Resilience quantification of Interdependent Infrastructure System: Means of optimising adaptation and mitigation measures

M. Imani¹, D. Hajializadeh¹

¹Department of Engineering and the Built Environment (EBE), Anglia Ruskin University, Chelmsford, Essex, CM1 1SQ, United Kingdom

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1. ABSTRACT

Infrastructure networks do not exist in isolation. Rather they are interconnected to other infrastructures and, as technological development increases, so too does the linkage between networks. Interdependencies among Critical Infrastructure (CI) can cause cascading failures and hence amplify negative consequences due to these failures. This can also affect CI’s service restoration rate and consequently reducing their resilience in coping with these hazardous environmental events. For example, failure of the water drain and sewer system due to 2002 Glasgow flooding affected many homes and closed many main roads and stations such as the A82 and A8 roads, Buchanan Street subway station and Dalmarnock through to Exhibition Centre stations on the Argyle Line.

As infrastructures are becoming more interdependent at some sectors, there is an increasing demand for more effective management of these interactions and interdependencies. This paper provides details of a quantitative metric for the robustness, recoverability, rapidity and resourcefulness of the interdependent infrastructure network in response to hazardous event. By generating a quantitative measure of network resilience, considering infrastructure interdependencies, the most severe failure scenarios and their spatial impacts can be identified and mapped. This can lead to prioritise future business planning strategies for CI asset owners and managers. To illustrate the application of the proposed approach, a case study in North Argyll, Scotland is analysed and presented in this paper.

2. Introduction

The frequency and magnitude of environmental hazards in Scotland and UK in general, have significantly increased in the last decade, resulting in widespread failures in critical infrastructure (CI) networks. UK infrastructure networks are highly complex and interconnected. The centralised nature of these infrastructure networks and the interconnectedness between services implies that damage at a point in the system can have knock-on effects through the system and other connected infrastructure systems (Guthrie & Konaris, 2012). Therefore, it is vital that these systems to be resilient to any type of disturbances (McDaniels, et al., 2008). The pursuit for infrastructure resilience requires a pursuit for the reduction of failure probabilities, reduction of negative consequences when failure does occur, and reduction in recovery time (Walker, et al., 2004; Chang, 2009). The importance of protecting this infrastructure from threat lies not only in its critical role of sustaining societies, but also in its role of helping communities and the economy to rebuild themselves post-disruptions (shocks and stresses). Service disruptions caused by asset damage can lead to economic and societal impacts which, in the case of vulnerable groups, can be difficult to recover from. As a result, planning for
adaptation and mitigation strategies in CI networks requires a sound understanding of CI networks’
interconnections and their behaviour when interdependency-induced failures occur.
The common challenge currently faced by asset owners and managers is the lack of a robust resilience-
informed business planning and management strategies in response to interdependent assets’ failures
particularly in low-probability/high-impact events. To manage the infrastructure interdependencies
and their interactions in response to disastrous events, in addition to holistic risk/vulnerability
mitigation approach; there is a need for resilience-informed management system. This will establish
the key components of existing CI network and will assess the sensitivity of these components to
disastrous events and their capacity in coping with such events. This paper aims to show some
achievements of the RV-DSS project in developing a resilience-informed decision making tool for the
CI networks of Water, Transport, and Energy in a case study in Scotland, UK and provide a measure of
interdependent networks’ resilience in response to hazardous events.

3. Methodology
An effective resilience-informed intervention plan, in an interdependent network of CIs, requires an
integrated network model and an appropriate resilience quantification technique. Therefore, this
section consists of a three-stage strategy:

3.1. Stage 1: Interdependent Network Modelling
Different approaches have been used for infrastructure interactions modelling, such as: empirical
approaches, agent-based approaches, system dynamics-based approaches, economic theory-based
approaches (input-output models), network-based approaches, and other approaches (Ouyang, 2014;
Saidi et al., 2018). This study has adopted the network-based approach to model the CI
interdependent network. For this purpose, the infrastructure network topology and layout features
were characterized by taking advantage of closed-form expressions and numerical simulations. This
method has been successfully and widely used to study the reliability of a power system under natural
and man-made shocks (Wang and Rong, 2011; Winkler et al., 2011). To model the network, the assets’
attributes and the topological characteristics of each infrastructure network are needed.

**Topological network:** it can be mathematically presented as a graph with nodes and edges
representing their connectivity. For the infrastructure network \( M \), network properties can be
represented by \( I_M = \{N_M, E_M, M_M\} \):

where, \( N_M \), is the node sets, \( E_M \), is edges set and \( M_M \) is a \( N_M \times N_M \) matrix representing the
mathematical function of edges to pair-wise nodes.

An interdependent network model comprises of nodes (e.g., power plans, transformers, pump
stations, tanks, junctions, bridges, etc.), links (e.g., distribution lines, information exchange, roads,
pipes, etc.) and flows (e.g. energy, water, traffic, information, people, etc.) in a given infrastructure
system. The actions and interactions of each individual infrastructure element (nodes and links) is
modelled with a view to assess their effects on the system as a whole. It combines elements of game
theory, complex systems and multi-agent system programming.

**Assets’ attributes:** all the assets’ attributes (e.g. number of users per node, node/link type, failure
travel time, node coordination, asset value, recovery time, etc.), in the interdependent network, are
stored in a data repository, with characterisation of their physical and functional interdependencies.
These information are then used to generate the asset inventory map and evaluation of resilience
across the whole network.

Figure 1a demonstrates an exemplar benchmark interdependent network created for preliminary
study in this research.
3.2. Stage 2: Failure Propagation

In an interdependent network of infrastructure, failure at an interdependent asset is propagated to all the interdependent assets, their services and the overall network performance. Assets failure (including the propagated failure in interdependent assets) can happen individually (single failure) across the whole network or concurrently (multiple failure – a schematic in Figure 1b). For simplicity, it was assumed all the multiple failures happen at the same time (no failure lag). The failure propagation times have been introduced as an asset attribute. This study assumes abrupt change in performance indicator, however, in practice this change could occur in linear or a nonlinear trend.

3.3. Stage 3: Resilience Quantification

The resilience assessment is meaningful if there is a recovery measure in place. Resilience is an endowed or enriched property of a system capable of effectively absorbing, adapting and rapidly recovering from the disruptive event (Francis and Bekera, 2014). Butler et al., (2016) defines resilience as “the degree to which the system minimises the level of service failure magnitude and duration over its design life when subject to exceptional conditions”. Hence, this study calculates resilience, given average recovery initiation time ($N_{TR_i}$) and recovery duration ($N_{TR_o}$) provided as an input/network attribute (see section 2.1). It also requires the average recovery cost which provides necessary metrics for a simple cost/benefit (resilience) assessment. To measure resilience a two-dimensional metric has been used to reflect on time and performance indicator (i.e. network functionality) at the same time (Figure 2).

As can be seen from Figure 2, resilience is defined as the area covered by the performance indicator diagram. This area reflects network robustness, recoverability, rapidity and resourcefulness in one single metric. The performance indicator has been defined as the number of users remain in service.
4. Case study
The case study hereafter referred to North Argyll in Scotland (Figure 3) consistent of an interdependent network of road system, railway system, ferry system, water system and energy system have been studies in this research. This study type requires a wide range of data. Given the variety of the organisations involved in data provision, the data sharing procedure proved to be very challenging and not achievable within the timeframe of the project. Therefore to illustrate the application of the framework, a dummy case study was produced using the open access data and shared with the project partners for further validation to make the feasibility study closest to practice. The dummy case study initiated with the assumption that water distribution network (in particular pipes) and energy transmission lines would naturally follow the transport network.

5. Results and Analysis
For the purpose of resilience evaluation across the whole network, the failure propagation ($N_{A, NO, T_{FP}}$), recovery initiation ($N_{A, NO, T_{RD}}$) and recovery duration ($N_{A, NO, T_{R}}$) are assumed constant for all assets (nodes and links). For the purpose of the analyses, these parameters are considered to be $N_{A, NO, T_{FP}} = 1hr$, $N_{A, NO, T_{RD}} = 1hr$ and $N_{A, NO, T_{R}} = 4hrs$, respectively. Also, to demonstrate the impact of recovery duration change, the scenarios with $N_{A, NO, T_{R}} = 3hrs$ have also been assumed to estimate and analyse the impact on savings given the unit cost of £100/no. users x time.

The impact of the optimised interventions have been assessed as the percentage of changes in resilience through a cost benefit analysis of the improved intervention. Figure 4 shows two exemplar results for a given 1 hour change in recovery duration (from 4 hours to 3 hours) in rail and water networks. This change in recovery can be in the form of improving the rapidity or increasing the resources available for the recovery process with the cost unit per hour (e.g., £2000 per hour). This cost then can be compared to resilient saving given the cost unit per 1% change in resilience. For the illustrative purposes, the unit cost saving per 1% change in resilient is considered to be £1000. For example, Figure 4 demonstrates the changes in resilience and the associated saving for all single failure scenarios in water and rail networks.
Figure 4 – Change in resilience and resulting saving for all single node failure scenarios and 1 hour difference in recovery duration a) rail network; b) water network

It can be seen from Figure 4a that, given the level of interdependency between every rail asset and water and energy network, 1 hour change in recovery process offers the maximum resilience change of up to 5.5% and hence, resilience saving of £5,500. Similarly in Figure 4b, the 1 hour change in recovery process in water network has resulted in maximum of 3.162% change in resilience and £3,162 of resilience saving.

It is crucial for infrastructure asset owners to have a better understanding of the dynamics of their networks’ ‘interdependency zones’, their resilience levels and the impacts of the resilience changes across the integrated network. Drawing on this, Figure 5b illustrates network resilience versus maximum failure (i.e. maximum loss of users) for all double failure scenarios in all CI networks. These plots are divided into four zones: a red zone: high failure with high resilience; a green zone: low failure
with high resilience; and two amber zones: high failure with high resilience and low failure with low resilience. The thresholds used in defining these zones are subjective and highly dependent on decision-making criteria, for the purpose of this study, the midpoint in the plot is used as a threshold – this is slightly different for the rail network with significantly higher number of red zone failure scenarios.

Figure 5a maps all the aforementioned interdependency zones in the case study as grey dots. The exemplar interdependency-induced double failure scenario shown in Figure 5a has been highlighted in red. As can be seen in Figure 5b, there are concerns in relation to double failures in Ferry and Rail networks (red zone) while water network mainly contains amber zone failure scenarios. The highlighted double failure in Figure 5a, doesn’t have much impact on road and energy networks as it falls in green area but it is quite concerning in ferry network as the maximum failure is high while resilience level is low (according to the user-defined thresholds). Water network is at the boundary of green and amber zones implying the vulnerability of water network to this interdependency-induced failure.

Figure 5 – a) interdependency zones in Benchmark network; b) Impact matrix for Double Failure scenario

6. Conclusions

This study demonstrates the resilience quantification and assessment of three interdependent CI networks of water, transport and energy in a case study in Scotland, UK. It is shown that the inherent interdependency in the infrastructure network can increase vulnerability of the network in response to cascading failures. Failure to understand the dynamic behaviour of these interdependent networks will result in ineffective response and poor coordination for adaptation and mitigation to tackle the emerging challenges. The results show that although interdependencies increase system vulnerability, specially in highly interconnected networks, but on the other hand, planning for shared interventions, through resilience-informed planning, can create shared opportunities for faster recovery and shared benefits. This implies that enhanced CI interdependencies management requires collaboration and shared intervention amongst all the role players. Resilience-informed interdependency management can transform the investment strategies in CI sectors.
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