SUPPLY CHAIN RESILIENCE

Submitted in partial fulfilment of the requirements

of the degree of

Master of Business Administration

by

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Supervisor

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Declaration

I hereby declare that the work which is presented here, entitled **Supply Chain Resilience**, submitted in partial fulfilment of the requirements for the award of the Degree of **Master of Business Administration** in the Department of Management Studies, Indian Institute of Technology Roorkee. I also declare that I have been doing my work from Month Year under the supervision and guidance of **Prof. Manu Kumar Gupta, Department of Management Studies, Indian Institute of Technology Roorkee**. The matter presented in this dissertation report has not been submitted by me for award of any other degree of institute or any other institutes.

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Certificate

This is to certify that the above statement made by the candidate is true to best of my knowledge and belief.

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Abstract

The project discusses the concept of supply chain resiliency, which is crucial for mitigating the risks and impacts of unexpected disruptions that can occur at any point in a supply chain. Supply chain disruptions come from various sources, both internal and external, and have far-reaching impacts both upstream and downstream.

In recent years, several significant trends, including globalization, outsourcing, and an increase in terrorist attacks, have highlighted the importance of managing supply chain risks. The report discusses the InfraRisk platform, a simulation platform that is capable of a comprehensive analysis of interdependent infrastructure systems. The simulation is conducted for a simple network and resilience metrics are calculated and network performance during the disruption is evaluated.

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Chapter 1: Introduction

Every activity within a supply chain comes with inherent risks, as unexpected disruptions may occur at any point in time. The global nature of supply chains, coupled with shorter product lifecycles and ever-increasing customer demands, has made it clear to businesses that supply chain disruptions can have undesirable operational and financial impacts. Events such as the loss of a critical supplier, a major fire at a manufacturing plant, or a terrorist attack can lead to reduced revenue and increased costs due to premium and expedited logistics services. To minimize this risk, supply chains must be designed with event readiness, capable of an efficient and effective response, and the ability to recover from disruptive events to their original or even better state. This is the essence of supply chain resiliency.

Supply chain disruptions can emerge from various sources, including external factors such as natural disasters, and internal factors such as failure to integrate all functions within a supply chain. Such events often occur suddenly and unexpectedly. Moreover, efforts to establish a more cost-effective and efficient supply chain environment may also lead to disruptions. Nowadays, many firms outsource logistics activities, such as raw material procurement, component assembly, manufacturing, and product distribution to global partners. This structure has resulted in a supply chain-dependent environment where any disruption can have a far-reaching impact upstream or downstream in the supply chain. As the risks to the supply chain increase, firms must develop logistics processes and capabilities that enable them to respond effectively and efficiently and continue their operations as planned. Thus, understanding the resilience of supply chains requires an assessment of logistics capabilities.

Supply chain risk management is defined as, "the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach among supply chain members, to reduce supply chain vulnerability." (Manuj and Mentzer, 2008)

During the past decade, several significant trends have contributed to the heightened significance of managing supply chain risks. These include factors such as globalization, outsourcing, the shift towards lean and agile operations, as well as an increase in terrorist attacks and other threats. Consequently, a considerable amount of recent research has been focused on categorizing the various risks, threats, and disruptions that affect supply chains. For instance, Manuj and Mentzer (2008) analyzed the existing literature across supply chain and related fields to propose a five-step model for global supply chain risk management. These five steps encompass risk identification, risk assessment and evaluation, selecting appropriate risk management strategies, implementing strategies, and mitigating supply chain risks.

Chapter 2: Overview of InfraRisk

Urban infrastructure systems, such as power, water, and transport, play a critical role in the functioning of businesses and communities. However, they are also highly susceptible to major hazards such as floods and earthquakes, as well as emerging threats like cyber-attacks and acts of terrorism, all of which are exacerbated by climate-induced extreme weather events. The interruption of these systems can result in significant short- and long-term economic and societal losses, which may be further amplified by interdependencies among critical infrastructure systems. For instance, the 2021 Texas snowstorm caused power blackouts and water supply disruptions in Central Texas, leading to a ripple effect in national and global supply chains. Previous events have demonstrated that the indirect economic impacts of infrastructure disruptions are considerably more substantial than the direct costs associated with restoration and failure.

Both real-world observations and computer modeling demonstrate that strategic measures aimed at enhancing resilience against infrastructure breakdowns caused by external factors have the potential to not only minimize operational disruptions in individual infrastructure systems but also lower the probability of extensive network-wide repercussions (de Almeida & Mostafavi, 2016; Sadashiva et al., 2021). These measures can be grouped into various categories based on the specific resilience aspects of the infrastructure system they aim to address, including its ability to resist, absorb, or recover from stressors (Ouyang, 2014; Vugrin, Warren, & Ehlen, 2011).

The main challenge lies in identifying and assessing multiple practical resilience options, both at the system and component level; and implementing those that are cost-effective (Najarian & Lim, 2020). Furthermore, this task requires comprehensive frameworks and tools that provide a holistic view of the network-wide impacts of various system-level and component-level resilience strategies (Ouyang, 2014; Setola, Luiijf, & Theocharidou, 2016) to facilitate cost-benefit analysis. As infrastructure resilience studies continue to gain importance in the social and economic spheres, there is a greater need for simulation tools capable of conducting more detailed analyses.

Although modeling and simulation tools have been widely used for analyzing the resilience of individual infrastructure systems, there was a lack of research on integrated infrastructure systems for component-level analyses (Saidi et al., 2018). Even among the available integrated infrastructure models, little attention has been paid to interdependent water-power-transport networks, despite their significant importance for the efficiency and resilience of cities. A study that aimed to introduce an open-source simulation package called "InfraRisk," developed was developed by Balakrishnan and Cassottana (2022) in Python, for analyzing interdependent power-water-transport networks. The overall objective of InfraRisk is to provide a simulation platform for the comprehensive analysis of interdependent infrastructure systems. The specific objectives of InfraRisk are:

1. To integrate existing infrastructure simulation libraries into a unified simulation package using an object-oriented interface. It aims to provide a sequential approach for the simulation of network-wide effects in interdependent power, water, and transport systems.
2. To incorporate sub models for hazard initiation and recovery in the integrated infrastructure model, to analyze the impact of disaster-induced infrastructure component failures and the subsequent restoration actions on the resilience capabilities of the infrastructure systems.
3. To provide functional metrics that can be used to evaluate the effectiveness of pre- and post-disaster resilience interventions.

In conclusion, InfraRisk is a simulation-based decision-making tool that aids in designing, testing, and evaluating resilience interventions for interdependent power-, water-, and transport systems.

2.1. Studies in Resilience Analysis and Simulation of Infrastructure Systems

The importance of considering the interdependencies of infrastructure systems in disaster resilience assessments has only recently gained attention in the last 30 years. Prior to that, the focus was solely on improving the physical security and robustness of individual infrastructure systems. However, disasters such as the World Trade Center attack, Northeast blackout, Indian Ocean earthquake and tsunami, and Hurricane Katrina highlighted the intensified societal and economic losses resulting from interconnections among critical infrastructure sectors. As a result, many countries have made infrastructure systems and their interdependencies a major consideration in national security, leading to increased support for research and development in infrastructure resilience. This has resulted in significant academic interest in identifying, classifying, and modeling infrastructure interdependencies, leading to the development of various frameworks, methods, and models for analyzing interdependent infrastructure networks.

2.2. Traditional infrastructure simulation models

Traditional infrastructure interdependency models can be classified into two groups: empirical models and computational models. Empirical models rely on historical infrastructure failures to determine the interactions between infrastructure systems. They can be built using qualitative or quantitative data, but they have limitations in identifying potential failure scenarios that have not yet occurred. In contrast, computational models use mathematical and logical functions to simulate real-world systems in a controlled environment. These models are effective in understanding infrastructure properties and resilience interventions in system response. The most common computational models are graph-based, system dynamics-based, and agent-based models.

Graph-based models create abstractions of infrastructure systems by representing infrastructure components as nodes and their interrelationships as edges. Network-flow optimization concepts and graph theory have been extensively applied to study the impacts of infrastructure component failures and their consequences. However, these models do not consider detailed functional aspects of system components.

System dynamics-based models use feedback loops, stocks, and flows to create abstractions of interdependent infrastructure networks. They simulate dynamic and evolutionary effects in the infrastructure system by testing various policies and investment alternatives using stock and flow variables. However, the notable drawbacks of system dynamics models are their incapability to analyze infrastructure systems at the component level, the need for a large amount of data for calibration, and excessive dependence on expert judgments for establishing feedback loops in the model.

Agent-based modeling is a bottom-up approach that models interdependent infrastructure networks at a granular scale by considering them as system-of-systems. ABMs simulate infrastructure components as agents and allow them to interact with each other in representative operating environments to obtain quantitative insights into the system behavior. However, key issues pertaining to ABMs are their over-dependence on assumptions, calibration of parameters, and validation of results.

Table 1
Examples of water, power and traffic simulation packages and tools.

Infrastructure systems	Simulation platform	Programming language	Open-source	Functionalities
Water	EPANET and its extensions	Standalone with GUI, versions in Python (wntr), R (Epanet2toolkit), Matlab (EPANET Toolkit).	Yes	Hydraulic simulation of water distribution systems.
	WaterGEMS	Standalone with GUI	No	Hydraulic simulation of water distribution systems
	Replica	Standalone with GUI	No	Dynamic simulation of fluids, including hydraulic simulation.
	TSNet	Python	Yes	Transient simulation of water distribution systems.
Power	Matpower	MATLAB	Yes	Steady-state power system simulation and optimization.
	Pandapower	Python	Yes	Analysis and optimization of power systems.
	PowerWorld Simulator	Standalone with GUI	No	Interactive simulation, analysis and visualization of power systems.
	OpenDSS	Standalone with GUI	Yes	Simulation of electric utility distribution systems.
	GridLAB-D	Standalone with GUI	Yes	Simulation and analysis of power distribution systems.
	Dome	Python	Yes	Power system analysis.
Transportation	MATSIM	Java	Yes	Agent-based simulation of large-scale transport systems, including road networks.
	MatLAB DTA package	MATLAB	Yes	Dynamic traffic assignment in road traffic networks.
	Vissim	Standalone with GUI	No	Microscopic and mesoscopic traffic simulation.
	Python STA package	Python	Yes	Static traffic assignment in road traffic networks.

In some other models, a hybrid approach that combines empirical models with computational models has been proposed. Economic theory models, such as input-output models, have also been extensively used for modeling interdependencies. However, such models, like empirical models, depend on disaster data for calibrating the strength of dependencies among infrastructure sectors.

2.3. Integrated infrastructure simulation models

Recent developments in computational modeling have allowed for the integration of infrastructure-specific simulation models as an alternative to traditional interdependency models. The goal of these integrated models is to make use of existing domain-specific models to simulate the behavior of complex heterogeneous systems. However, developing such models presents challenges, such as time synchronization and coupling of constituent simulators with different functional dynamics, complexity, and timescales.

Integrated models have been applied in various fields, including critical infrastructure systems. Monti et al. (2009) developed an integrated model combining simulation tools for power, control, and communication systems to study the role of communication systems in power grid performance. Erdener et al. (2014) developed an electricity and gas network simulation and analysis platform by integrating infrastructure-specific simulation models using a MATLAB interface. More advanced integrated models, known as co-simulation models, adopt a distributed simulation approach to enhance efficiency and usability by operating domain-specific submodels on different computers and seamlessly interacting with each other in real-time.

Several frameworks and standards, such as FMI, HLA, and DIS, have been developed to implement co-simulation of complex systems. HLA has become increasingly popular in recent years for developing interdependent infrastructure models to perform simulations in a distributed environment.

Integrated infrastructure models have also been extended to combine infrastructure-specific simulators with other urban system models to investigate disaster resilience of urban regions. For example, Marasco et al. (2021) developed a Python-based integrated platform for assessing the vulnerability and resilience of urban power and water systems against seismic events by combining infrastructure simulators and agent-based socio-technical models. Yang et al. (2021) combined GIS tools, BIM tools, and domain-specific infrastructure simulation models to analyze the risks of urban flooding on both infrastructure and communities. Similarly, Franchin and Cavalieri (2015) studied the resilience of urban infrastructure and communities against seismic hazards by integrating existing seismic models, an urban infrastructure network model, and a community vulnerability model.

2.4. Simulation of power, water, and transport systems and their interdependencies

There exist various standalone simulation tools that can imitate the operational characteristics of power, water, and transport systems. Table 1 enlists some commonly used software packages for simulating power, water, and transport systems and their functions.

Table 1
Examples of water, power and traffic simulation packages and tools.

Infrastructure systems	Simulation platform	Programming language	Open-source	Functionalities
Water	EPANET and its extensions	Standalone with GUI, versions in Python (wntr), R (Epanet2toolkit), Matlab (EPANET Toolkit).	Yes	Hydraulic simulation of water distribution systems.
	WaterGEMS	Standalone with GUI	No	Hydraulic simulation of water distribution systems
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Transportation	MATSIM	Java	Yes	Agent-based simulation of large-scale transport systems, including road networks.
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	Vissim	Standalone with GUI	No	Microscopic and mesoscopic traffic simulation.
	Python STA package	Python	Yes	Static traffic assignment in road traffic networks.

For hydraulic modeling of water distribution systems, most tools employ concepts from network simulation, statistical analysis, and classical optimization methods such as EPANET. Power system simulation tools usually concentrate on power flow optimization, stability analysis, and short circuit detection, and utilize a combination of algebraic and differential equations like pandapower. Various methods are used to model and simulate traffic flow on road networks, including network-flow optimization techniques, multi-agent simulation models, microscopic/mesoscopic simulation, and cellular automata. Additionally, some studies have endeavored to model the dependencies in interdependent power-water, power-transport, and water-transport networks using traditional and integrated simulation approaches. The major component-level dependencies modeled between water and power systems typically include pumping stations and storage tanks (which require electric power to operate water pumps) and cooling stations in power plants (which require water as a coolant). The most commonly found dependency between the transport system and the other two systems is related to road accessibility following a hazard occurrence, such as cascading failures resulting from fallen electric poles and damaged pipelines/sewers.

2.5. Research gaps addressed by InfraRisk

The major research gaps related to simulation of interdependent infrastructure networks include:

1. Most of the available traditional simulation models for interdependent infrastructure provide a system-level abstraction of performance but lack detailed component-level operational characteristics.
2. Traditional simulation models are limited by their intrinsic constraints and homogeneous modeling approaches, which restrict their ability to make use of domain knowledge in constituent infrastructure sectors. Consequently, these models often have limited capacity to perform analyses that involve realistic resilience interventions.
3. Integrated modeling techniques have recently advanced and are increasingly being adopted in interdependent infrastructure modeling and analysis. However, the use of integrated models in infrastructure analysis is an emerging field that is still in its early stages of adoption, particularly in civil infrastructure systems.

The significance of power, water, and transport systems for economic and community resilience in cities has been demonstrated by several disasters, including Hurricane Harvey in 2017 and the Texas snowstorm in 2021 (Doss-Gollin et al., 2021; Frame et al., 2020). The continuous and coordinated operation of these systems is crucial for normal functioning and post-disaster recovery. However, despite their relevance and interdependencies in city disaster resilience, there is a lack of integrated infrastructure tools to analyze the interdependent power, water, and transport network.

To address this gap, an open-source integrated platform InfraRisk was developed that can simulate the impacts of disasters on large-scale interdependent power, water, and transport networks could benefit various stakeholders involved in urban resilience decision-making. This would help in advancing the use of integrated models for analyzing other interdependent infrastructure networks. InfraRisk integrates individual infrastructure simulators through a simpler sequential approach, rather than distributed simulation frameworks like HLA and DIS, while maintaining adequate simulation performance.

Chapter 3: Methodology

3.1. Methodological framework

The methodology employed by the InfraRisk simulation platform is depicted in Fig. 1. This platform follows established risk and resilience analysis frameworks, which have been presented in prior research by Argryoudis et al. (2020) and Balakrishnan (2020). The key component of this framework is an interdependent infrastructure model that includes various sub models for different infrastructure systems of interest. Hazards that are relevant to the region can also be modeled, and vulnerabilities in the network to those hazards can be mapped. Direct impacts, such as physical and functional failures in infrastructure components, can be simulated using the hazard model. The platform also includes a recovery model to schedule post-disaster restoration and repair actions. Specific recovery strategies or optimization methods are used to prioritize the restoration actions. Indirect failures in the network are simulated using the interdependent infrastructure model based on the initial failure events and subsequent repair actions. Component and system-level operational performance are measured using appropriate resilience metrics.

3.2. Implementation in Python

Python programming language is used for the development of InfraRisk due to its versatility, ease of use, and vast open-source libraries. Python libraries, such as wntr for water systems and pypower and pandapower for power systems, provide efficient tools to model individual infrastructure systems that can be used as domain-specific infrastructure simulators.

The main objective of InfraRisk simulation package is to integrate existing infrastructure-specific simulation models through an object-oriented interface to achieve interdependent infrastructure simulation. The integration process involves identifying and modeling dependencies among various infrastructure components and time synchronization among infrastructure simulation models. To address these challenges, InfraRisk was built using a sequential simulation framework (Fig. 1). This approach simplifies data preparation efforts and enables full use of component-level modeling features of domain-specific infrastructure models.

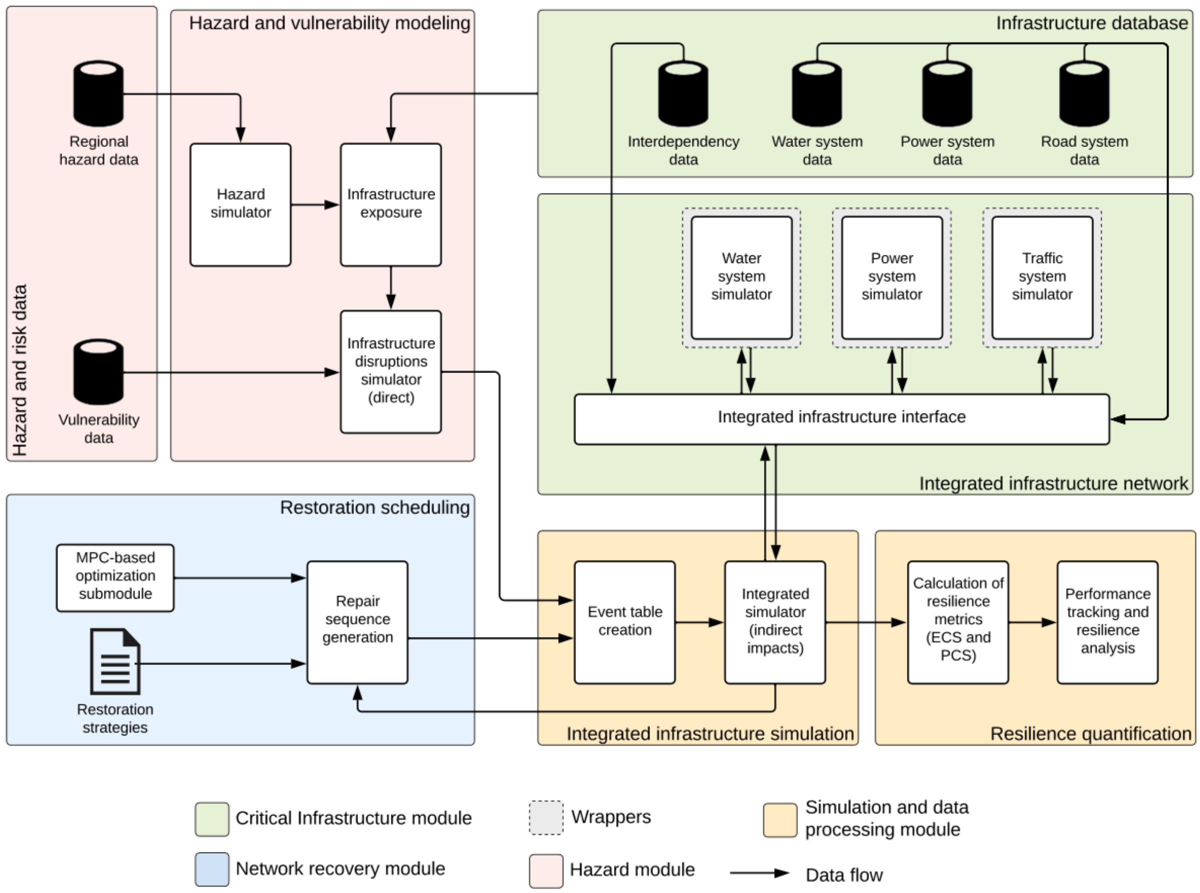


Fig. 1. Software implementation framework adopted in the InfraRisk simulation platform.

InfraRisk is made up of five modules: (a) integrated infrastructure network simulation, (b) hazard initiation and vulnerability modeling, (c) recovery modeling, (d) simulation of direct and indirect effects, and (e) resilience quantification. Each of these modules will be discussed in detail in the following sections.

3.3. Integrated infrastructure network simulation

This module of InfraRisk contains three infrastructure models that simulate power, water, and transportation systems. To simulate the power system, InfraRisk uses pandapower (Thurner et al., 2018). To model the water distribution system, wntr package (Klise et al., 2020) is used. Static traffic assignment method (Boyles, Lownes, & Unnikrishnan, 2020) is used to model the traffic flow and provide the travel costs for traveling from one point in the network to another. These packages have network-flow optimization models that identify the steady-state resource flows in the respective systems, taking into account operational constraints. Using pandapower, we can determine the optimal power flow for a given set of system conditions, attempting to minimize the total power distribution costs in the system under load flow, branch, bus, and operational power constraints (Eq. (1)) (Thurner et al., 2018).

$$
\begin{array}{lll}
\min & \sum\limits_{i \in gen, sgen, load, extgrid} P_i \times f_i\left(P_i\right) & \\
\text{s.t.} & P_{min,i} \leq P_i \leq P_{max,i} & \forall i \in gen, sgen, extgrid, load \\
& Q_{min,i} \leq Q_i \leq Q_{max,i} & \forall i \in gen, sgen, extgrid, load \\
& V_{min,j} \leq V_j \leq V_{max,j} & \forall j \in bus \\
& L_k \leq L_{max,k} & \forall k \in trafo, line, trafo3w
\end{array}
\tag{1}
$$

where i, j, and k are the power system components, gen is the set of generators, $sgen$ is the set of static generators, $load$ is the set of loads, $extgrid$ is the set of external grid connections , bus is the set of bus bars, $trafo$ is the set of transformers, $line$ is the set of lines, and $trafo3w$ is the set of three winding transformers, $fi(\cdot)$ is the cost function, Pi is the active power in i, Qi is the reactive power in i, Vj is the voltage in j and Lk is the loading percentage in k.

The wntr package has the capability to simulate water distribution systems by utilizing two methods: demand-driven analysis (DDA) and pressure-dependent demand analysis (PDA). DDA assigns pipe flows based solely on the demands, whereas PDA assumes that the demand is a function of the pressure at which water is supplied. The PDA method is more effective in pressure-deficient situations, like disruptions caused by disasters to water infrastructure. In this case, the actual node demands are calculated as a function of the available water pressure at the nodes, as demonstrated in Eq. (2) (Klise et al., 2020).

$$
d_i(t) = \begin{cases} 0 & p_i(t) \leq P_0 \\ D_i(t)\left(\frac{p_i(t)-P_0}{P_f-P_0}\right)^{\frac{1}{e}} & P_0 < p_i(t) \leq P_f \\ D_i & p_i(t) > P_0 \end{cases} \tag{2}
$$

where $di(t)$ is the actual demand at node i at time t, $Di(t)$ is the desired demand at a node i at t, $pi(t)$ is the available pressure in node i at t, Pf is the nominal pressure, and $P0$ is the lower pressure threshold, below which no water is consumed. In InfraRisk, the hydraulic simulation is performed using the PDA approach.

In InfraRisk, the transport system's traffic is simulated using the static traffic assignment method, which is based on the principle of user-equilibrium where each user tries to minimize their travel costs. The traffic assignment problem is formulated as follows (Eq. (3)) according to the InfraRisk package's approach developed by Boyles et al. in 2020.

$$\begin{aligned} \min_{\mathbf{x},\mathbf{h}} \quad & \sum_{(i,j)\in A} \int_0^{x_{ij}} t_{ij}(x_{ij})dx \\ \text{s.t.} \quad & x_{ij} = \sum_{\pi\in\Pi} h^\pi \delta_{ij}^\pi && \forall (i,j)\in A \\ & \sum_{\pi\in\Pi^{rs}} h^\pi = d^{rs} && \forall (r,s)\in Z^2 \\ & h^\pi \geq 0 && \forall \pi \in \Pi \end{aligned} \tag{3}$$

where A is the set of all road links with i and j as the tail and head nodes, tij is the travel cost on link (i, j), xij is the traffic flow on link (i, j), $h\pi$ is the flow on path $\pi \in \Pi$, $\delta\pi\ ij$ is an indicator variable that denotes whether (i, j) is part of π, drs is the total flow between origin–destination pair r, s.

The module includes an interdependency layer that acts as an interface between infrastructure systems, allowing for the exchange of information and formats. It also stores information about the connections between infrastructure systems, enabling communication and information transfer in response to dependencies. The interdependency layer is currently set up to handle power-water dependencies, which include water pumps and electric motors, and road traffic dependencies, as transport infrastructure is essential for the other two systems. The module stores information about the functionality of all infrastructure components, including their status after a disaster. To communicate with the infrastructure simulators, the interdependency layer uses built-in functions.

Chapter 4: Experiment simulation

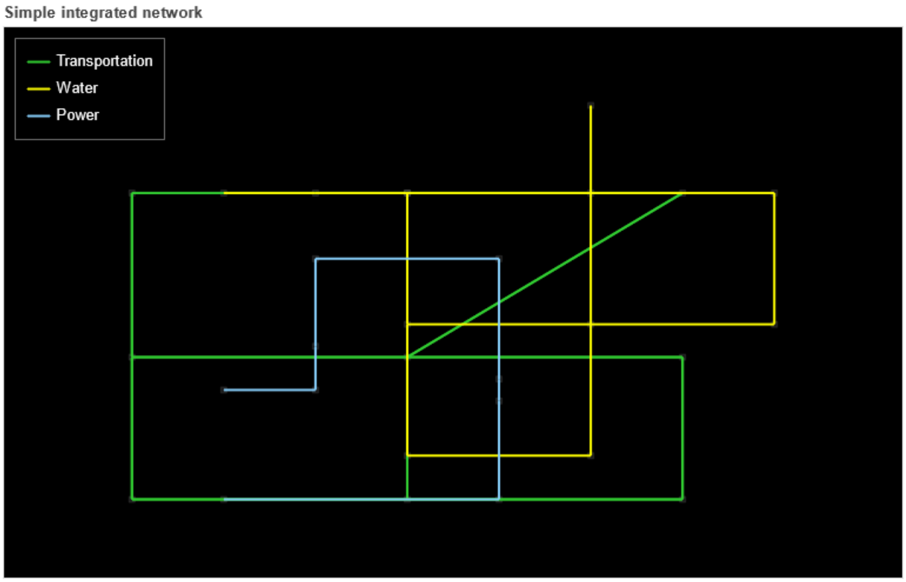
4.1. Simple Network

The simple integrated network combines small power, water, and traffic systems using basic infrastructure components. The power system includes three loads, one external grid connection, and five power lines. The water system includes 12 pipelines, nine demand nodes, one water pump, and a tank. The traffic system includes 22 road links and nine trip generator and attractor zones. The table presents more information on the infrastructure components used in the integrated network.

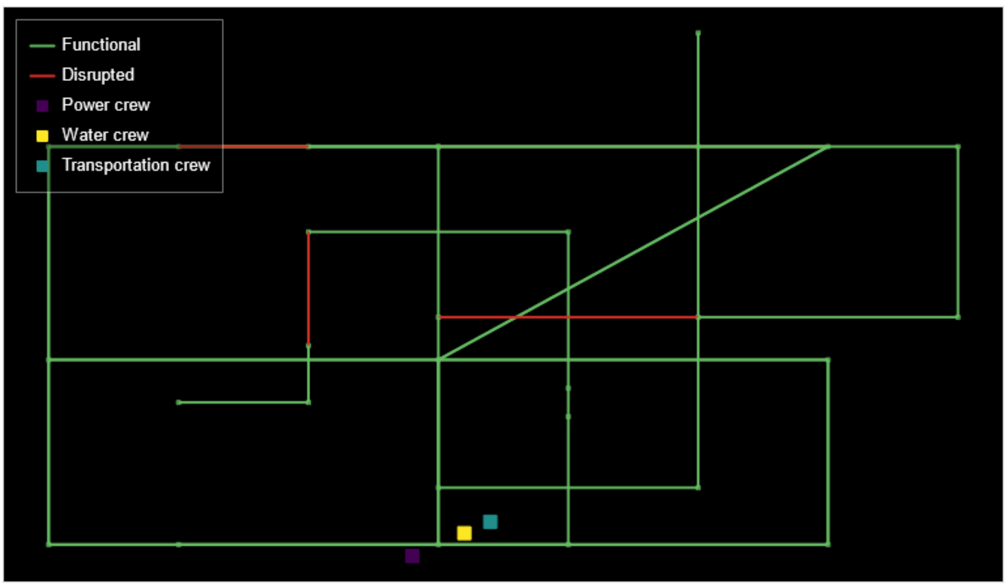
Component details of the simple network.

Power system		Water system		Traffic system	
Component	Count	Component	Count	Component	Count
Buses/poles	9	Main pipelines	12	Arterials	22
Loads	3	Demand nodes	9	Attractor zones	9
Motors	1	Pumps	1	Generator zones	9
Switches	0	Tanks	1		
External grids	1	Reservoirs	1		
Power lines	5				
Transformers	2				

The experimental simulation is carried out in a simple network with the aim of measuring the operational risks to infrastructure systems at the component level, both directly and indirectly. The direct risks are assessed by the hazard initiation module, while the interdependent simulations are conducted to assess the indirect risks. Statistical analysis is then applied to evaluate the effectiveness of different resilience strategies based on heuristics.



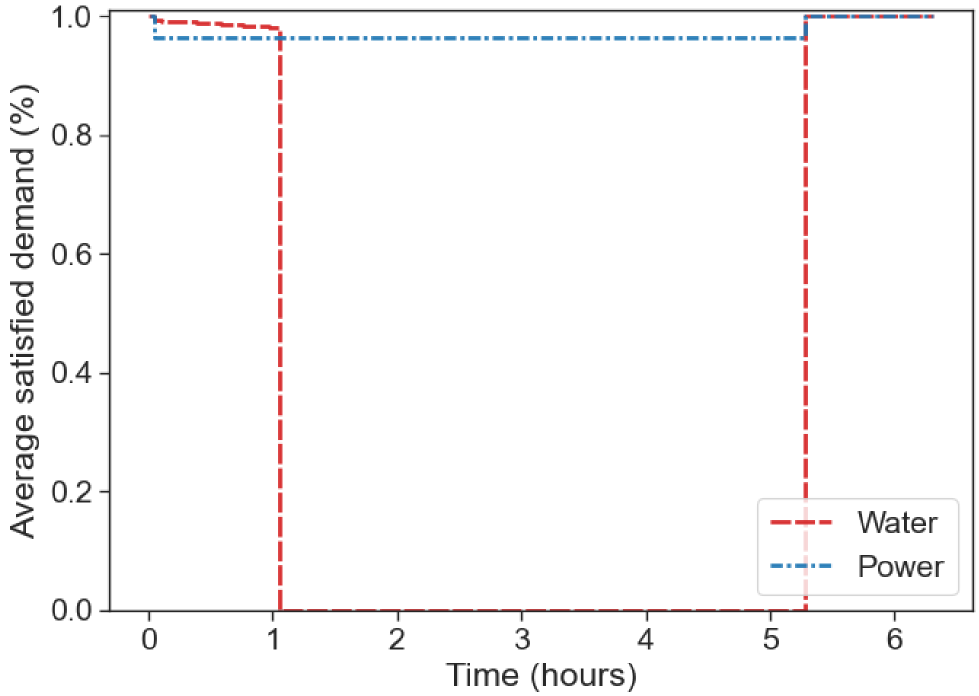
The disruptions and crew deployment are plotted below as follows:



We observe the following results from the simulation:

1. The weighted AUC value based on ECS is 2.7775
2. The weighted AUC value based on PCS is 2.2195

An overall system performance considering the indirect effects during the disruption is plotted:



Chapter 5: Conclusion

The report discusses about an open-source simulation package called InfraRisk that can simulate the impacts of disasters on interconnected power, water, and traffic systems and analyze their network-wide effects. It integrates existing infrastructure-specific simulation models using a sequential simulation framework for interdependent infrastructure simulations. The constituent modules developed for the integrated infrastructure network modeling, hazard initiation and vulnerability modeling, recovery modeling, simulation of direct and indirect disaster impacts, and resilience quantification. The simulation package's features and capabilities are demonstrated using a simulation on a simple network. While the infrastructure model simulates the component-level performance of the infrastructure systems, considering interdependencies, the resilience indices are designed to track the quality of infrastructure services at the consumer-level. This makes the simulation platform unique and capable of testing realistic resilience policies, strategies, and interventions in a controlled environment. The object-oriented nature of the platform would also help users to use more accurate vulnerability and recovery models with InfraRisk to gain more precise insights into interdependent power, water, and transport network resilience.

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