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ORIGINAL RESEARCH

Modeling Fault Dynamics of Interdependent Assets in Complex Urban Environments Using Open-Data: Extended Version

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Abstract
Dependency effects between Critical Infrastructure (CI) elements are essential for predicting the impact of disturbances, but such data is often scarce. This study builds a dependency network of critical sectors using open data and guidelines from the US and EU Directives on Critical Infrastructures. Focusing on the Marche region (Italy), particularly the city of Ancona, the network is analyzed to identify key nodes critical for preventing cascading failures. Centrality measures highlight essential infrastructure like hospitals and transport hubs, which are crucial for network resilience. The insights provided can support decision-makers in prioritizing interventions and developing strategies to enhance infrastructure resilience and mitigate the risk of cascading failures.

Keywords Cascading failure · Open-data · Graph · Openstreetmap · Critical infrastructure · Risk analysis

Introduction

Resilience is a fundamental property of complex systems, particularly in Smart Cities, where the interplay of infrastructure, structural assets, and essential services is crucial for maintaining urban functionality. These systems are highly interdependent, making their management and protection a challenging task. Disruptions in one sector can propagate across multiple domains, leading to cascading failures that compromise the availability of critical services for citizens. A well-known example of such cascading failures occurred during Hurricane Sandy in 2012, when power outages led to widespread disruptions in transportation, healthcare, and telecommunications, exacerbating the crisis and delaying emergency response efforts [1]. This highlights the need for systematic approaches to assess and mitigate infrastructure vulnerabilities.

To address these challenges, various methodologies have been developed, including dependency network modeling, which represents interconnections between critical infrastructures; cascading effects analysis, which evaluates failure propagation through dependency chains; and system resilience modeling, which quantifies a system's ability to withstand and recover from disruptions.

A well-established approach within this framework is Dependency Risk Graphs (DRGs) [2], which model infrastructure dependencies through directed networks. In a DRG, nodes represent infrastructure components, while edges denote functional dependencies, indicating the potential risk that a failure in one component poses to another.

The MARIS (Modeling infrAstructuRe dependencIes at an urban Scale) methodology [3, 4] builds upon this framework by leveraging open data to construct DRGs for urban infrastructure analysis. A fundamental component of this approach is the concept of Points of Interest (POIs), which represent key installations or assets within specific

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sectors-such as energy distribution, water supply, finance, or transportation-that provide essential goods and services. By structuring these elements within DRGs, the methodology enables a systematic analysis of interdependencies, helping to identify vulnerabilities that could trigger cascading failures across urban infrastructure.

Previous applications of MARIS focused on modeling cascading outages in CI networks. This work extends the methodology by incorporating a broader set of POI types and refining dependency detection strategies to uncover hidden interdependencies. Furthermore, it introduces centrality measures to identify critical nodes within the network, providing actionable insights for enhancing resilience. The findings contribute to the ongoing development of national and multinational directives aimed at strengthening CI protection, integrating expertise from infrastructure operators, policymakers, and the scientific community.

Building on previous research [3], which introduced the MARIS methodology, this paper extends its application by conducting a risk assessment for the city of Ancona. In addition to analyzing infrastructure dependencies, this study evaluates the potential impact of disruptions, identifying key vulnerabilities and critical intervention points. By applying MARIS to a real-world urban context, this research provides a data-driven foundation for enhancing urban resilience and safeguarding critical infrastructure against cascading failures.

Related Works

The MARIS methodology is grounded in well-established methodological frameworks in the field of infrastructure risk analysis and cascading failure modeling, specifically drawing from dependency network modeling, cascading effects analysis, and system resilience modeling. These methodologies provide the theoretical foundation for understanding interdependencies among critical infrastructures and the mechanisms driving failure propagation. Below, we outline the methodological influences on MARIS, referencing key contributions that have informed its development.

In the context of dependency network modeling, this approach enables the representation of interconnections among infrastructure components and their potential failure propagation. A recent study by Yabe et al. [5] introduced a behavior-based dependency network framework to assess economic resilience to shocks, highlighting the role of interdependencies in shaping systemic vulnerability. Similarly, Wrobel [6] explored the "double dimension" of efficiency and susceptibility to disruptions within critical infrastructures, emphasizing how these dependencies affect overall system resilience. Almoghathawi [7] further contributed by proposing methods to identify critical network components and assess their influence on resilience and recovery processes in interdependent infrastructure systems.

The study of cascading effects analysis focuses on understanding how failures propagate across interconnected infrastructures, amplifying systemic risks. Early foundational work in this domain was conducted by Theoharidou et al. [8], who developed models for analyzing cascading failures and quantifying their risk. Stergiopoulos et al. [9] extended this approach by incorporating temporal dynamics and centrality metrics to refine the assessment of cascading risks. More recently, Shi et al. [10] examined proactive defense strategies and dynamic repair mechanisms to mitigate cascading failures in complex networks, offering novel insights into risk containment strategies. Additionally, Mbanaso et al. [11] employed neural networks to model Nth-order dependencies, allowing for a deeper evaluation of infrastructure vulnerability and failure propagation pathways.

In terms of system resilience modeling, this methodological perspective focuses on quantifying the robustness of interconnected infrastructures and developing predictive models for system behavior under stress conditions. Akbarzadeh [12] provided a quantitative framework for assessing multi-order dependencies in cyber-physical systems, contributing to the understanding of resilience parameters. Zhang et al. [13] developed techniques for detecting vulnerabilities in infrastructure systems, applying tone mapping and visual saliency detection to enhance anomaly identification. A more recent advancement in resilience modeling has been proposed by Liu et al. [14], which utilizes machine learning-based approaches for resilience assessment in high-consequence systems, providing an adaptive framework for risk mitigation.

The MARIS Methodolgy

The MARIS methodology combines dependency network modeling, cascading failure analysis, and resilience assessment to analyze critical infrastructure dynamics. By leveraging open data and hierarchical dependency trees, it enables the evaluation of topological structures, functional relationships, and failure propagation, supporting risk preparedness and infrastructure resilience.

To construct a Dependency Relationship Graph (DRG) of Points of Interest (POIs), MARIS relies on three fundamental steps: (i) mapping POI data to relevant critical infrastructure (CI) sectors, (ii) translating sector-level dependencies into POI-level dependencies, and (iii) applying specific criteria, such as geographic proximity, to resolve unknown dependencies. The resulting DRG consists of consumer POIs, which rely on other elements to function, and producer POIs, which supply essential resources or services.

The following sections provide a detailed description of the techniques that implement this methodology, outlining their role in modeling dependencies, assessing cascading failures, and evaluating resilience.

Classification of POI Facilities

The first step in mapping POI data to relevant Critical Infrastructure (CI) sectors involves classifying each POI into a specific functional category. This classification enables the construction of a network where POIs serve as nodes, and links represent the dependencies between them, reflecting the exchange of essential services.

POI classification can be guided by existing legal definitions of CI sectors, leveraging national frameworks that categorize entities based on their role in societal, industrial, and economic activities. Dependencies between POIs are then inferred from established "dependency maps," which have been developed to support regulatory directives for managing the complexity of critical infrastructure systems.

The CER and CISR Directives

The classification of POIs into relevant sectors can be guided by national or federal laws and directives. At the European level, the Critical Entities Resilience (CER) Directive (2557/2022) [15] defines a resilience strategy for EU Member States (MS) to establish a common and consistent security framework for critical infrastructure (CI) against natural and anthropic hazards. This strategy mandates that MS implement specific measures to ensure the resilience of essential services, as well as economic and industrial activities, in times of crisis.

The CER Directive aligns with a similar initiative in the United States, the Critical Infrastructure Security and Resilience (CISR) Directive [16], which requires all federal departments and agencies to identify, prioritize, and implement protection plans for their physical and cyber-critical infrastructure. Both directives define key essential services and their corresponding critical entities (including infrastructures and their managing organizations), identifying 11 CI sectors in the EU and 16 in the US, as reported in Table 1.

In the US, the CISR Directive also led to the development of 16 Sector-Specific Plans (SSP) within the framework of the National Infrastructure Protection Plan (NIPP) [17]. These documents provide a comprehensive description of CI sectors, their interdependencies, and their criticality. Given the level of detail in these SSP documents, they have been used as a reference to: (i) map CISR-defined CI sectors to POI types, and (ii) translate CI sector dependencies into POI dependencies.

Table 1 Classification of the type of points of interests acquired for each CISR sector [3]

Sector (CISR)	Sector (CER)	POI types
Energy	x	1
Transport	x	4
Finance	x	3
Healthcare	x	9
Water	x	7
Information Technology	x	–
Communications	x	2
Government	x	15
Defense Industrial	x	–
Food and Agriculture	x	27
Nuclear	–	–
Commercial facilities	–	42
Critical Manufacturing	–	–
Dams	–	–
Emergency services	–	6
Chemical	–	–

POI Data Acquisition and Categorization

The POI data used in this study were acquired from OpenStreetMap (OSM) which is one of the most widely used map services in the world, providing free geospatial information of real world features, with more than 10 million users. Based on the initial 29 primary types or *features* of POI provided by OSM, the data used in the analysis were simplified to 20 different features to address a subset of the CISR sectors and subsectors (Fig. 1). Each POI data contains attribute information including geographical entity name, address, affiliation type, longitude, and latitude, administrative region and were stored locally into a geospatial database.

Table 3 lists a detailed description of each POI considered in the analysis.

Defining POI Dependencies

Based on the sector dependencies defined in the SSP documents (where the type of dependency is expressed as physical, logical or cyber [18], a classification of POIs as producers or consumers was performed. This process involved manual verification and categorization of POIs according to their primary function within the network. The resulting POI dependency mapping is shown in Fig. 2 in terms of *consumer* POIs i.e. elements that are dependent on other elements to work and *producer* POIs i.e. elements that provide resources or services to other elements.

Commercial facilities
Retail (florist, mall, department store, general, clothes, fashion accessories, shoes, bicycle rental), **Sports (**sports centre, pitch, swimming pool, tennis), **Accommodation** (hotel, motel, guest house, hostel apartment, chalet, caravan site), nightclub, park, **Public assembly** (playground, arts centre, cinema, refugee site, museum, library, shelter, stadium, theatre), **Outdoor events** (water park, running fairground), **Real Estate** (property management, apartments, detached house, residential, place of worship, semidetached house) **Gaming** (casino, gambling),

Healthcare
hospital, clinic, doctors, dentist, physiotherapist, psychotherapist, veterinary, laboratory, pharmacy,

Government
post office, public building, townhall, prison, diplomatic, courthouse, telephone, community centre, nursing home, social facility, university school, kindergarten college

Emergency services
police, fire station, phone, siren, ambulance station,

Communications
communications tower, connection point,

Financial services
payment terminal, bank, atm

Transportation
stop position, port, motorway, airport,

Food and Agriculture
Distribution (restaurant, fast food, cafe, pub, bar, biergarten, food court, supermarket, bakery, kiosk, greengrocer, agrarian), **Storage** (barn, silo), **Processing, Packaging and Production** (cowshed, distillery, brewery, winery, stable), **Supply** (windmill, greenhouse, farm, oil mill, allotments, farmyard, farmland)

Water
Drinking water (water tap, fountain, fire hydrant, water tower, water well, water works), **Waste water** (wastewater),

Energy
substation,

Fig. 1 List of POI grouped by CISR sector [3]

Assumptions

In order to focus the analysis on cascading failures i.e., disruptions occurring in one CI which causes the failure of a component in one or more CIs [19], intra-dependencies, i.e. the relations among subsystems of the same sector, were not considered. For example, considering the Transport sector, the dependencies existing among the POI facilities *airport* and *motorway* were not considered although an airport may require a motorway to be connected with the nearby territory and to be fed by the needed resources (personnel, supply of different goods etc.).

Regarding the number of dependencies selected for the POIs of each sector, where possible, the same dependencies for multiple POIs were grouped together. In addition, considering that the ultimate goal of this approach is to create an urban level of dependencies, only direct (i.e. first-order) dependencies were considered.

In the following, we analyse the dependency connections which are established among different elements of different sectors which represent the territorial dependency map of CIs. In particular, considering that most POIs depend on the supply of energy, water, communications, transportation, emergency, healthcare and financial services (Fig. 2), only dependencies not included in those mentioned above will be discussed.

Government (POI consumer)	Other sectors (POI producer)
public building, townhall, prison, social facility, community centre,	substation, water tower, wastewater, police, fire station, connection point, stop position, clinic, atm, general, motorway
nursing home,	substation, water tower, wastewater, ambulance station, fire station, connection point, stop position, clinic, atm, general,
post office,	substation, water tower, wastewater, police, connection point, stop position, hospital, atm, bank, general,
grave yard,	substation, water tower, wastewater, stop position, florist
school, kindergarten, college, university,	substation, water tower, wastewater, fire station, connection point, stop position, hospital, atm, library
telephone,	connection point, substation
diplomatic, courthouse,	substation, water tower, wastewater, police, connection point, stop position, bank, general, airport

Commercial facilities (POI consumer)	Other sectors (POI producer)
retail*, accommodation*, sports*, public assembly*, gaming*,	substation, water tower, wastewater, fire station, police, connection point, stop position, motorway, hospital, bank, atm
playground, park,	substation, water tower, wastewater, fire station, police, stop position, motorway, hospital,

Energy (POI consumer)	Other sectors (POI producer)
substation,	connection point, communication tower,

Transportation (POI consumer)	Other sectors (POI producer)
port, airport,	substation, water tower, wastewater, police, fire station, connection point, hospital, bank, atm,
stop position,	substation, communication tower,
motorway,	substation, wastewater, fire station, connection point, police, hospital, communication tower, ambulance station, phone,

Healthcare (POI consumer)	Other sectors (POI producer)
doctors, dentist, physiotherapist, psychotherapist, veterinary, laboratory, pharmacy,	substation, stop position, water tower, wastewater, fire station, connection point, motor way,
hospital, clinic	substation, stop position, motorway, water tower, wastewater, ambulance station, fire station, police, communication tower, connection point,

Emergency services (POI consumer)	Other sectors (POI producer)
police, fire station, phone, ambulance station,	substation, stop position, motorway, connection point, water tower, wastewater, hospital,
siren	substation, communication tower,

Communications (POI consumer)	Other sectors (POI producer)
communication tower,	substation, stop position, motorway, water tower,
connection point,	substation, stop position, water tower,

Water (POI consumer)	Other sectors (POI producer)
water tap, fountain	substation, ambulance station,
fire hydrant, water well,	substation, ambulance station, fire station, connection point, bank, laboratory, motorway,

Food and Agriculture (POI consumer)	Other sectors (POI producer)
distribution*, processing & packaging & production*	substation, water tower, wastewater, fire station, police, connection point, stop position, motorway, hospital, bank, atm
barn, silo,	substation, water tower,
supply*,	substation, water tower, wastewater, motorway, airport

Financial services (POI consumer)	Other sectors (POI producer)
payment terminal, bank, atm,	substation, wastewater, connection point, police, hospital, communication tower,

Fig. 2 POI dependencies grouped by CISR sector [3]

Energy POIs

The **Energy Substation** is the core facility that ensures the distribution of electricity in both urban and rural environments. It is the backbone of the energy network and is critical to the functioning of various sectors. Substations are heavily dependent on **Communication Towers** and **Connection Points**, which enable SCADA (Supervisory Control and Data Acquisition) systems to monitor and control the electrical grid. The operational continuity of these facilities is vital for the stability of the entire energy network, especially during emergencies.

Transport POIs

Stop Positions serve as essential nodes in public transportation networks, providing passengers with access to buses, trams, and trains. These positions are interconnected with **Substations** for power supply, ensuring that critical functions like lighting and signaling systems operate smoothly. Additionally, **Communication Towers** at these stops offer Internet connectivity for passengers, enhancing their travel experience and providing real-time updates.

Motorways are major roads designed for the fast movement of goods and people. Their operation depends on **Substations** for lighting, toll booths, and other essential infrastructure. Furthermore, facilities such as **Ports** and **Airports** are critical transport hubs that not only rely on energy but also require a robust emergency response infrastructure. This includes access to **Ambulance Stations**, **Police Stations**, **Fire Stations**, and **Hospitals**. These hubs are equipped with **Phones** and **Communication Towers** to maintain continuous communication and ensure a swift response during emergencies.

Financial Service POIs

Payment Terminals and **ATMs** are integral to the financial services sector, facilitating transactions for millions of people daily. These facilities are closely linked to **Banks**, which require a reliable energy supply to power their operations, including vaults and security systems. **Telecommunications** are also critical for processing transactions and maintaining customer service channels. In case of emergencies, these facilities depend on medical assistance, **Emergency Services**, and **Transportation** networks to continue operations.

Healthcare POIs

Healthcare facilities, including **Hospitals**, **Clinics**, **Doctors' Offices**, **Dentists**, and specialized facilities like **Veterinary Clinics**, **Laboratories**, and **Pharmacies**, are essential for public health. These facilities require an uninterrupted supply of energy, clean water, and telecommunications to provide care effectively. The transportation of medical supplies and personnel is facilitated by the Transportation sector, ensuring that healthcare services are not disrupted. During emergencies, the availability of **Emergency Services**, such as **Ambulance Stations**, is crucial for the swift treatment of patients.

Water POIs

Water infrastructure is critical for both daily life and emergency scenarios. A **Fire Hydrant** is a vital source of water for firefighting, while a **Water Well** provides access to groundwater, especially in rural areas. Both facilities depend on a steady supply of electricity for pumps and purification systems. **Water Works** facilities treat water to make it safe for human consumption, whereas **Wastewater Treatment Plants** manage and treat wastewater to prevent environmental contamination. These facilities require energy and support from **Emergency Services** to handle emergencies, such as contamination events or natural disasters.

Communications POIs

A **Communications Tower** is essential for enabling mobile and internet connectivity across sectors. These towers support various communication services, including voice, data, and emergency communications. The operation of these towers relies on energy, which powers their backup generators, and the Transportation sector, which ensures the delivery of fuel for these generators. In addition, water resources are necessary for cooling systems within communication facilities, preventing overheating and ensuring uninterrupted service.

Government POIs

Government facilities encompass a wide range of buildings and services that are essential for the functioning of the state. These include **Post Offices**, **Public Buildings** such as **Townhalls**, **Prisons**, **Embassies**, and **Courthouses**. Educational facilities, such as **Schools**, **Universities**, and **Kindergartens**, are also part of this sector. Government facilities depend on a reliable supply of energy, telecommunications, and transportation networks to function effectively. In emergency situations, these facilities coordinate closely with **Emergency Services** to ensure public safety and continuity of operations.

Food and Agriculture POIs

The **Food and Agriculture** sector is critical for feeding the population. It includes facilities for **Distribution** (e.g.,

Restaurants, **Supermarkets**), **Storage** (e.g., **Barns**, **Silos**), **Processing and Packaging** (e.g., **Breweries**, **Cowsheds**), and **Supply** (e.g., **Farms**, **Greenhouses**). These facilities are heavily dependent on energy for operations such as refrigeration and processing. Transportation networks are crucial for the timely delivery of products, and telecommunications are necessary for coordinating supply chains. During emergencies, the availability of food and agricultural products is vital, and emergency services may be required to ensure the continued operation of this sector.

Commercial Facility POIs

Commercial Facilities are diverse and include **Retail** outlets (e.g., **Malls**, **Department Stores**), **Sports Facilities** (e.g., **Sports Centers**, **Swimming Pools**), **Accommodation** (e.g., **Hotels**, **Guest Houses**), and **Public Assembly** spaces (e.g., **Museums**, **Stadiums**). These facilities cater to large numbers of people daily, providing essential services and recreation. The operation of commercial facilities relies on energy, telecommunications, and transportation networks. In addition, emergency services are required to ensure safety during large public events or in case of incidents.

Emergency Services POIs

Emergency Services facilities are critical for public safety and include **Police Stations**, **Fire Stations**, and **Ambulance Stations**. These facilities are equipped with **Phones**, **Sirens**, and other communication devices that enable them to respond quickly to emergencies. Emergency services work closely with other sectors, such as healthcare, transportation, and government, to ensure a coordinated response during crises. Their operation depends on a reliable supply of energy, telecommunications, and transportation networks.

Constructing Dependency Risk Graphs

In discrete mathematics, a graph is understood as a collection of abstract entities-termed vertices or nodes-interconnected by edges that represent relationships between pairs of these entities. The total number of vertices, or the graph's order, provides a basic measure of its size. Graphs can be either directed, where relationships have a specified direction, or undirected, where connections are bidirectional. Within this framework, dependency refers to the unidirectional reliance of one asset or system (in our case, POI) on another for proper functioning, offering a conceptual basis for analyzing interconnected components.

When applied to complex systems such as urban infrastructure, dependency analysis focuses on the interplay among individual nodes-representing POIs in city blocks. This approach emphasizes the structural relationships and functional reliance between components, thereby identifying pivotal nodes that are crucial to the overall integrity and resilience of the network. Such insights enable stakeholders to understand critical interdependencies and inform strategies for mitigating vulnerabilities in system operations.

This allows us to tailor results based on path length, defined as the number of nodes (or city blocks) included in the path. In that way, we can identify the most critical dependencies for the specific POI path length selected. This means that, for a given dependency path length k, the methodology provides a set of city POIs (represented as nodes) that collectively have the highest cumulative impact to the city's well-being.

A Dependency Risk Graph can be defined as a weighted digraph $\hat{G} = (V, E, W)$ where the different sets of $\hat{G}$ are described in the following:

- $V = \{v_k\}$ with $|V| = N$ is the POI instance set;
- $E = \{e_{jk}\}$ with $|E| = M$ is the POI instance dependency set;
- $W = \{w_i\}$ is the set of weights indices associated to each edge $e_{jk} \in E$;

This mathematical representation defines the set of POI instances (or "nodes") representing infrastructure facilities and considers their relationships in terms of producer and consumer nodes, where the link weight reflects the importance of a dependency.

To apply this modeling to a real scenario, some dependencies might be unknown. For example, the dependency of a hospital on telecommunication and electrical network elements might not be explicitly defined. Rather than arbitrarily assigning a dependency, a more logical approach is to use inference criteria such as geographical proximity. For instance, if a hospital lacks an explicitly defined provider for water supply, the closest water treatment facility can be assumed as its primary supplier.

Other criteria can also be considered depending on the context. These may include functional relevance, where dependencies are assigned based on the specific services required (e.g., a data center relying on a high-capacity fiber optic connection rather than the nearest network node), or administrative jurisdiction, where dependencies are inferred based on operational agreements or service areas (e.g., a hospital being served by a designated emergency response center regardless of distance).

Case Studies

In this section, we present two case studies of different extension and apply topological indices to analyze the network of POIs.

For both scenarios we created two different DRGs by using open-data of a specific area of interest and applying the methodology described in the previous paragraphs. The first graph $\hat{G}_1$ represents the Marche region, highlighting the role of key nodes in controlling the flow of resources and information across the broader infrastructure network. Building on this analysis, the second graph $\hat{G}_2$ focuses on a more localized area, specifically the greater Ancona area, to identify the most critical nodes and assess the potential risks of cascading failures.

In both graphs, the weight set is defined as: $W = \{w_{ij} = 1 \mid (i,j) \in M_1\}$ which means that all dependencies are considered equally important. This assumption ensures a uniform influence of connections across sectors, allowing for a structural evaluation of the network without introducing bias from differentiated weight assignments.

The Marche Region

The Marche Region is located in central Italy, with approximately 1.5 million inhabitants spread across an area of 9.350 km^2. The regional scenario includes $N_1 = 27.324$ nodes distributed across 10 CISR sectors (as shown in Table 2), where dependencies among nodes were established using a proximity-based approach. The resulting network, comprising the full set of (N_1) nodes, contains ($M_1 = 279,663$) oriented links.

A preliminary analysis was conducted by examining the fundamental properties of the network, specifically the degree distribution of nodes and their centrality measures. Table 3 highlights that, on average, the number of incoming links per node is lower than the number of outgoing links. This implies that a typical node serves as a provider for multiple nodes in other sectors that rely on its services. Notably, nodes within the Government and Food & Agriculture sectors function exclusively as consumers, as they have no outgoing connections.

Table 2 Major topological properties of POIs for the different CISR sectors: d_{in} is the node degree of incoming links (constant), $d_{out-MAX}$ is the maximum degree of outgoing links [3]

Sector	POI instances	d_{in}	$d_{out-MAX}$
Energy	281	2	1506
Transp	426	5,4	1.748
Finance	461	6	2.033
Health	599	6,8	3.640
Water	493	4,2	3.130
Commun	9	3,1	12.895
Governm	840	–	–
Food&A	5.497	–	–
Commerc	18.594	0,04	118
Emergen	201	7	4.642

Figure 3 presents the distribution of outgoing links for nodes in four of the most critical sectors. Energy nodes, which primarily consist of electrical substations, exhibit a wide range of outbound connections. A similar pattern is observed in the Emergency, Finance, and Transport sectors, where fire stations, ATMs, and public transport stops act as key source nodes, particularly in urban areas. Specifically, POI instances with the highest outbound degree include a connection point, a hospital, a water tower, a motorway junction, a department store, a fire station, an ATM, and an electrical substation.

As shown in Table 3, certain sector nodes act as major providers for a large number of other nodes. Some of these function as terminal nodes, while others, in turn, supply services to additional nodes across different sectors. Nodes with high outbound degree play a *strategic* role, as they are central to multiple subnetworks and are crucial for maintaining network functionality.

Furthermore, highly strategic nodes - those exhibiting high inbound degree centrality within the Dependency Risk Graph (DRG) - can be considered natural sinkholes of incoming dependency risk. These nodes are particularly relevant when prioritizing mitigation strategies, as reinforcing them could reduce multiple cascading failure chains simultaneously (Fig. 4).

Figure 5 illustrates the resulting network, constructed by interconnecting all POI instances across sectors within the Marche Region, according to the adopted methodology. Nodes are color-coded by sector, and their sizes are proportional to their total degree (sum of incoming and outgoing links), visually emphasizing the most interconnected and influential points within the infrastructure network.

The City of Ancona

The city of Ancona, a critical hub in the Marche region, features a network of interconnected infrastructures, making it an ideal area for in-depth analysis. The network, consists of ($N_2 = 7.314$) nodes and contains ($M_2 = 159.719$) edges, spread across various sectors within the city. This complex infrastructure provides valuable insights for resilience studies, as the primary goal of the risk analysis is to identify critical POI nodes whose failure could cause widespread disruptions across the city. The risk analysis helps to understand the network's vulnerabilities, offering guidance to enhance its resilience and ability to adapt and recover from potential failures. To achieve this, we apply several topological indices that allow to rank the POI instances based on their importance to the network's stability and functionality. These indices include:

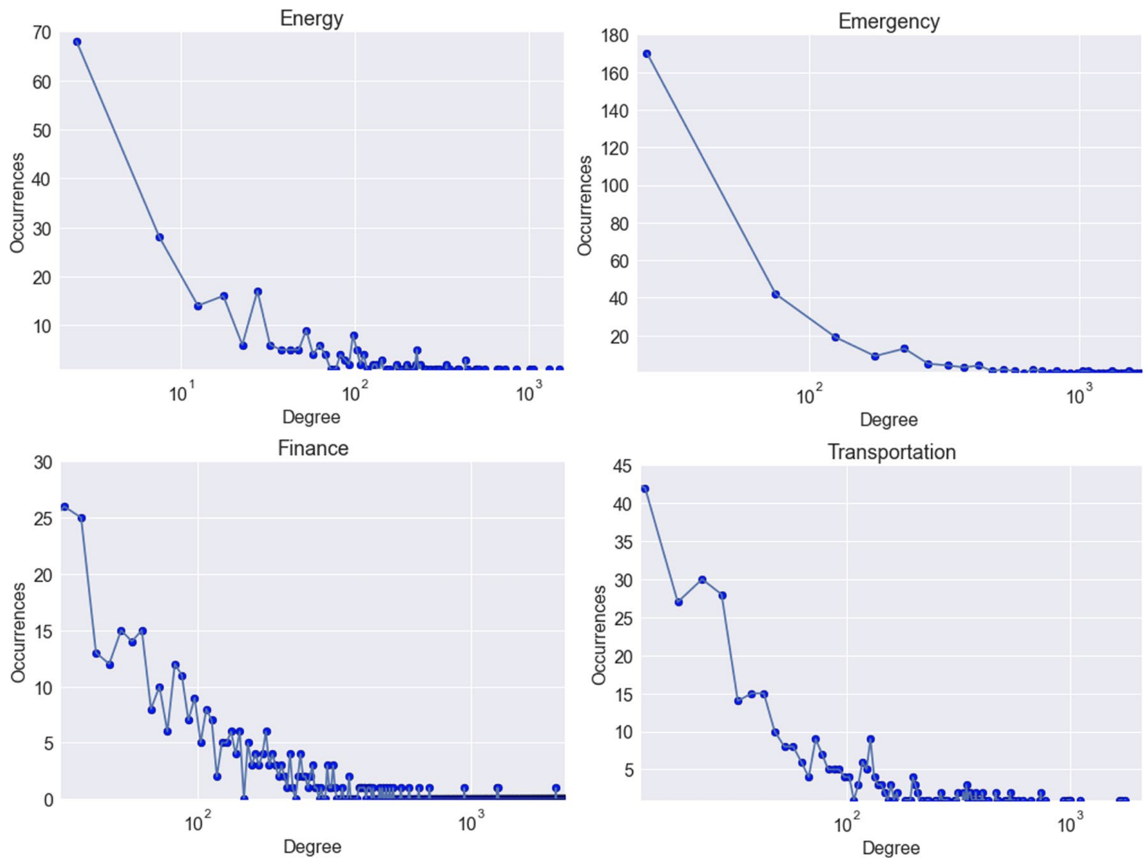

Fig. 3 Distribution of the outgoing node's degrees in several sectors (abscissa, in log scale, represents the node degree; in the ordinate the number of nodes with the given outgoing degree. Up-left: nodes of the Energy sector. Up-right: node of the Emergency sector. Bottom-left: nodes of the Financial sector. Bottom-right: nodes of the Transportation sector. Lines are drawn as a guide for the eye [3]

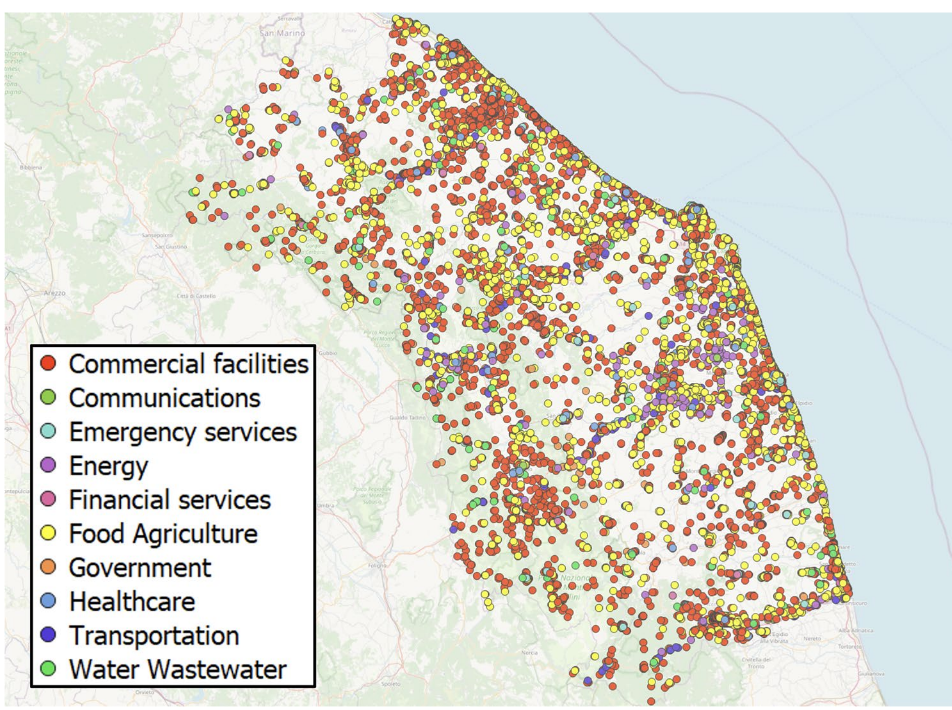

Fig. 4 A GIS map of the area under analysis (Regione Marche, Italy) with the different sectors nodes highlighted in different colors, according to the CISR sector to which they belong [3]

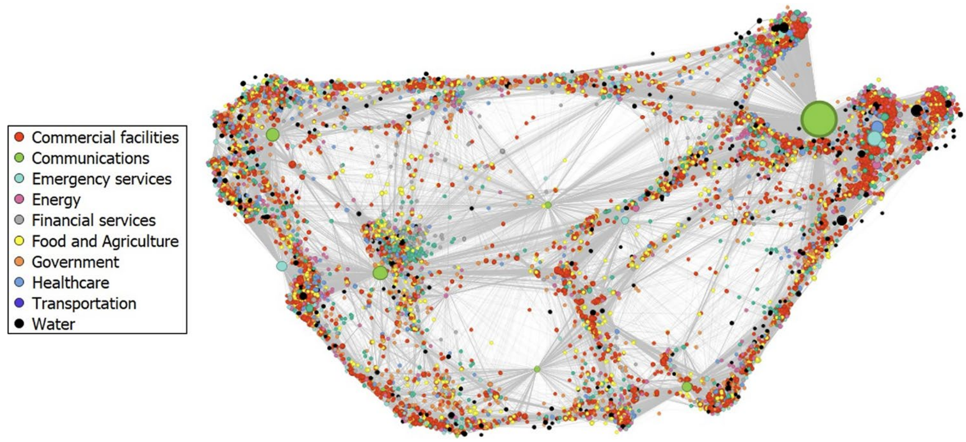

Fig. 5 A representation of the graph of the network under analysis (Marche region) where node's size is proportional to the out-degree value [3]

- **Eigenvector Centrality**: This index identifies POI nodes that are well-connected to other influential nodes. The failure of such POIs could disrupt the overall network, as they link key infrastructure components.
- **Betweenness Centrality**: This index highlights POI nodes that act as critical connectors within the network. Their failure could isolate entire infrastructure sectors, disrupting the flow of resources.
- **Closeness Centrality**: This index reveals POIs that are located close to many other nodes. A failure at such a POI could cause widespread disruptions by affecting multiple interconnected sectors.

To estimate the risk, we first define the impact of failure at each node. By incorporating these impacts, we then quantify the risk associated with failure propagation through dependency chains. The total risk R is calculated by the formula:

$$R = \sum_{i=1}^{n} P_i \cdot I_i$$

where P_i represents the probability of failure for the i-th POI node, and I_i denotes the impact of failure at node i.

This approach allows us to calculate the cumulative risk along dependency chains, which can help prioritize mitigation efforts. Indeed, the failure of a critical POI at the start of a chain can trigger successive failures, leading to widespread disruptions across the infrastructure network. The chains with the highest cumulative risk are particularly concerning, as they highlight the system's vulnerability to cascading failures, especially at key POI nodes. This analysis assumes a worst-case scenario, where each failure propagates to the dependent nodes, amplifying the overall impact on Ancona's infrastructure.

The impact of failure was normalized based on the population of the municipality within the Province of Ancona where the POI is located. This approach simplifies the consequences of failure by assuming an equal effect on all citizens, regardless of proximity to the affected infrastructure. Moreover, the probability of failure for each POI was set to one, implying that the failure of any POI node is considered certain. This assumption maximizes the potential for failure propagation and provides a comprehensive view of the risks involved.

Figures 6 and 7 illustrate the distribution of POI nodes across the 30 highest-risk chains. Figure 6 shows the

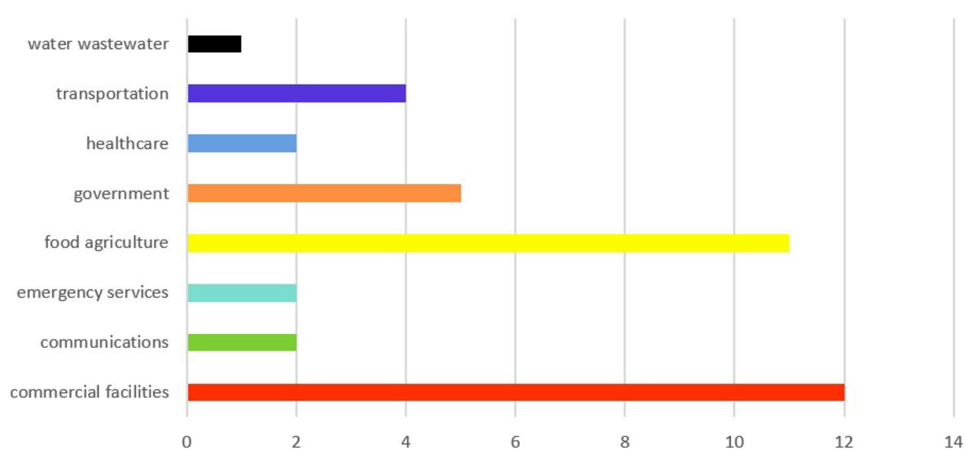

Fig. 6 Vulnerability map of key Infrastructure sectors in Ancona for the 30 most critical chains

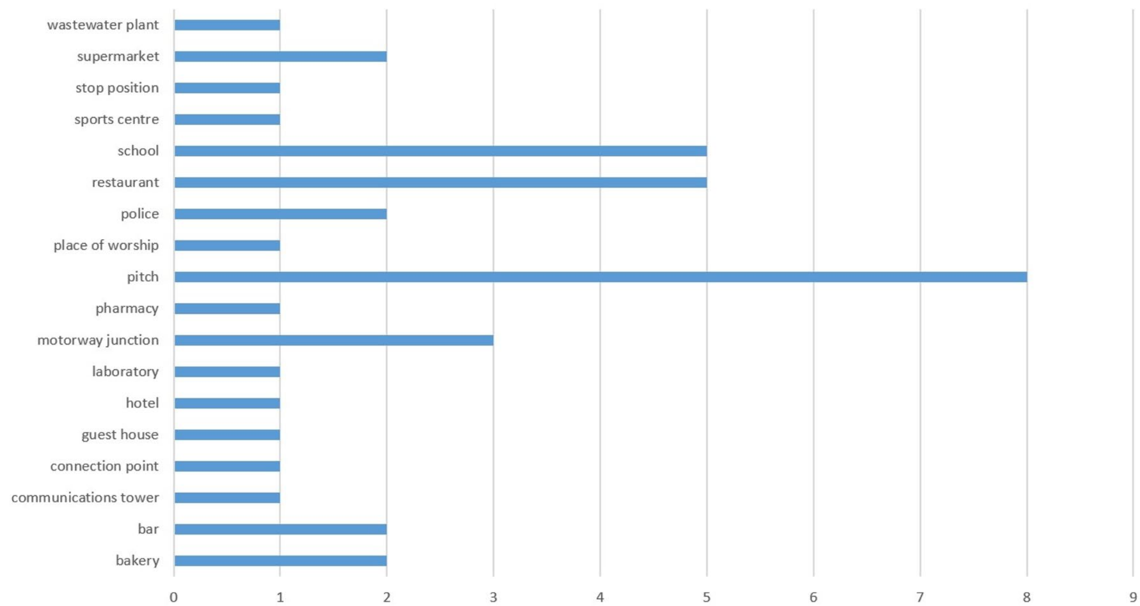

Fig. 7 Vulnerability map of key POI instances in Ancona for the 30 most critical chains

distribution by infrastructure sector, revealing that "commercial facilities" and "food agriculture" are the most represented sectors in the high-risk chains. These sectors, which include shopping centers, food distribution points, and logistics facilities, are crucial for the stability of the city's infrastructure and represent significant points of vulnerability.

Figure 7 offers a more detailed view, showing specific POIs such as "school," "pitch," and "motorway junction." These POIs frequently appear in high-risk chains, acting as hubs where failure could disrupt multiple sectors. For instance, a failure at a "motorway junction" could severely affect transportation and logistics, while disruptions at a "school" or "sports center" could have profound social impacts.

The results of this analysis suggest that POIs acting as hubs or intermediaries-such as transportation junctions and essential service centers-should be prioritized in mitigation strategies. By focusing on these critical nodes, it is possible to prevent cascading failures and minimize the overall risk to Ancona's infrastructure network.

Conclusions

In this study, we leveraged the US CISR and EU CER Directives to identify critical entities across various sectors and created a comprehensive regional network by integrating open data from Points of Interest (POIs) and dependency maps derived from the Sector-Specific Plans (SSPs). This network links elements across sectors through oriented dependencies, enhancing our understanding of sector interactions and infrastructure vulnerabilities. We focused on Ancona within the Marche Region, using data from OpenStreetMap to analyze the infrastructure and its interdependencies.

Centrality measures such as betweenness and degree centrality were applied to identify key nodes critical for network stability. These nodes, representing vital infrastructure such as hospitals, substations, and transportation hubs, are central due to their high connectivity and potential influence on cascading failures. Prioritizing these nodes is essential for risk mitigation and building a more resilient infrastructure.

Our analysis highlighted dependency chains with high cumulative risk, where failures in key nodes could trigger widespread disruptions. However, we noted some limitations in our current methodology, particularly the simplistic approach of quantifying impact solely based on the number of affected citizens. This does not account for the varying socio-economic impacts or the complex, stochastic nature of failures where dependencies and failure probabilities differ. Additionally, assuming a fixed likelihood of failure at 1, while useful for highlighting vulnerabilities, does not reflect the dynamic nature of real-world failures.

Future research could focus on integrating weighted links between nodes to account for the severity of specific dependencies, which would improve network analysis and help identify critical weak points and subnetworks. Additionally, refining the models for impact and likelihood by considering node-specific failure probabilities and incorporating restoration actions would enhance the accuracy of risk assessments and provide a more nuanced view of network resilience.

Detailed List of Points of Interest Analysed

See Table 3.

Table 3 POI description. Source: (OpenStreetMap, 2024)

Sector	POI type	Description
Government	Post office	Post office building with postal services
	Public building	An office of a (supra)national, regional or local government entity
	Townhall	Building where the administration of a village, town or city
	Prison	A prison or jail where people are incarcerated
	Diplomatic	An embassy, diplomatic mission, consulate or liaison office
	Courthouse	A building home to a court of law, where justice is dispensed
	Telephone	Public telephone
	Community centre	A place mostly used for local events, festivities and group activities
	Nursing home	A structure for disabled or elderly persons who need permanent care
	Social facility	A facility that provides social services e.g. homeless shelters, etc
	Grave yard	A (smaller) place of burial, often you'll find a church nearby
	University	An university campus: an institute of higher education
	School	An university campus: an institute of higher education
	Nursery school	School and grounds - primary, middle and secondary schools
	College	Campus or buildings of an institute of Further Education
Healthcare	Hospital	A hospital providing in-patient medical treatment
	Clinic	A medium-sized medical facility or health centre
	Doctors	A doctor's practice/surgery
	Dentist	A dentist practice/surgery
	Physiotherapist	Someone who practices physical therapy but is not a Physician
	Psychotherapist	Someone who practices psychotherapy but is not a Physician
	Veterinary office	A place where a veterinary surgeon practices
	Medical laboratory	Is a place that analyses body fluids such as blood, urine, faeces, etc
	Pharmacy	A shop where a pharmacist sells medications
Emergency services	Police	A police station where police officers patrol from
	Fire station	A station of a fire brigade
	Phone	Emergency telephone
	Siren	A loud noise maker, such as an air raid siren or a tornado siren
	Ambulance station	Structure set aside for storage of ambulance vehicles, equipment, etc
Communication	Comm. tower	A huge tower for transmitting radio applications
	Internet conn. point	Last point of telecom local loops allowing connections to households
Water	Water tap	Publicly usable water tap
	Fountain	A fountain for cultural/decorational/recreational purposes
	Fire hydrant	An active fire protection measure
	Water tower	Structure with a water tank at a high altitude to increase pressure
	Water well	A structural facility to access groundwater
	Water works	A facility where water is treated to make it suitable for human use
	Wastewater plant	A wastewater plant is a facility used to treat wastewater

Table 3 (continued)

Sector	POI type	Description
Commercial facilities	Mall	A shopping mall - multiple stores under one roof
	Department store	A store - often multiple storeys high - selling a large variety of goods
	Generic items shop	A store that carries a general line of merchandise
	Clothes shop	Shop focused on selling clothes and/or underwear
	Fashion accessories	Shop focused on selling fashion accessories
	Shoes shop	Shop focused on selling shoes
	Bicycle rental	Shop to rent a bicycle
	Florist	Shop focused on selling bouquets of flowers
	Sports centre	A building that was built as a sports centre
	Pitch	An area designed for practicing a particular sport
	Swimming pool	A swimming pool
	Tennis	A tennis court
	Hotel	A building with separate rooms available for overnight accommodation
	Motel	Short term accommodation, particularly for people traveling by car
	Guest house	Accommodation smaller than a hotel and typically owner-operated
	Hostel	Cheap accommodation with shared bedrooms
	Bed and breakfast	A flat with cooking and bathroom facilities that can be rented
	Chalet	A holiday cottage with self-contained cooking and bathroom facilities
	Caravan site	A place where you can stay in a caravan overnight or for longer periods
	Nightclub	A place to drink and dance (nightclub)
	Park	A park, usually in an urban setting, created for recreation and relaxation
	Playground	An area designed for children to play
	Arts centre	A venue where a variety of arts are performed or conducted
	Cinema	A place where films are shown
	Refugee site	A human settlement sheltering refugees or internally displaced persons
	Museum	A building which was designed as a museum
	Library	A public library to borrow books from
	Shelter	A small shelter against bad weather conditions
	Stadium	A building constructed to be a stadium building
	Theatre	A place where live performances occur, (e.g., musicals, concerts)
	Water park	An amusement park with features like water slides
	Fairground	A site where a fair takes place
	Running area	An area for running (jogging) routes
	Property manag	Office of a property rental company for commercial or residential use
	Apartment	A building arranged into individual dwellings, often on separate floors
	Detached house	A free-standing residential building usually housing a single family
	House	A dwelling unit inhabited by a single household
	Residential building	A general tag for a building used primarily for residential purposes
	Place of worship	A church, mosque, or temple, etc
	Semidetached house	A residential house that shares a common wall with another on one side
	Casino	A gambling venue with at least one table game that takes bets
	Gambling	A place for gambling
Food and agriculture	Restaurant	A normal restaurant that sells full sit-down meals
	Fast food	A place for very fast counter-only service and take-away food
	Cafe	An informal place that offers casual meals and beverages (coffee or tea)
	Pub	A place selling beer and other alcoholic drinks
	Bar	A place that sells alcoholic drinks to be consumed on the premises
	Biergarten	An open-air area where alcoholic beverages along with food are served
	Food court	An area with several restaurant food counters and a shared eating area

Table 3 (continued)

Sector	POI type	Description
	Supermarket	a large store with groceries and other items
	Bakery	Shop focused on selling bread
	Kiosk	A small shop selling magazines, tobacco, newspapers, etc
	Greengrocer	Shop focused on selling vegetables and fruits
	Agrarian	Shop that sells agrarian products, e.g. seeds, agricultural machinery
	Barn	An agricultural building that can be used for storage
	Silo	A storage container for bulk material, often grains e.g. corn, wheat
	Cowshed	A cow barn is a building for housing cows, usually found on farms
	Distillery	An establishment for distilling, especially alcoholic liquors
	Brewery	A dedicated building for the making of beer
	Winery	A place where wine is produced
	Stable for horses	A building constructed as a stable for horses
	Windmill	A traditional windmill, historically used to mill grain with wind power
	Greenhouse	A greenhouse is a glass or plastic covered building used to grow plants
	Farm	A residential building on a farm (farmhouse)
	Oil mill	A mill to crush or bruise oil-bearing seeds, e.g. linseed or peanuts
	Allotments	A piece of land given for growing vegetables and flowers
	Farmyard	An area of land with farm buildings e.g. farmhouse, dwellings
	Farmland	An area used for tillage (cereals, vegetables, oil plants, flowers)
Energy	Substation	A power facility with transformers, switchgear or compensators
Transportation	Public transport stop	The position on the street or rails where a public transport vehicle stops
	Port	A coastal industrial area where commercial traffic is handled
	Motorway junction	A type of road junction linking highway facility to another
	Aerodrome	An aerodrome, airport or airfield
Financial services	Payment terminal	Self-service payment kiosk/terminal
	Bank	A financial establishment to make financial operations
	ATM	Cash point

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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