the resilience cycle.

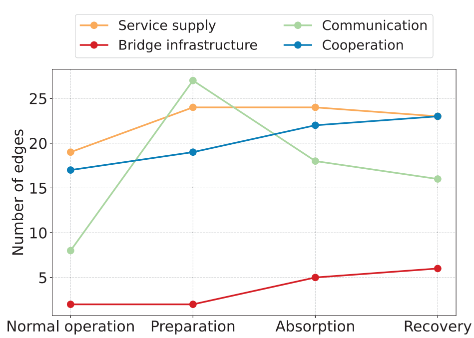

Fig. 3. Representation of the number of respective processes and network density across the four phases

tained and further acute measures are taken in response to actual damages. Accordingly, in these phases, the number of bridge infrastructure dependencies increases as well (e.g. CSS provides alternative power source to support ICT). Regarding the lower overall number of dependencies in these later phases (absorption and recovery), it should be noted that this is partly due to the limited representation of these phases (especially the recovery phase) in the interviews. Experts noted that the tasks and processes in these phases depend heavily on the specific manifestation of the crisis, requiring a more responsive approach than the processes in the preparation phase. To better address this, a very specific and detailed description of the crisis scenario would have been required. However, this was not part of the interview setup. Consequently, it can be assumed that the number of dependencies in these phases is underestimated in the present analysis.

In this context, it should also be noted that the absorption and recovery graphs are derived based on the assumption that coastal protection fails. However, if coastal protection would not fail at the time of the storm surge, only minor damages to the coastal area could be expected and thus, once all protective measures have been taken, the system would return to a state close to normal operation. Accordingly, the two later phases of the resilience cycle would change drastically. This showcases that the importance of coastal protection for the dynamic evolution of the network of dependencies goes beyond the connectivity of the corresponding CP node within the graph.

4.2.1. *The most important nodes in the network*

We use the in-degree centrality to display how the importance of actors and infrastructures evolves over the course of a disruption. To this end, in each phase of the resilience cycle, we rank all nodes according to their in-degree centrality from most to least central (Fig. 4).

First of all, the phase-dependent ranking shows that ICT, which enables the communication between all actors, ranks highly in all phases. A failure or disruption in this sector can have a major impact on the efficiency of the entire system of interdependent actors and thus also on the overall crisis response. The other two sectors (TT and PS), which are responsible for providing basic services to the population and to other infrastructures, also obtain relatively high ranks in all phases. This shows that maintaining basic infrastructure services at all times is a key task in dealing with crisis situations.

While ICT obtains the highest rank during normal operation, ES become the most central node in the preparation and the subsequent phases (i.e. during the entire emergency). This change in the ranking displays the central role of ES in coordinating the emergency response. ES are responsible for many focal tasks such as setting up the crisis management team, collecting information, passing it on to other actors and to society, and coordinating emergency relief forces. A similar dynamic can be observed for CSS (higher rank from preparation onwards), which perform important tasks during the crisis and provide support in various areas.

The ranking also shows significant changes in

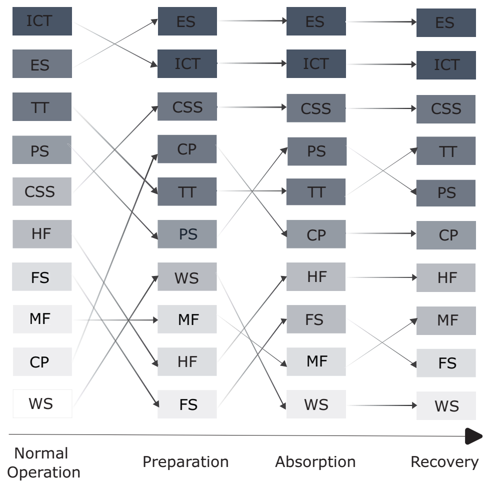

Fig. 4. Ranking of nodes according to their in-degree centrality, with the most central node obtaining the top rank. The coloring of nodes shows their in-degree centrality (the darker the color, the higher the in-degree centrality). The arrows display the changes in the ranking over the four phases of a storm surge (normal operation, preparation, absorption, and regeneration).

the lower ranks, especially between the three earlier phases (normal operation, preparation and absorption). Particularly noteworthy are the spikes in importance of the WS and the CP in the preparation phase. The reason is that both represent critical sources of information and expertise in the phase of an impending storm surge. In addition, CP is a key player in preparing protective measures. While these findings are not surprising, they illustrate that the network graphs can capture fundamental characteristics of real emergency dynamics.

4.2.2. *The most dependent nodes in the network*

We use node rankings based on the out-degree centrality to display how the degree of dependence of actors and infrastructures evolves over the course of a disruption (Fig. 5). In contrast to the in-degree centrality rankings, the results show that basic infrastructures (ICT, TT and PS) obtain comparatively low ranks. This is particular evident in the TT and the ICT sectors. Due to their supra-regional orientation, they are only loosely linked

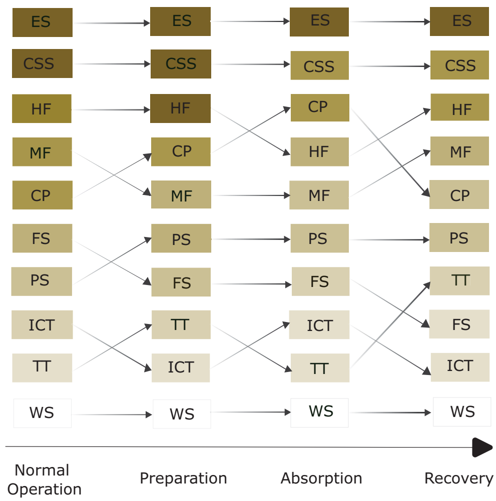

Fig. 5. Ranking of nodes according to their out-degree centrality, with the most central node obtaining the top rank. The coloring of nodes shows their out-degree centrality (the darker the color, the higher the out-degree centrality). The arrows display the changes in the ranking over the four phases of a storm surge (normal operation, preparation, absorption, and regeneration).

to regional infrastructures. The same applies to the WS, which shows no local dependencies as it is managed on a supra-regional level.

A particular interesting finding is that the ES, which have already taken the top spot in three out of four phases in the in-degree ranking (see Fig. 4), are also on the top of the ranking in the out-degree ranking in all four phases (Fig. 5). This further highlights the key role played by the ES in managing crises: a lot of actors rely on input by ES but, on the other side, ES require the input from other actors in order to coordinate the crisis preparation and response effectively. The same can again be said for CSS, albeit to a lesser degree, which rank second throughout the entire resilience cycle.

5. Conclusion

The inter-dependency between different infrastructures is a topic of great significance for analyzing potential impacts of hazardous events, since the failure of one infrastructure could trigger the failure of others, ultimately resulting in a failure cascade. In infrastructure systems in the emergency response context, the trigger of such a cascade does not necessarily correspond to a technical failure but can also constitute a lack of assistance or information. This paper shows that expert interviews can be used to gain insights into this complex net of interrelationships and dependencies between CI and actors within the emergency response context. Even a comparatively small number of interviews was sufficient to reconstruct a dense network of dependencies and to showcase that this network evolves over the course of a crisis event. Furthermore, the analysis shows that techniques from the field of graph theory, like centrality, can be applied to gain insights regarding the most important as well as the most vulnerable nodes in the network.

However, the specific results of this work should be treated with caution. The displayed networks are solely based on the information obtained from interviews with experts that cover only a subset of the included infrastructures sectors (e.g. no interviews with TT). Accordingly, to obtain more trustworthy insights, the underlying dependency data should be complemented by further information sources, such as a detailed literature review or complementing questionnaires with further representatives from the various infrastructure sectors. Furthermore, the information concerning the dependencies is exclusively qualitative in nature and some of the links contain multiple underlying processes (e.g. different ways in which one actors supports another). Accordingly, the networks are not suitable for a detailed failure analysis. In this light, the results of this work should be seen as a proof of concept. Expert interviews that are structured using the resilience cycle can be a valuable and complementary tool for gaining a better understanding of inter-dependencies between different infrastructure sectors.

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