Review of existing gaps in CI asset exposure and vulnerability data

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Executive Summary

This deliverable presents an extended literature review on existing exposure datasets and vulnerability data and models on Critical Infrastructure (CI) assets. Moreover, state-of-the-art frameworks and tools to assess vulnerability and losses of CI in a single and multi-hazard environment are reviewed. It satisfies the remit of Task 1.1 within the Work Package 3 (WP1) Multi-hazard Infrastructure Risk Assessment for Climate Adaptation (MIRACA) project. The focus is to identify the gaps in existing data needs on CI exposure and vulnerability and create the building blocks for a pan-European harmonised exposure and vulnerability database.

Concerning the exposure data, OpenStreetMap seems the most complete database. For roads and rails, OSM can be used for both direct damage estimates (because it is rather complete and geometrically precise) and indirect network effects (because it returns a good quality and consistent network graph). On the other hand, OSM data is insufficient for an analysis of the energy systems: for electrical power, natural gas and oil pipelines, too much information is missing. This also holds true for the telecommunication system as well as for single critical assets such as schools and hospital buildings.

Concerning vulnerability data, although there is a substantial increase of the studies quantifying the vulnerability of CI assets due to different natural hazards, significant gaps on vulnerability data and models still exist depending on the considered network (electric power, gas, oil, road, port, etc.) or the specific asset (e.g., telecommunication tower or school building). Generally, more vulnerability models are available for hazards such as earthquake or floods, while for other climate related hazards the available models are principally based on empirical data and judgement and they tend to be more qualitative.

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1. Introduction

Critical infrastructure (CI) refers to the assets, networks and systems that are vital for society, and whose damage or destruction can lead to serious consequences to the health, safety, and socioeconomic well-being of the population (Council Directive 2008; PCCIP 1997, Hall et al. 2016, Poudel et al. 2023). When natural hazards strike, the importance of these systems becomes apparent: a disruption of a single CI service can quickly result in a knock-on effect to households, companies, and other CI systems, thereby causing widespread impacts on society. For instance, the direct economic impact of infrastructure disruption due to natural disasters has been estimated at least $90 billion per year (Hallegatte et al. 2019). Within MIRACA, we focus on Europe's CI aiming at providing a multi-hazard risk assessment framework and appropriate tools for climate adaptation. Table 1 summarises the CI assets, networks and systems that are considered in D1.1 of MIRACA.

Table 1. *List of assets, networks and systems that are considered in D1.1. of MIRACA.*

System	Network	Asset
Energy	Electric power network	Transmission electric power grid, substations, distribution networks, power plants
	Natural gas network	Buried/elevated pipelines, compressor stations, natural gas storage
	Oil network	Pipelines, refineries, pumping plants, storage tank farms
Transportation	Roadway network	Road segment, bridge, tunnel
	Railway network	Railway bridge, tunnel, track, roadbeds, facilities
	Port network	Waterfront structures, buildings (warehouse, sheds), fuel facilities
	Airport network	runways, control towers, terminal buildings, maintenance facilities and hangars, air route traffic control system and fuel facilities
Telecommunication		Stations and transmitters
Healthcare		Hospitals and medical centres

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Education		Schools

The objective of Work Package 1 (WP1) is to identify and possibly fill gaps in CI exposure and vulnerability data and models, and to collect single and multi-hazard models that capture both present-day and climate change. Specifically, in D1.1 an extended literature review on existing exposure datasets and vulnerability data and models on different CI assets is performed with the focus to identify existing gaps. Moreover, state-of-the-art frameworks and tools to assess vulnerability and losses of CI in a multi-hazard environment are reviewed.

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2. Definitions and Concepts

D1.1 is critical as it lays the foundation for MIRACA project. For this reason, it is important to clearly define the various concepts concerning hazard, infrastructure and risk herein. MIRACA follows the definitions per the 'D1.2-Handbook of Multi-hazard, Multi-Risk Definitions and Concepts' (Gill et al. 2023) of the MYRIAD-EU project. The definitions and concepts are grouped into three major categories namely the hazard definitions, infrastructure definitions, and disaster impact/risk definitions.

2.1 Hazard definitions

The following hazard-related definitions will be used in the project.

- **Hazard:** A process, phenomenon, or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation (UNDRR 2016).
- **Natural hazards:** Hazards that are predominantly associated with natural processes and phenomena (UNDRR 2016).
- **Hydrometeorological hazards:** Hydrometeorological hazards are of atmospheric, hydrological, or oceanographic origin (UNDRR 2016).
- **Geological / Geophysical hazards:** Geological or geophysical hazards originate from internal earth processes (UNDRR 2016).
- **Hazard severity:** the potential of a hazard to cause damage to critical infrastructure
- **Multi-hazard:** The selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects (UNDRR 2016).
- **Cascading hazard:** Cascading hazard processes refer to an initial hazard followed by a chain of interrelated hazards (e.g., earthquake-triggering landslide, landslide triggering flooding, flooding triggering further landslides) (UNDRR 2019).

2.2 Infrastructure definitions

The following infrastructure-related definitions will be used in the project.

- **Exposure**: refers to the location, attributes, and value of important community assets that are exposed to the hazard, such as people, buildings, agricultural land, and infrastructure[1].

[1] https://www.gfdrr.org/riskier-future/

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- **Elements at risk:** are categorised as populations, communities, built environment, natural environment, economic activities, and services, which are under the threat of hazard in a given area (Alexander 2000).
- **Asset:** a specific element within an infrastructure system.
- **Network:** An interconnected set of assets in a specific infrastructure system.
- **System:** The interdependent technical, economic, social and environmental entities that deliver CI services and/or may be disrupted by CI failure through knock-on effects from a single asset within a single infrastructure network, to the impact on other infrastructure networks and the economy.
- **Infrastructure:** A network of independent, mostly privately owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services (Roche 1998).
- **Critical infrastructure (CI):** Infrastructures whose incapacity or destruction would have a debilitating impact on the defense and economic security.
- **Interdependencies:** *a) Physical* - The state of one infrastructure system is dependent on the material output(s) of another infrastructure system *b) Cyber:* The state of one infrastructure system depends on information transmitted through the information infrastructure *c) Geographic:* A local environmental event can create state changes in two or more infrastructure systems and *d) Logical:* The state of one infrastructure system depends on the state of others via a mechanism that is not physical, cyber, or geographic (Rinaldi et al. 2001).

2.3 Disaster impact/risk definitions

The following disaster impact-related definitions will be used in the project.

- **Disaster:** A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to one or more of the following: human, material, economic, and environmental losses, and impacts (UNDRR 2016).
- **Consecutive disasters:** Two or more disasters that occur in succession, and whose direct impacts overlap spatially before recovery from a previous event is completed (Ruiter et al. 2020).
- **Criticality:** A comprehensive measure of consequences resulting from disruptions, either individual or groups of disruptions, used to measure the risk of CI (Šarūnienė et al. 2024).
- **Robustness:** The ability of an asset, network or system to recover after the occurrence of a disruptive event and its capacity to adapt to previous disruptive events (Rehak et al. 2019)

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- **Vulnerability:** The conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards (UNDRR 2016).
- **Risk assessment:** A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend (UNDRR 2016).
- **(Residual) Risk:** The disaster risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained (UNDRR 2016).
- **Systemic risk**: Risk of a 'System' due to interaction effects of elements of a system. WP2 (MYRIAD-EU), UNDRR (2022)
- **Multi-hazard Risk**: Risk generated from multiple hazards and the interrelationships between these hazards (but not considering interrelationships on the vulnerability level) (Zschau, 2017).
- **Direct economic loss:** The monetary value of total or partial destruction of physical assets existing in the affected area. Direct economic loss is nearly equivalent to physical damage.
- **Economic loss:** Total economic impact that consists of direct economic loss and indirect economic loss.
- **Indirect economic loss:** A decline in economic value added as a consequence of direct economic loss and/or human and environmental impacts.
- **Cascading failures:** "the uncontrolled successive loss of system elements triggered by an incident at any location" [Vaiman et al. 2011].
- **Resilience**: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (UNDRR 2016).
- **Climate change adaptation:** In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

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3. Review on existing information gaps on exposure data

Considerable effort has been made in the last few decades towards the development of exposure datasets of single CI assets (e.g., healthcare, and educational facilities) and assets within more complex networks and systems (e.g., road, rail, ports, power, gas). Such datasets can be used within a synergetic risk assessment framework to evaluate the damages and losses of CI assets and networks due to different natural hazards in a single or multi-hazard environment considering also systemic effects and cascading failures. The usefulness of the available datasets for risk assessment purposes, however, depends on the completeness of the data at systemic level, data quality as well as on the existence of the main attributes (e.g., construction type, material, quality, and cost) necessary for the risk calculations. The goal of this section is to collect the available in literature exposure data and methods and after a critical review to identify the existing gaps. This section will pave the way for the development of the European harmonised exposure database (D1.4).

One of the most well-known database with a variety of exposure datasets is OpenStreetMap (OSM). It is a powerful and freely accessible global geographic database. This open data download service is offered free of charge by, for example, Geofabrik GmbH[2]. OSM is a Voluntary Geographic Information (VGI) project[3] launched in 2004 with continuously increasing data coverage and data quality currently including over 1.75 million different user contributors around the globe[4]. OSM data contains geo-referenced vector (line and point) features which can be mapped, e.g., administrative boundaries, buildings, roads, power plants, ports, airports, health care and educational facilities, rivers, forests, etc. There are several ways to collect geo-references data (Bennet 2010). The OSM database is available under the share alike Open Database License 1.0 (ODbL)[5] allowing data download, modification and sharing. The open access policy of OSM is a very important advantage, as it contributes to many research areas, such as risk assessment studies. For example, in the field of energy system modelling, it has been used successfully in the creation of power grid models (Medjroubi et al. 2017). OSM data are hierarchically structured and categorized in three types: nodes, ways, and relations. Fig. 1 presents an example of visualization of raw OpenStreetMap data. OSM nodes are geo-referenced points in space. They are used to represent smaller standalone features, e.g., telecommunication towers. They are also referenced in OSM ways, to define the shape of a way. OSM ways represent none-closed linear features (such as roads or rivers) or closed linear features (such as buildings or electrical substations). OSM relations are ordered

[2] https://download.geofabrik.de
[3] www.openstreetmap.org
[4] https://wiki.openstreetmap.org/wiki/Stats
[5] https://opendatacommons.org/licenses/odbl/

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lists of nodes, ways and/or other relations. A relation is the most complex data type in OSM. Relations are used to represent a logical or spatial association relating their different components, like a bus route that contains multiple bus stops and road parts. All OSM data types are also associated with tags, that are dictionary-like entries which have two attributes (i.e., a key and a value text) and describe a specific detail of the data.

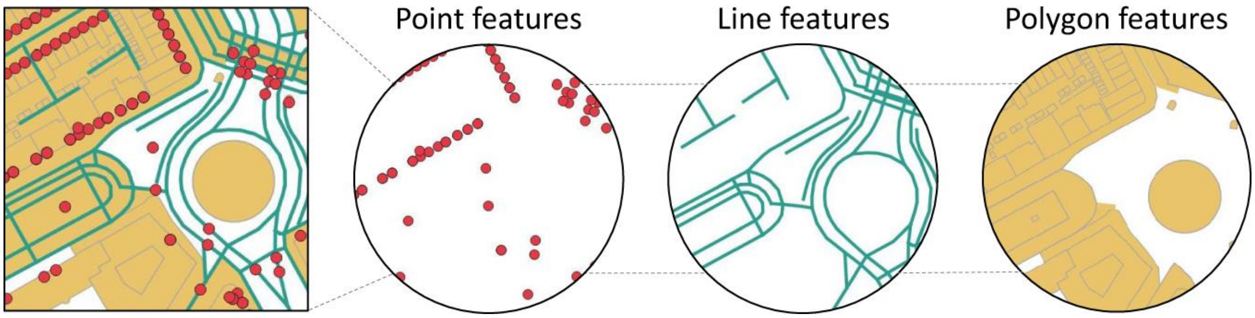

Fig. 1. *Visualization of raw OpenStreetMap data of a given area, with a breakdown by the datatypes (Nirandjan et al. 2022).*

In the following paragraphs the existing information on the exposure data for each network separately is analysed and the information gaps are highlighted.

3.1 Energy system

The energy system is composed of different networks, namely electric power, natural gas, and oil, each of which consists of a variety of assets. Regarding the electric power network, it consists of transmission electric power grid, substations, distribution networks, power plants and transmission lines with towers. Their classification depends on the asset, e.g., substations are classified to low, medium, or high voltage; with anchored or standard components, distribution networks to seismically designed or with standard components, power plants to small or medium/large, with anchored or unanchored components. In the case of the natural gas network, the main assets are buried/elevated pipelines, compressor stations and natural gas storages. Compressor stations are distinguished between those who have anchored or unanchored components. Oil network comprises pipelines, refineries, pumping plants, and tank farms. Refineries, pumping plants, and tank farms are classified to small or medium/large depending on their capacity and with anchored or unanchored components. To date, only limited information on the structure of the European transmission networks is available for research and other scientific purposes. The lack of these data impedes scientific attempts to analyse, characterise and compare high resolution energy system models (Matke et al. 2012). Energy infrastructure data are crucial

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for an integrated risk assessment of the energy system components and for enabling the EU to meet its broader climate and energy goals. Some of the most important efforts gathering European energy system exposure data concentrated on the electric power, natural gas and oil networks are described below, while existing information gaps on these data are also identified.

3.1.1 Electric power network

The Transparency Platform[6] is a public information system available to every EU citizen in line with the TEN-E Regulation (EU No 347/2013), Art.18, that provides detailed information about Projects of Common Interest (PCIs), including their geographical representation, technical description, implementation plan and dates, the benefits they bring to the Member States and local communities and the European Union financial support. In particular, the PCI Transparency Platform provides up to date information on the geographic location for the networks of electricity, natural gas, smart grids, cross-border carbon dioxide and oil. The user can download the information displayed at the viewer and reuse them if reference is mentioned. Fig. 2 displays the electric power, natural gas, and oil networks in Europe. However, the data and metadata are not downloadable.

The ENTSO-E Transparency Platform[7] is designed and developed by Unicorn Systems A.S. in order to provide free, continuous access to pan-European electricity market data for all users, across six main categories: Load, Generation, Transmission, Balancing, Outages and Congestion Management. Registered users can download data tables and graphs and customise their own dashboard and data views, but the spatial data is not easily accessible.

The **Global Power Plant Database**[8] is a comprehensive, open-source database of power plants around the world (Byers et al. 2021). It leverages existing data sources and methodologies to build a comprehensive and open-access power sector database. Approximately 35.000 power plants from 167 countries are contained, including thermal plants (such as gas, oil, coal, geothermal, waste, biomass, nuclear) and renewables (such as solar, wind, hydro). Each power plant is geolocated and entries contain information on fuel type, technical characteristics (fuel, technology, ownership), operational characteristics (generation), and plant capacity. The database is published under a Creative Commons-Attribution 4.0 International license (CC BY 4.0), allowing it to be used and republished in any fashion, with source attribution. There is also the **European Joint Research Centre Open Power Plants Database**[9] (JRC-PPDB-OPEN), which is mainly based on information from ENTSO-E's lists of installed capacity in Europe, extended through information contained in other open datasets, as well as analysis of historical

[6] https://ec.europa.eu/energy/infrastructure/transparency_platform/map-viewer/main.html

[7] https://transparency.entsoe.eu/

[8] https://datasets.wri.org/dataset/globalpowerplantdatabase

[9] https://data.jrc.ec.europa.eu/dataset/9810feeb-f062-49cd-8e76-8d8cfd488a05

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hourly generation time series data (Kanellopoulos et al. 2019). The JRC-PPDB-OPEN is a first attempt towards a more detailed and coherent, albeit still incomplete, dataset of European power plants. It contains production unit name, generating unit name, production unit capacity net (MW), generating unit capacity net (MW), ENTSO-E classification for the generation unit, Latitude (WGS84), Longitude in the range -180 (WGS84), name of the country, NUTS2 code according to the NUTS 2016 definition, status of the generating unit, year of commissioning, year of decommissioning. In addition, **the Europe Beyond Coal database**[10] maintains information on all major coal power plants covering 27 EU countries, UK and Turkey, as well as all countries in the Western Balkans. This database includes key information such as geodata, capacity, status, commissioning year, ownership, historic emissions of CO_2 and pollutants, modelled plant-level health impacts on population caused by pollutants and more. The minimum plant size included in the repository is 15 MWe. The Europe Beyond Coal database is under an Open Database License (ODbL) v1.0, while the data are updated quarterly.

The Global Transmission Network dataset[11] contains a vector shapefile of global transmission networks from OSM power lines from 2016. However, except for the geo-location, no metadata are included. In addition, regarding transmission network datasets, a short comparison among the various existing databases, related to their license and format, the year they were published, the region they refer to, the data they contain as well as if their data are downloadable can be found in [12]. From these databases, only two are openly licensed, the PyPSA-Eur which is published under a Creative Commons-Attribution 4.0 International license (CC BY 4.0) and the SciGRID which is available under the Open Database License (ODbL).

The PyPSA-Eur[13] is an open model repository of the European transmission power system which covers the full ENTSO-E area (Hörsch et al. 2018). The database consists of 6001 lines (all high voltage direct current lines as well as alternating current lines at and above 220kV voltage level), 3657 substations, an open database of conventional power plants, time series for electrical demand and variable renewable generator availability, and geographic potentials for the expansion of solar and wind power. It is proper for both operational and generation and transmission expansion planning studies.

[10] https://beyondfossilfuels.org/database/
[11] https://energydata.info/dataset/global-transmission-network
[12] https://wiki.openmod-initiative.org/wiki/Transmission_network_datasets
[13] https://zenodo.org/record/7646728#.Y_8alnZBy3B

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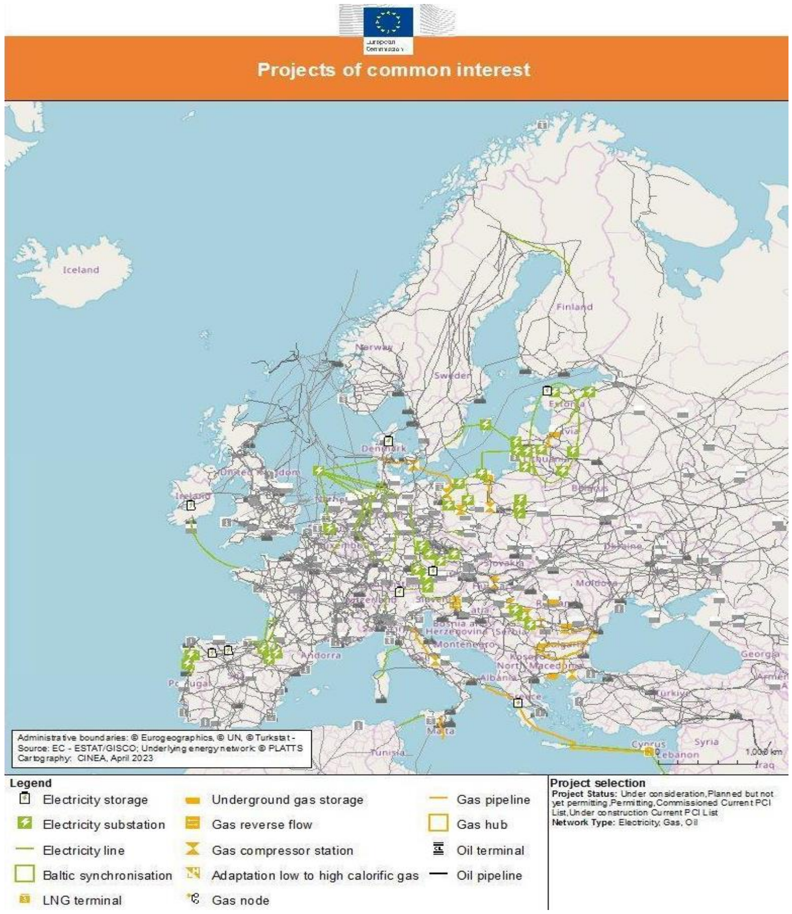

Fig. 2. *Electricity, natural gas, and oil networks in Europe (figure downloaded from the PCI Transparency Platform)*

The SciGRID database[14] is free, open-source code and contains open data, which builds on OSM transmission network data (Medjroubi et al. 2017). It was initiated in October 2014 for scientific purposes to address lack of transmission grid data. OSM power data is represented by the OSM types mentioned above, i.e., nodes, ways, and relations. OSM nodes represent electrical poles and line-carrying towers. OSM transmission lines and underground cables are depicted by open ways, while power plants, generators and substations are depicted by closed ways. OSM power relations represent electrical circuits and are constituted of one or several transmission lines, substations, and towers, while they have the key=value combination route=power. The SciGRID vertices of the transmission network represent the geometrical centers of the OSM substations. The SciGRID transmission lines between two vertices are

[14] https://www.power.scigrid.de/pages/downloads.html

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abstracted to direct connections with individual lengths calculated from the detailed layout in OSM. The abstracted transmission lines constitute the links (or edges) of the transmission network. Additionally, the voltage level, number of cables and wires of the transmission lines are adopted from OSM data. To ensure a better quality of OSM data, there are some quality assurance tools that can be used to automatically detect bugs[15]. A main drawback of the dataset is that for the high, medium, and low voltage levels the data coverage and quality decreases. This is due to the higher complexity and extent of the power grid at the lower and medium voltages, as well as the restricted access to the lower voltage power elements (especially underground cables and transformers boxes).

3.1.2 Natural gas network

Regarding gas networks, there is the project “Open-Source Reference Model of European Gas Transport Networks for Scientific Studies on Sector Coupling” with the acronym “SciGRID_gas”. This project intends to develop methodologies to create an automated network model of the European gas transportation network. The **IGGIELGN dataset**[16] is a collection of open-source European gas network data produced by the SciGRID_gas team. The database contains geographical and meta information on the European gas transport network. The IGGIELGN database contains data about 241.000km of European gas pipeline network as well as production, liquefied natural gas (LNG) terminals, storages, compressors, interconnection points and entry points. Within the SciGRID_gas project, esy-osmfilter was used to extract the European gas transport pipelines from OSM and to further identify the other relevant components (such as gas storages, pipeline marker, gas compressor stations) of the European gas transport network (Pluta and Ontje Lünsdorf 2020).

The ENTSOG Transparency Platform[17] is a Union-wide platform where all Transmission System Operators for gas shall make their relevant data publicly available according to Regulation (EC) № 715/2009 and its amendments. It provides technical and commercial data on gas transmission systems, which include interconnection points and connections with storages, LNG facilities, distribution networks, final consumers, and production facilities.

3.1.3 Oil network

Regarding oil network, there is an open and complete database including also EU oil pipelines[18], published under a Creative Commons Attribution license (CC BY), allowing the data to be visible and

[15] https://wiki.openstreetmap.org/wiki/Quality_assurance
[16] https://www.gas.scigrid.de/downloads.html
[17] https://transparency.entsog.eu/
[18] http://catalogue.msp-supreme.eu/dataset/emodnet-pipelines

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downloadable. The database contains lines representing the actual routes of offshore pipelines (where available) in the following countries: Croatia, Denmark, Estonia, Finland, Germany, Ireland, Netherlands, Norway, Poland, Russia, Spain (Andalucía). Each line has the following harmonized attributes (where available): code, country, name, year, length (metres), size (inches), medium (oil, gas, air, condensate, 'control', cooling water, geothermal heating, glycol, methanol, sewage, water), operator, from and to locality or facility, and status (in service, decommissioned, under construction, proposed, planned).

3.2 Transportation system

The transportation infrastructure as a system comprises different networks, namely roadway, railway, port, and airport, each of which consists of various assets.
In the case of the **roadway network**, the main asset is the road itself, which passes over bridges or through tunnels and other civil works. Different classification schemes exist based on its function and capacity, speed limits, number of lanes and other criteria. The key assets of the **railway network** are the railway tracks and roadbeds, railway bridges and tunnels as well as other different railway facilities. The classification schemes for the rail network are commonly based on speed limits, construction materials, usage of track and other parameters (Argyroudis and Kaynia 2014). **Port transportation networks** contain a wide variety of facilities for passenger operations and transport, cargo handling and storage, rail and road transport of facility users and cargoes, communication, guidance, maintenance, administration, utilities, and various supporting operations. In a port system, the key assets are the waterfront components, the cargo handling and storage components, the infrastructures, the buildings, and transportation lifelines. **Airports** include runways, control towers, terminal buildings, maintenance facilities and hangars, air route traffic control system and fuel facilities. Below some of the most important efforts are described for the European transport system; exposure concentrated on the roadway and railway networks, ports and airports and existing gaps are identified.

The Trans-European Transport Network (TEN-T) policy addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports, and railroad terminals. The TEN-T policy is based on Regulation (EU) No 1315/2013 that is currently being revised to make the network greener, more efficient, and more resilient. EU Regulation 1315/2013 provides the creation of a network based on two levels for the development of the international network: i) The Comprehensive Network, i.e., a global network (to be created by 2050) aimed at guaranteeing full coverage across the EU and accessibility to all regions. The Comprehensive Network consists of all the existing and planned transport infrastructure aimed at achieving the territorial cohesion objectives and integrates and interconnects the Core Network. It comprises road, rail, port, and airport network as well as Intermodal centers. ii) The Core Network, i.e., a central EU network (to be created by 2030) which includes the global network sections most strategically important for achieving

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the development objectives of the trans-European transport network. Its completion is based on a "corridor approach". The Core Network is the strategic part of the Comprehensive Network consisting of densely populated urban areas (urban nodes), the most important intermodal nodes (ports, airports, terminals) and relevant multimodal connections. High resolution maps of the nine TEN-T Core Network Corridors are available in pdf format[19] (Fig. 3). A TENtec Interactive Map Viewer maintained by DG Mobility and Transport of the European Commission is available presenting the TEN-T trajectories and TEN-T nodes consisting of all existing and planned transport infrastructure[20].

The **OpenStreetMap (OSM)** has collected an enormous amount of free spatial data including transportation infrastructures e.g., road and rail networks, ports and airports, and the database is growing every day.

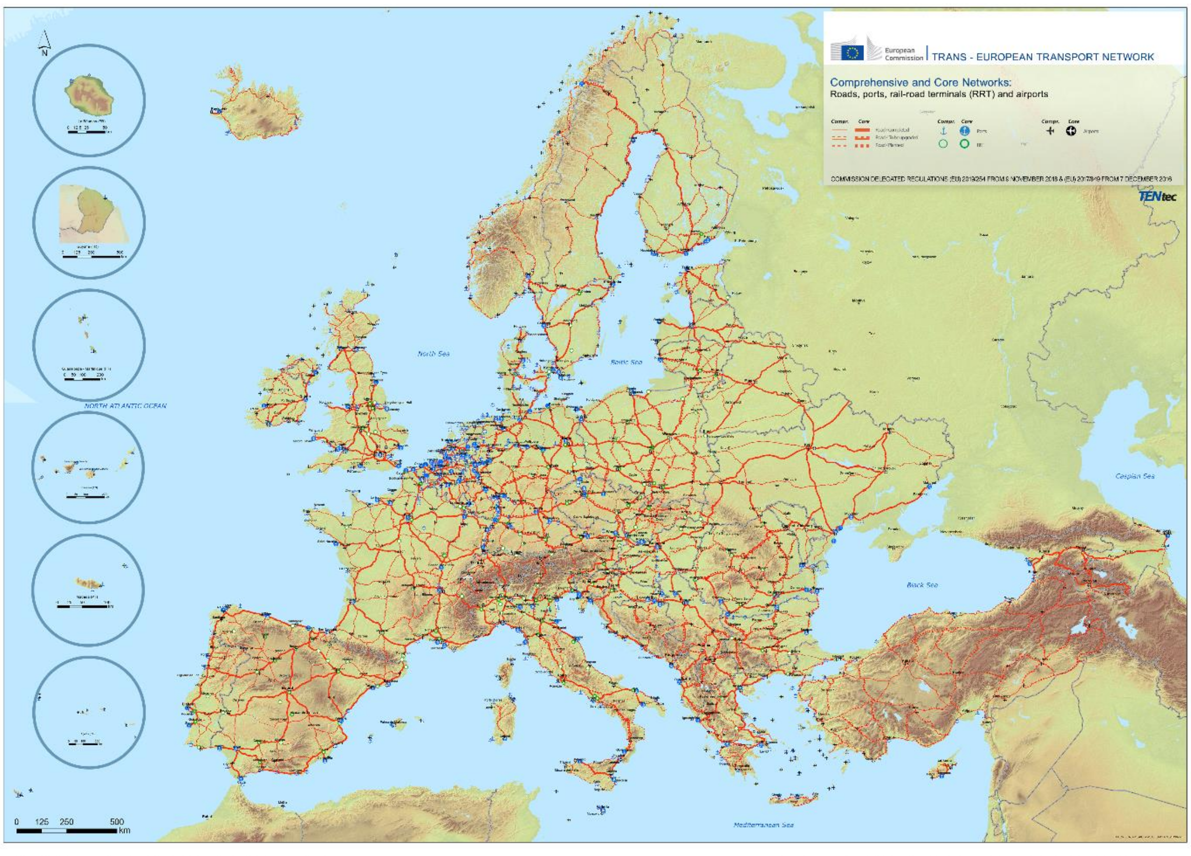

Fig. 3. *TRAN-European transport network including roads, ports, rail-road terminals and airports*[17]

[19] https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/site/en/maps.html
[20] https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/mobile.html

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The RRG GIS Database[21] builds upon and is a direct successor of the IRPUD GIS database of trans-European transport networks by mutual agreement between RRG and IRPUD. The RRG GIS Database is subdivided into the following branches: transport networks, regions and administrative boundaries, geography layers and interaction data and regional data. The transport network layers form the core part of the RRG GIS Database. They comprise roads and railway lines, railway stations (including intercity train stations, high-speed train stations, regional and local train stations), inland waterways and shipping routes, inland ports and seaports, and airports and flight networks, as well as transport terminals and intermodal transshipment facilities for the whole of Europe. **The RRG European road network** layer contains all motorways, highways, dual-carriageway roads, E-roads, and national roads as well as additional principal roads in agglomerations and important car ferries. **The RRG European rail network** layer contains all passenger and freight railway lines under operation today, and rail ferries of 38 European countries. The database contains all passenger train stations which are in operation today, plus planned (future) ones (as far as information are available) and many of those that are currently closed or abandoned. The RRG European road and railway network layers are not publicly available and can be ordered upon request.

The GRIP dataset (Meijer et al. 2018) consists of global and regional vector datasets of road infrastructure in ESRI file geodatabase and shapefile format, and global raster datasets of road density at a 5 arcminutes resolution (~8x8km). GRIP dataset covers 222 countries and includes over 21 million km of roads, which is two to three times the total length in the currently best available country-based global roads datasets. Regarding the European road network, crowdsourced OSM data was used to cover Europe, as best available seamless dataset. GRIP dataset is publicly available in order to ensure that the GRIP database can be easily shared with others.

To support the visualization of collected data and to give higher visibility to CEDR's Performance Report on the Pan-European Road Network (2021 Pan European Road Network Performance Report, CEDR, September 2022), a GIS web map of the road network has been developed. **The Pan-European Road Network Performance** GIS web map[22] comprises motorways and high-quality roads that are part of the European Union's TEN-T (Roads) network and their equivalent strategic routes in non-EU countries.

The most comprehensive European-wide dataset of railway infrastructure is **OpenRailwayMap**[23], a detailed online map of the world's railway infrastructure, built on OSM data. The OpenRailwayMap includes all rail-mounted and automotive vehicles, e.g., railways, subways, trams, miniature railways, and funiculars. OpenRailwayMap is Open-Source software and is freely available for download.

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[21] http://www.brrg.de/database.php?language=en&cId=2

[22] https://cedr.eu/ten-t-roads-performance-gis-web-map

[23] https://www.openrailwaymap.org/

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EuroGlobalMap[24] (EGM) (last release January 2022) is a pan-European dataset updated annually containing basic geographic information at the scale 1:1 million covering 47 European countries and 9 administrative areas. The data is seamless and harmonized and is produced by the EGM Project Coordinator (IGN France) in cooperation by the National Mapping Agencies of Europe. EuroGlobalMap contains five themes: Administrative Boundaries, Hydrography, Named Location, Settlement and Transportation. EGM is provided under an open data license and may be used for any legal purpose, including commercial exploitation. EuroGlobalMap allows cartographic visualisation across Europe enabling a wide range of applications from planning, monitoring and network analysis to presenting environmental policies. The transportation theme holds information on European roads and railways, ferry lines, and airports as well as connections between ferry stations and other transport modes.

The official portal for European data[25] comprises the major road and rail networks of different European countries at national or regional level. For instance, in the catalogue data.gov.uk one may freely download OS (Ordnance Survey) Open Roads Shapefile containing links pertaining to the Major Road Network of UK, as created by the Department for Transport in 2018.

The topic of bridges and tunnels in the road and rail network deserves some special attention. Data about bridges is essential for accurate assessment of flood damage, for two reasons. Firstly, because bridges are intended to cross water, which is a challenge for the commonly applied depth-damage approach in flood risk assessment. Normally, one assumes damage upon inundation of a road/rail segment, but this does not work in the case of the bridge (Van Ginkel et al. 2021). Secondly, during actual flood events, bridge damage is a major source of overall damage to transport infrastructure (Jongman et al. 2012, Koks et al. 2022). Bridge data is present in OSM as a separate attribute for a road segment. In countries like The Netherlands, this data looks quite complete.

The **Global Airport Database**[26] is a comprehensive database of airports around the world, maintained by the International Civil Aviation Organization (ICAO). The database includes information on airport location, runway length and orientation, and other important features. The **National Oceanic and Atmospheric Administration (NOAA)**[27] provides a range of GIS data related to ports and coastal areas, including data on coastal bathymetry, shorelines, and maritime boundaries. The United Nations Conference on Trade and Development (UNCTAD) maintains a database of port statistics, including information on port throughput, cargo volumes, and other important indicators. The **OpenFlights**[28] is an open-source database of airports around the world, providing information on airport location, runway

[24] https://www.mapsforeurope.org/datasets/euro-global-map
[25] https://data.europa.eu/data/
[26] https://www.partow.net/miscellaneous/airportdatabase/
[27] https://www.noaa.gov/
[28] https://openflights.org/

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data, and other features, using data from OpenStreetMap. The **Eurostat**[29] provides a range of statistical data on European transport infrastructure, including data on ports and airports. This includes information on passenger and cargo traffic, as well as data on transport infrastructure investments and performance.

The **European Maritime Safety Agency (EMSA)**[30] provides a range of data on European ports and maritime transport, including information on port infrastructure, maritime traffic, and environmental risks. The **OpenSeaMap**[31] is a free, open-source map of European and global seaports, using data from OpenStreetMap. The map includes data on port location, infrastructure, and other features. The **European Environment Agency (EEA)**[32] provides data on air quality and other environmental indicators across Europe, including near airports and ports. This can be used to assess the environmental risks associated with these transportation hubs. These data sources can be used in a variety of ways, including analyzing transportation flows, identifying infrastructure gaps, and assessing environmental risks associated with ports and airports. However, it is important to note that not all data sources are comprehensive or up-to-date, and users should exercise caution when interpreting and using the data.

The United Nations Economic Commission for Europe (UNECE)[33] has a dedicated regional commission that works on Transport in Europe. The geographical coverage of this initiative reaches beyond the 27 EU member states. They have undertaken a project to map Pan-European and Euro-Asian transport corridors, that gives some insight in the major trade flows that reach beyond the European Union. This data is only as visualisations (UNECE 2019).

3.3 Telecommunications

A telecommunication system consists of several basic components that work together to enable the transmission, reception, and processing of information. Two main types of telecommunication infrastructure are communication networks and telecommunication towers. The former can be categorized into various types, such as wired networks (e.g., copper cables, fiber optics) and wireless networks (e.g., cellular, satellite, Wi-Fi). These networks interconnect devices and facilitate the exchange of voice, data, and multimedia. Telecommunication towers or masts are tall structures that support antennas and equipment for wireless communication over long distances. In particular, communication towers, constructed from concrete or steel, are utilized for transmitting various applications such as radio, mobile phone, television, and official radio. These towers can reach heights of up to 100 meters. In contrast, masts are typically dedicated to a single application. According to a dataset compiled by

[29] https://ec.europa.eu/eurostat/data/database
[30] https://www.emsa.europa.eu/
[31] https://www.openseamap.org/index.php?id=openseamap&L=1
[32] https://www.eea.europa.eu/en
[33] https://unece.org/DAM/trans/doc/2019/wp5/ECE-TRANS-265e_re.pdf

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Nirandjan et al. in 2022, there are approximately 141,478 communication towers and 80,750 masts worldwide.

Open Infrastructure map[34] (Fig. 4) visualizes world's infrastructures mapped in the OpenStreetMap database. Through this website, the user is capable of exploring the communication towers and cables all over the world. The cables are represented with lines while communication towers and masts with discrete points. A commercial export service is available to fetch and process large amounts of data from OSM.

OpenCellID[35] is a large community project that collects GPS positions of cell towers. The whole database is free of charge and provides data which can be used for either commercial or private purposes. Actually, it's a data source for GSM localization, and as of October 2017, the database contains almost 36 million GSM Cell IDs.

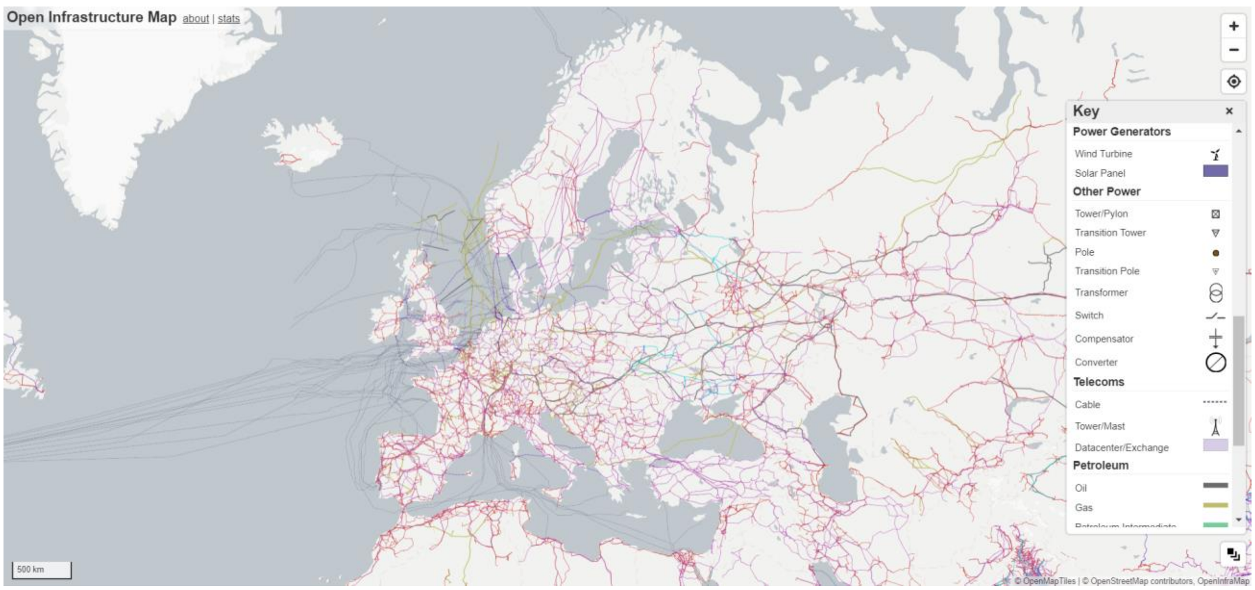

Fig. 4. *Global dataset on communication cables and towers/masts*[32]

3.4 Single assets

Within MIRACA, healthcare facilities and education systems will be considered as single CI assets focusing mainly on exposure data for schools and hospitals. **Healthcare facilities** play a vital role in providing accessible, efficient, and effective healthcare services to individuals and communities and may

[34] https://openinframap.org
[35] https://opencellid.org

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vary in size, scope, and the types of services offered. A healthcare system comprises several key components including hospitals, clinics and medical centres, long-term care and ambulance facilities, as well as diagnostic centres. Hospitals belong to the so-called ''complex-social'' systems (Pitilakis et al. 2014) since they depend on several components of different nature to function properly. These complex medical facilities provide a wide range of services and amenities to support patient care and treatment. Some common hospital facilities are emergency and operating rooms, laboratories, administrative areas, cafeterias, warehouses, etc. It's important to note that the availability of specific facilities may vary from one hospital to another, as some hospitals specialise in certain areas of care or have different resources and capacities. **An education system** encompasses various types of facilities and resources that support the delivery of education. In particular, the main infrastructure types of the education system are the following: college, kindergarten, library, school, and university.

Eurostat[36] is the statistical office of the European Union, dedicated to providing accurate and reliable statistics and data on Europe. It collaborates with National Statistical Institutes and other national authorities in EU Member States through the European Statistical System (ESS). This partnership extends to include the statistical authorities of European Economic Area (EEA) countries and Switzerland. One of the datasets offered by Eurostat focuses on healthcare information, aiming to facilitate spatial analysis at the European level for services within the European Commission and other users of Geographic Information Systems (GIS). This geospatial dataset specifically provides the locations of major healthcare services across several European countries (Fig. 5). The locations are represented as point geometries, denoting their geographic coordinates (longitude and latitude) based on the WGS84 coordinate system (EPSG:4326). It's important to note that the position of a healthcare service is sometimes determined automatically through geocoding, which relies on postal addresses and may result in potential inaccuracies. Moreover, it is noted that the dataset is not complete as the healthcare facilities in several European countries (e.g., Germany) are not available.

[36] https://ec.europa.eu/eurostat/

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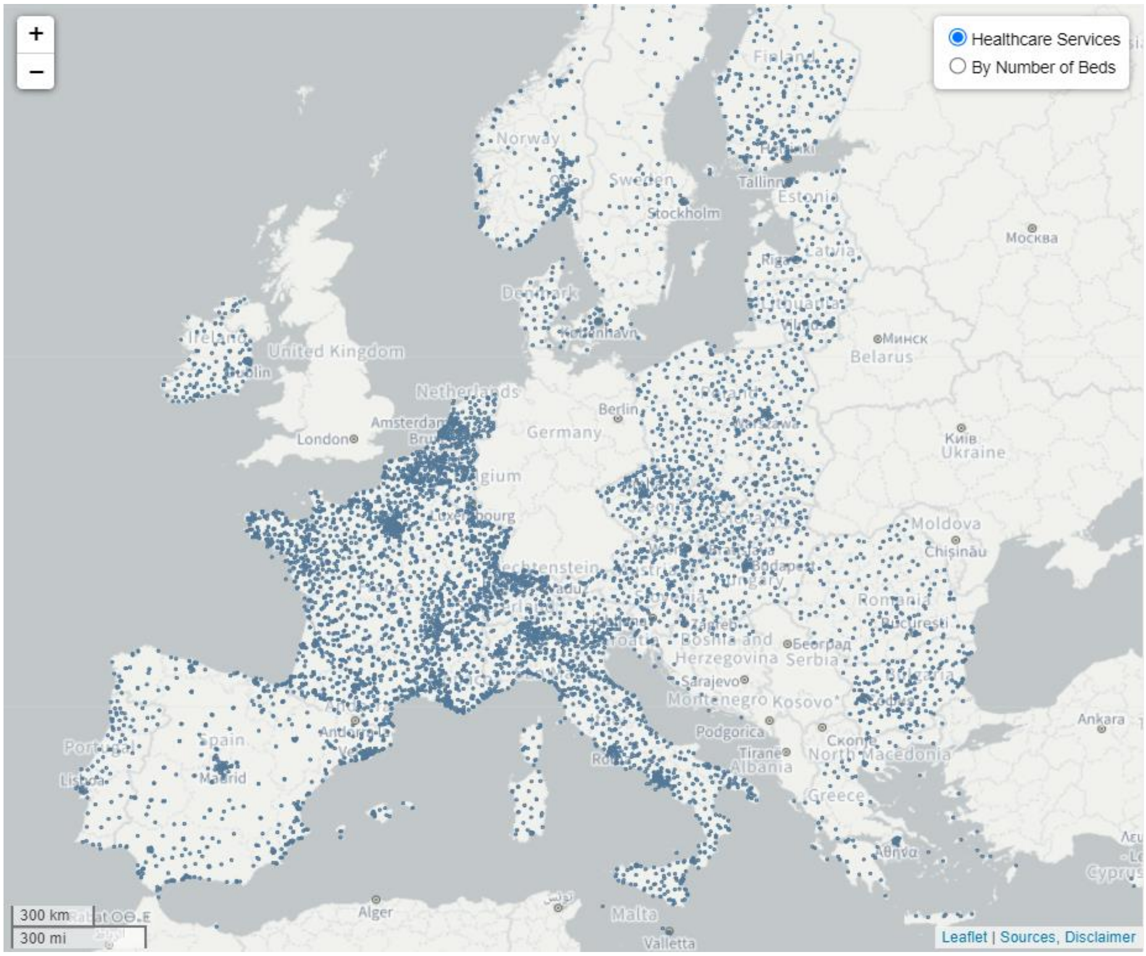

Fig. 5. *Healthcare services in Europe*[34]

The **Global Healthsites Mapping Project**[37] offers an online map containing information on existing healthcare facilities worldwide. During natural disasters or disease outbreaks, it becomes crucial to quickly establish accurate data on healthcare locations to provide support on the ground. This urgency has been highlighted in past events like the Haiti earthquake and the Ebola epidemic in West Africa. Healthsites.io ensures easy accessibility to this data through various formats, including an API, GeoJSON, Shapefile, KML, and CSV. The project collaborates with users, trusted partners, and OSM to validate the location of each facility and provides the data freely under an Open Data License (ODBL). As a result, users can explore the available healthcare facilities, services, and resources at any global location. The dataset encompasses a

[37] https://healthsites.io/

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range of facility types, including doctors, pharmacies, hospitals, clinics, dentists, physiotherapists, alternative healthcare providers, laboratories, optometrists, rehabilitation centers, and blood donation centers.

The **ESPON 2020 Database**[38] provides access to numerous data and information resources that are stored in various formats. Initially developed in 2006, the database has undergone continuous enhancements, accommodating different types of data and functionalities related to territorial analysis and monitoring. It efficiently stores and distributes a wide range of data, including local and global data, tabular and GIS data, as well as administrative and gridded data. Within the available datasets, there is comprehensive information on hospital and school locations across Europe. This information has been compiled by utilizing OSM as the primary data source, supplemented by additional national data sources. The locations of hospitals, as well as primary and secondary schools are represented as point geometries with geographical coordinates, specifically longitude and latitude, using the RRG Lambert Conformal Conic projection.

There are also some initiatives in Europe focusing at developing exposure data for single critical assets at regional scale. For example, as part of the **RiskSchools** project[39], a novel and user-friendly product has been developed to facilitate rapid visual inspection, seismic vulnerability assessment, and seismic risk evaluation of school buildings in the Region of Central Macedonia and beyond. This product comprises two main components: a smartphone application at the prototype stage, designed in accordance with European Union standards (Technology Readiness Level 6 - TRL6), and a unified platform for managing and processing diverse data and information. The smartphone application enables on-site data collection through pre-seismic building rapid visual screenings. It allows inspectors to assess the vulnerability and risk of school buildings of various forms and types. The collected data can be combined with existing files and applications available on the internet, providing a comprehensive platform for vulnerability and risk assessment. To validate the effectiveness of the product, a pilot application is implemented in the school buildings within the Region of Central Macedonia. This initiative aims to enhance the safety and resilience of school infrastructure in the face of seismic events.

3.5 Discussion and gaps on the exposure data

In Table 2, the most robust datasets per CI network that may be further exploited within MIRACA are summarized. Among them, the most complete datasets per CI network that could be used as a basis for the EU-wide analysis in MIRACA are shown in bold. As also evident in the table, although several efforts have been made to develop exposure datasets for CIs, a pan-European harmonized, accessible, and

[38] https://database.espon.eu/
[39] www.riskschools.gr

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complete dataset of the different CI assets also containing the appropriate attributes to be used within the risk calculations is not available.

Table 2. *Exposure datasets per CI network that may be used in MIRACA*

System	Network	Exposure data
Energy	Electric power network	OSM, Transparency Platform, ENTSO-E Transparency Platform, Global Power Plant Database, European Joint Research Centre Open Power Plants Database, Europe Beyond Coal database, Global Transmission Network dataset, **PyPSA-Eur**, **SciGRID database**
	Natural gas network	OSM, Transparency Platform, **IGGIELGN dataset**, ENTSOG Transparency Platform
	Oil network	OSM, Transparency Platform, **http://catalogue.msp-supreme.eu/dataset/emodnet-pipelines**
Transportation	Roadway network	TEN-T, **OSM**, RRG European road network, GRIP dataset, Pan-European Road Network Performance, EuroGlobalMap, official portal for European data, UNECE data
	Railway network	TEN-T, **OSM**, RRG European rail network, **OpenRailwayMap (OSM)**, EuroGlobalMap, official portal for European data
	Port network	TEN-T, **OSM**, RRG GIS Database, official portal for European data, National Oceanic and Atmospheric Administration, Eurostat, European Maritime Safety Agency, OpenSeaMap, European Environment Agency
	Airport network	TEN-T, **OSM**, RRG GIS Database, EuroGlobalMap, official portal for European data, Global Airport Database, OpenFlights, Eurostat, European Environment Agency

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Telecommunications		Open Infrastructure map, OpenCellID, **OSM**
Healthcare		Global Healthsites Mapping Project **(Healthsites.io),** Eurostat, **OSM**, ESPON 2020 Database
Education		**OSM**, ESPON 2020 Database

As seen, OSM datasets include all considered systems and constitute the base for several of the above databases. However, the fact that they are based on Voluntary Geographic Information (VGI) collected data implies issues with the data accuracy, completeness, and quality. These issues are known and have already been dealt with in several studies in literature, such as for buildings footprints mapping (Fan et al. 2014; Herfort et al. 2023) and road mapping (Haklay 2010). The risks associated with these issues need to be considered when using OSM data. In addition, the simplifications or assumptions made to infer erroneous or missing OSM data should be given to the users of databases or models built with or using OSM data (Medjroubi et al. 2017).

Despite these limitations, OSM data seems to be the most complete. The OSM data is directly usable for analysis of the transport network: both the road and rail network are nearly complete. On the other hand, OSM data is insufficient for an analysis of the energy systems: for electrical power, natural gas and oil pipelines, as too much information seems to be missing. This also holds true for the telecommunication system as well as for the single critical assets such as schools and hospitals.

More specifically, regarding energy system exposure datasets, an important gap for power elements is that many attributes are insufficient or completely missing for their detailed use in a vulnerability or risk assessment study. For example, there are no mandatory fields for mapping power lines or natural gas and oil pipelines. This also holds true for power substations and power plants. Thus, various metadata may be missing that are useful in specific analysis such as vulnerability assessment. Circuit breakers, switches and transformers are some of the elements in a power substation that may be important when more modelling analysis is required. However, such details cannot be extracted from the above databases and are missing due to the layout of power substations. These elements are included in the models and databases within companies, but never shared in some publicly available databases, since it is too detailed and not really needed for some general analyses. The same is with gas and oil networks. Another example specifically for the OSM electric power database, that is the base for many of the databases, is also the missing electrical branching details of transmission lines referring to an explicit definition and allocation of electric networks. Transmission lines are mapped with different voltage levels, which need to match the cable taggings. However, mappers do not follow this recommendation in all cases resulting in the difficulty of defining the number of circuits present (Medjroubi et al. 2017). Nevertheless, despite the above limitations, PyPSA-Eur and SciGRID databases seem to be the most complete databases for electric

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power networks, as they include more information compared to the others and address lack of power and transmission grid data. In addition, the IGGIELGN database data produced by SciGRID_gas team and the open database available in EMOD-NET[40], which also includes EU oil pipelines, even not fully complete, seem to be the most proper databases for gas and oil networks respectively.

Concerning the transportation system OSM datasets, recent studies have shown that their accuracy has increased substantially over the last few years. According to Barrington -Leigh and Millard-Ball (2017) the globally mapped road network in OSM is more than 80% complete, and more than 40% of countries including several in the developing world have a fully mapped street network. Moreover, recent studies of European countries have found that the road network in OSM is virtually complete and is comparable to or even better than official or proprietary data sources (Neis et al. 2011, Graser et al. 2014, Sarretta and Minghinib 2021). Koks et al (2019) have recently used OSM road and railway asset data for a global multi-hazard risk assessment. Although OSM can be considered a globally reliable and complete source of road and rail infrastructure data (Koks et al. 2019), various metadata are still missing that are useful in risk assessment studies. Furthermore, there are several gaps in the main attributes needed for a complete vulnerability assessment of specific CI transportation networks such as ports or airports. For instance, information regarding the cargo and container movements or airport operations is not available. These existing information gaps on exposure data of port and airport networks make it difficult to assess in detail their vulnerability and losses both in a single- and multi-hazard environment. At the same time, the many attributes that are frequently available especially for roads (and rails), e.g., the road type, number of lanes, tunnels and bridges etc., and the other attributes such as street lighting that are sometimes available, make OSM a natural starting point for EU-wide analysis of the transport infrastructure.

While the telecommunication infrastructure has evolved significantly in the last decades, there are still gaps in exposure data or information related to telecommunications. Some of the common gaps include limited geographic coverage, insufficient data sharing and accessibility, as well as limited spatial resolution. OpenStreetMap database seems to be the most appropriate resource for obtaining information about the telecommunications network. Although, the quality and completeness of telecom infrastructure data in OSM may vary, depending on the region and the contributions of local mappers. In some areas, there is detailed information, while in others, data could be sparse or outdated.

Databases of single critical assets (e.g., schools and hospitals), mainly include data concerning the coordinates or the surface of the buildings. Especially, Global Healthsites Mapping Project, for hospitals, as well as OSM, for educational buildings, provide the most valuable information about the locations of the above buildings. While these databases offer valuable insights, they may not always have the same level of detail or coverage as national or local databases in some areas. Also, there is a general lack of attributes that influence their vulnerability and losses such as the age of construction, the building height,

[40] http://catalogue.msp-supreme.eu/dataset/emodnet-pipelines

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the construction material, the lateral load resisting system and the ductility level. Finally, there is no information and data on schools' and hospitals' non-structural components that can affect their overall performance during a natural hazard. Hence, there is a general lack of big data integration for both telecommunication systems and single assets.

While data exists regarding CI assets that connect different modes of transportation (e.g., ports connecting inland waterways with railways in the TEN-T interactive map), this information is lacking across systems. This makes it difficult to understand interdependencies among systems, such as which power lines feed telecommunications equipment and how rail lines are electrified.

Finally, for all systems CI assets, one significant information gap is the lack of standardised data collection methods and reporting frameworks. There are no globally agreed-upon standards for collecting and reporting exposure data. This makes it challenging to compare and analyse data across different locations, and it limits the ability to make informed decisions about risk assessment. Another significant gap is the limited availability of long-term exposure data. Most existing data on exposure are short-term measurements taken during specific events or in response to specific concerns. Long-term exposure data are necessary to understand the chronic effects of exposure to natural hazards and climate change. These gaps pose significant challenges to understanding and mitigating the risks associated with natural hazards and climate change. Addressing these gaps will require a collaborative effort from governments, industry, and research institutions to develop standardized data collection methods and reporting frameworks and conduct further research on the impacts of natural hazards and climate change on CI. However, it is important to note that not all data sources are comprehensive or up-to-date, and users should exercise caution when interpreting and using the data.

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4. Review on existing information gaps on vulnerability data and methods for the different hazards

Critical infrastructure (CI) is vulnerable to natural hazards such as earthquakes, floods, wildfires or other climate-change related hazards. If the CIs were to undergo significant damage, the social and economic welfare of society could be jeopardised. Thus, the issue of vulnerability of CI has attracted considerable attention from both the academic and policy-making spheres. Vulnerability data and methods are important as they provide the authorities or stakeholders with details on the performance and weaknesses of the CI under their responsibility. Vulnerability information is the roadmap for enhancing security preparedness, also providing direction on how to assess the risks associated with these weaknesses. Thus, the goal of this section is to compile and critically review the available in literature vulnerability data and methods to improve our understanding of CI vulnerability and identify the existing gaps. This effort aims to support more effective mitigation and adaptation strategies. Additionally, this section will pave the way for the development of the MIRACA harmonized European vulnerability database (D1.5).

Risk assessment to natural disasters may be defined as 'a qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend' (UNDRR 2016). An extension to risk assessment is the 'criticality assessment' (Fekete 2019). Criticality is a comprehensive measure of consequences resulting from disruptions, either individual or groups of disruptions, used to measure the risk of CI (Šarūnienė et al. 2024). It is based on the overall consequence of failure; higher consequences mean higher criticality. Vulnerability represents a key component in the risk assessment procedure. Vulnerability is generally defined as 'the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards' (UNDRR, 2016) (see also Section 2.3 for the definition of other main terms).

Vulnerability of CI under a given natural hazard is commonly quantified using fragility/vulnerability (or damage) functions (Figure 6) or vulnerability indices (VI). Vulnerability (or damage) functions describe the degree of losses on a scale from 0 to 1 (e.g., monetary costs, casualties, down-time, environmental degradation etc.) of a given asset (or system of assets) as a function of the hazard level. Fragility functions express the probability that the asset exceeds some predefined damage limit states (e.g., serviceability, severe damage) for a given level of hazard intensity. A two-parameter lognormal distribution function is usually adopted, due to its simple parametric form, to represent a fragility curve for a predefined damage/limit state. The vulnerability and fragility functions can be derived using empirical, analytical, expert elicitation and hybrid methods (FEMA 2024b, Pitilakis et al. 2014, Argyroudis et al. 2018).

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Vulnerability index approaches assess CI damages and losses based on different parameters, which describe its vulnerability. Weighting factors are commonly employed to assess the contribution of each parameter to the CI vulnerability. The VI method is considered important in rating and prioritisation of assets (El-Maissi et al. 2021).

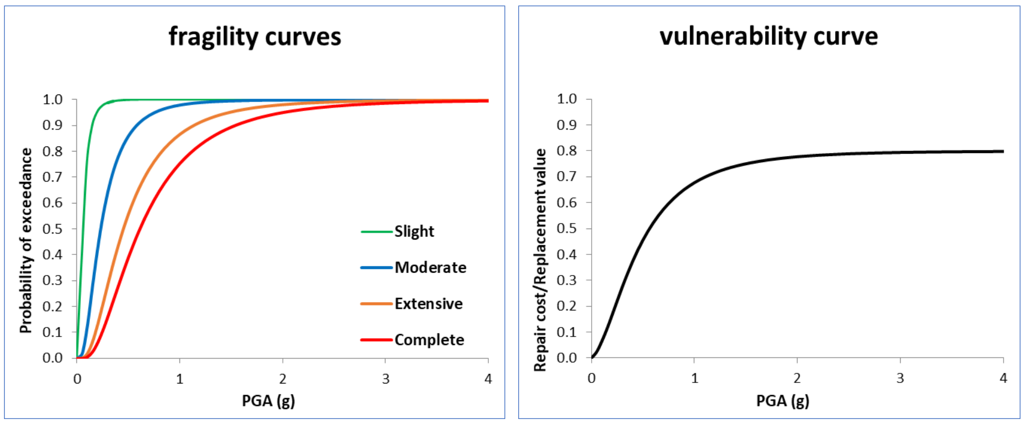

Fig. 6. *Example of fragility curves (left) for different damage states (Slight, Moderate, Extensive, Complete) and of a vulnerability (or damage) curve (right)*

4.1 Floods

One of the most destructive and frequent natural hazards worldwide are floods (Waseem and Manshadi 2020). Every year, the flood frequency increases, ruining lives and properties. Most structures are vulnerable to floods due to several reasons, including their **location**, the **type of infrastructure** they have, and the **impact of climate change**. CI are often located in low-lying areas, such as river deltas, estuaries, and coastal plains, that are susceptible to flooding. In addition, the proximity to the water makes these facilities more vulnerable to flooding caused by storm surges, tidal waves, and heavy rainfall. Climate change is causing more frequent and intense weather events, including heavy rainfall and storm surges, which increase the probability of flooding. Rising sea levels also increase the probability of flooding and coastal erosion, which can affect any kind of infrastructure. Overall, the vulnerability of CIs to floods is influenced by a combination of factors related to their location, characteristics, and climate. Implementing adaptation measures to improve resilience, such as improving drainage systems and elevating infrastructure, is essential for reducing the risk due to flooding events, but initially we need to define appropriate vulnerability models of the different assets per system due to flood hazard, which is done In the following paragraphs.

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Energy system

The assessment of potential flood damage is a widely accepted process for studying the vulnerability of energy systems in view to assisting the decision-making processes (Merz et al. 2010). Hazus (FEMA 2024a) provide damage (vulnerability) functions for electric power network components (i.e., substations, transmission lines and power plants), which relate the flood hazard intensity (flood depth) to the damage ratio of the component, which is expressed as the expected value of the ratio between the component's repair cost over its replacement value. According to Karagiannis et al. (2017), for flood risk analysis damage functions are preferable to fragility functions, because, once a facility is inundated, water damages all the equipment and buildings inside. Hazus (FEMA 2024a) also provides damage functions for natural gas and oil network components (namely, exposed and buried transmission pipelines, control valves, control stations and compressor stations). One weakness of these damage functions is that they provide information for flood depths of up to 10 ft (3,048 m) only. Additionally, Eleuterio et al. (2013) present a methodology for evaluating potential network infrastructure and damage in cases of flooding, resulting in the construction of damage matrices based on expert interviews. Power supply and gas distribution are among the network components analysed for the construction of damage matrices. The flow velocity, duration of submersion, and the amount of sediment/debris carried by floodwater are found to be crucial parameters affecting damage. A drawback of this method is the amount of data needed for the application of damage matrices. Moreover, Espinoza et al. (2016) present a multi-phase resilience assessment framework that can be used to analyse any natural threat that may have a severe single, multiple and/or continuous impact on the electric power network. They provide fragility functions for electrical components (lines and towers) with respect to accumulated rainfall expressed in millimetres (mm).

Energy sector is considered one of the most complicated due to complex configuration and automatic generation control among all systems (Augutis et al. 2016). Failure of critical national infrastructures, such as energy infrastructure can cause disruptions with widespread economic impacts. Thus, the scientific community also uses other methods to assess flood vulnerability and risk in energy infrastructure, focusing on the asset-level vulnerabilities of energy individual components and/or on a more systemic approach resulting to the estimation of 'business disruption' and 'economic losses'. A method to quantitatively investigate the vulnerabilities of the electric grid against floods based on the Hazus methodology (FEMA 2009) is proposed by Vasenev et al. (2016) providing a detailed risk framework. In addition, Pant et al. (2018) propose a method to evaluate the flood risk of the electrical assets, where through spatial network models identified and compared the risk of CI on flooded areas. Also, Karagiannis et al. (2017) propose a methodology for the assessment of the risk posed by floods to electrical assets given the change in flood hazard (severity and frequency) due to climate change. More recently, Koks et al (2019) presented an integrated modelling framework combining geospatial information on electricity infrastructure and flood hazard and geospatial modelling of the reliance of businesses upon infrastructure

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services to assess flood risk in terms of business disruption (either direct due to the flood hazard or systemic due to infrastructure failure) and economic losses (either due to direct or systemic business disruption) in the event of electricity failures. Sánchez-Muñoz et al (2020) present a method able to analyse flood hazard maps quantifying the probability of failure risk of the electrical assets (i.e., Distribution Centres (DCs)) and their potential impacts using a probabilistic approach. The method can be implemented to any city where the locations of the DCs and a flooding model are available.

Transportation system

Flood vulnerability of transportation infrastructure is usually defined as the relationship between the characteristics of the transportation components (i.e., the physical structure, traffic flow and traffic velocity) and the variables characterizing the intensity of the flood hazard (i.e., flood depth and flood velocity) (Pregnolato et al. 2017) using flood intensity–damage (vulnerability) functions (e.g., Green et al. 2011). Flood intensity–damage functions represent relationships between flood intensity (typically the flood depth) and the resulting monetary damage. For a given flood intensity, the function gives expected losses to a specific property or land use type, either as a percentage of a pre-defined asset value (relative function) or directly in financial terms (absolute function). Many flood damage assessments rely on flood depth as intensity parameter, though sometimes other intensity measures (or a combination of measures) have been used such as the duration of flood or the flow velocity (e.g., Scawthorn et al. 2006). According to NRE (2000), the main aspects that influence the level of damage for road infrastructure are the water depth, the velocity of the flow, the period of inundation, the condition of the road, the classification of road, the direction of flowing water relative to the pavement and the presence of structures and bridges. In the following, a brief description of the available flood damage models is made with a focus on the transportation infrastructure.

A first pan-European damage model has been developed on the request of the European Commission – Joint Research Centre (Huizinga 2007; Huizinga 2017) which is considered appropriate for (coarse) grid-based assessments but lack detail for accurate assessment of damage to transportation infrastructure (Jongman et al. 2012). They estimate the maximum damage to their 'infrastructure' class at some 25 euro/m^2 for Europe (2015 price level). Multi-Coloured Manual (MCM) is one of the most advanced methods for flood damage estimation within Europe (e.g., Penning-Rowsell et al. 2013; Jongman et al. 2012). Therein, direct flood damages in the transport infrastructure sector are only roughly estimated by a percentage share of property losses based on empirical data of the summer floods in the UK in 2007 (Jongman et al. 2012). However, the focus of the MCM lies on the estimation of indirect losses due to traffic disruptions (e.g., additional travel time). A few established flood damage models, e.g., the Rhine Atlas damage model (RAM) or the Damage Scanner model (DSM) (Klijn et al. 2007), do also consider direct damage to infrastructure by use of flood depth-damage curves. However, only aggregated Coordinated Information on the European Environment (CORINE) land-use data containing a large variety of urban

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infrastructure and lifeline elements are used therein (Bubeck et al. 2019; Jongman et al. 2012). The HAZUS Flood Model (FEMA 2024a, Scawthorn et al. 2006) has been applied in different settings, to assess potential flood risk or plan actual emergency support for upcoming flood events including various applications at city, country, and state scale. The flood model default data includes over 700 depth-damage functions for buildings, essential facilities, transportation and utility systems, agricultural products and vehicles developed based on modelling, expert opinion and historical data that relate water depth to structure and content percent damage. The damage functions for transportation system are estimated based on the vulnerabilities of the various components to inundation, scour/erosion, and debris impact/hydraulic loading. The impact on system functionality, the relative cost of components, and the overall time to recover from damage are also taken into consideration. Based on an extensive review of road (re)construction costs in Europe, van Ginkel et al. (2021) have recently developed a set of new damage functions for the European roadway network, which differentiate between three dimensions: road type, road accessories and flow velocity. The proposed damage functions include several aspects of the direct tangible costs (e.g., clean-up costs, resurfacing of top and deeper asphalt layers, repairs of road embankments, and where applicable also the repair of electronic signalling and lighting.) Van Ginkel et al. also provide an object-based (instead of the original grid-based) version of the Huizinga (2007, 2017) damage curves, showing that these likely underestimate damage to highways/motorways and overestimate damage to the underlying road network.

The so-called RAIL model developed by Kellermann et al. (2015) can estimate structural flood damage to the railway infrastructure and the resulting direct economic losses. The development of the flood damage model is essentially based on the significance of the correlation between the hydraulic flood impact and empirical damage patterns that occurred in the Northern Railway in Lower Austria caused by the March River flood in 2006. In Bubeck et al. (2019) the RAIL model is first applied at the European scale using three vulnerability indicators to rank the vulnerability of the European railway network, namely the length of the rail network (per kilometer), freight volumes (per thousand tons), and passengers (per thousand passengers) for the historic period. Espinet et al. (2018) calculated the flood vulnerability of the road infrastructure expressed as the cost of repairing or rebuilding bridges, culverts and road surface when a flood occurs. They also considered two supplementary parameters, namely drainage capacity rate (d_c) and condition rate, to be applied to the damage functions. The damage cost on the road surface was based on three thresholds depending on the water depth above surface. For each of the three water level thresholds, a percentage % of total replacement cost was defined differently for paved or unpaved roads.

Several researchers use an index-based approach to assess flood vulnerability and risk. For instance, Benedetto and Chiavari (2010) present an analytical model for the vulnerability assessment of roads based on Multi-Criteria Analysis (MCA). The model assigns a vulnerability value to each road element (embankments, viaducts, etc.) depending on its structural and functional characteristics. Moreover, the RIMAROCC method (Bles et al. 2010) apply a multi-criteria analysis that couples hazard, exposure and

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vulnerability indicators (e.g., age of the infrastructure, design standards, maintenance practice, flood intensity and duration) to assess the flood risk of roads. Bil et al. (2014) use the 'criticality' term to address vulnerability as the impact of interruption of a specific segment on the serviceability of the whole network (repair costs will be directly proportional to the length of an affected road and will differ according to the types of objects at the location of the interruption; repair costs will be highest in the case of repairs of bridges and tunnels). Another example of the use of the criticality concept in the vulnerability analysis of roads is the use of the Network Vulnerability Index, which considers the serviceability and criticality of each road link in the network (Balijepalli and Oppong 2014).

A system-level perspective is highly recommended to properly assess transportation system vulnerability due to flooding. Recently, Zhu et al. (2021) present a simulation framework to analyse the system vulnerability and risk of the railway system to floods. System vulnerability curves are generated to present the relationship between performance loss (the percentage of daily affected trains/passengers and increased time) and flood intensity.

Several research efforts to assess flood vulnerability and risk have recently been developed within a multi-hazard environment. For example, Koks et al. (2019) present a global multi-hazard risk analysis of road and railway infrastructure assets. The most frequently recorded and costliest disasters, namely tropical cyclones (wind speed only), earthquakes, surface flooding, river flooding, and coastal flooding are considered. Results are presented in terms of the annual cost of repairing transport infrastructure damaged by natural hazards (globally and by country). The direct economic benefits of improving infrastructure standards against flooding are also assessed.

There have been few research efforts to estimate the flood vulnerability of bridge assets. The typical depth-damage approach in flood risk management is unsuitable for bridges since these are intentionally designed to withstand some amount of water without damage. Therefore, there have been some attempts to calculate damage by comparing extreme event return periods to design return periods. See for example, Lamb et al. (2019), for railways bridges crossing rivers in the UK. In the USA, it is often assumed that bridges collapse starting from the 1:100 year event, see Flint et al. (2017) for a critical reflection on this assumption. Among them, Kim et al. (2017) propose flood fragility curves for bridges accounting for multiple failure modes, including lack of pier ductility or pile ductility, pier rebar rupture, pile rupture, and deck loss. Hung and Yau (2017) investigated the effects of scour depths and foundation retrofitting work on the failure mechanism and vulnerability of bridges subjected to flood-induced loading. A complex nonlinear three-dimensional finite element model that accounts for the interactions between bridge structures, soils, water flow, and pile foundations has been utilised. Ahamed et al. (2020) propose a comprehensive fragility analysis framework that can effectively incorporate both flow hydraulics (i.e., the hydraulic model of the river) and geotechnical uncertainties (i.e., the geotechnical model of the bridge foundation), in addition to commonly considered structural components in flood-

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fragility analysis of bridges. Argyroudis and Mitoulis (2021) propose new fragility models for flood-critical bridges for single hazards (flood) and combined hazards (flood-earthquake).

As described above in detail, there are many studies on flood vulnerability of transportation infrastructure, but most of them focus on road and railway infrastructure assets. For road and rail, bridges over the water are particularly challenging. The infrastructure of ports and airports have not received the same attention in the literature. Yesudian et al. (2021) performed a global analysis for the risk assessment of airports in terms of expected annual disruption to routes. The method integrates globally available data of airport location, flight routes, extreme water levels, standards of flood protection and scenarios of sea level rise. Pulupula and Solanki (2023) developed a model for integrating flooding resilience analysis into water-sensitive spatial planning in airports in India.

Single assets

Most of the studies that are analysed in the following paragraph concern residential buildings as there are only few available damage (vulnerability) models for schools and healthcare systems against floods. Among them, Nofal et al. (2020) develop fragility and vulnerability functions for different occupancy classes including school and hospital buildings. They extended the typical single-variable flood vulnerability function (based on flood depth) to a multi-variate flood vulnerability function (that is based on both flood depth and flood duration) creating fragility surfaces.

Jongman et al. (2012) and Merz et al. (2010) have developed vulnerability models for residential buildings in flood situations. The predominant type of vulnerability model employed is known as a stage-damage curve, which establishes a relationship between the depth of floodwater and the resulting damages. Depending on the specific model, damages can be expressed in terms of absolute monetary values (absolute damage curve) or as a proportion relative to the value of the building (relative damage curve). Examples of relative damage curves, both empirically based on flood damage databases and/or on expert judgment, can be found in Germany with Flood Loss Estimation MOdel (FLEMO) (Thieken et al. 2008), in the Netherlands with the Standard Method (Kok et al. 2005) or in the USA with HAZUS (Scawthorn et al. 2006). The HAZUS Flood Model (FEMA 2024a) has been applied in different settings, to spatially assess potential flood risk or plan actual emergency support for upcoming flood events. The damage module of the model relies on two main inputs to estimate building damage, including the building's occupancy type and first floor elevation, as well as the depth of flooding. By combining these inputs, the HAZUS Flood Model can generate estimates of the potential damage to buildings, providing valuable insights for flood risk assessment and mitigation planning.

The level of damage to buildings caused by floods depends on various factors, the most important being the flood characteristics (primarily water depth, water velocity, inundation duration) and the building characteristics (type of structure, material, etc.) (FEMA 2024a). Although depth is the most common variable used in the calculation of flood damage, the importance of velocity is likely to have been

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undervalued in countries where high water velocity is relatively rare. Scouring of foundations, debris entrained within flood flows, contamination and post-event aeration of a flooded building are also important factors in the overall level of damage that occurs (Gissin and Blong 2004).

Fedeski and Qwilliam (2007) develop a methodology for assessing the impact of climate change on the risk from floods and geological instability, using GIS. The presented method involved collecting data on a building-by-building basis through the examination of GIS maps and field observations. This data was then aggregated to provide estimates for specific regions within the city.

Arrighi et al. (2020) develop empirical vulnerability curves for residential buildings based on a flash flood incident that took place in Livorno, Italy. These curves were derived by analysing the hydrologic and hydraulic aspects of the flood, as well as the documented damages suffered by residential properties.

It has been assumed that fragility curves developed for residential dwellings can be extended to include commercial buildings such as offices and schools, given their comparable construction and use of similar materials. Research conducted in Germany has demonstrated that the average flood damage experienced by both residential and commercial buildings was comparable (Reese 2003). Although commercial buildings typically feature higher ceiling heights, any notable differences in terms of structural damages are not anticipated.

4.2 Earthquakes

Experience from devastating earthquakes worldwide (e.g., 1994 Mw 6.7 Northridge, 2010 Mw 8.8 Maule, 2011 Mw 9.1 Tohoku, 2011 Mw 6.2 Christchurch, 2015 Mw 7.8 Gorkha, 2017 Mw 7.1 Puebla) have revealed that even CIs at developed societies are quite vulnerable to them affecting many people’s lives and producing significant economic losses. Therefore, the vulnerability assessment of CI to earthquakes represents a crucial step towards effective risk assessment mitigation. Some factors that can affect the vulnerability of CIs to earthquakes are summarized below: i) The **location** of the CI can affect its vulnerability to earthquakes. For example, CIs located in regions with high seismic activity, such as along tectonic plate boundaries or near fault lines, are at a greater risk of damage from earthquakes. Secondly, **the age and design** of the CI can also affect its vulnerability to earthquakes. Older CIs may not have been built to withstand seismic events, while newer CIs may have been designed to meet modern seismic safety standards. iii) Next, the **type of soil and foundation** on which CI is built can also affect its vulnerability to earthquakes. Soil liquefaction, in which soil loses its strength and stiffness during seismic activity, can cause significant damage to infrastructure built on top of it. iv) In addition, **the CI may be located near other infrastructure**, such as buildings or bridges, which can also be vulnerable to earthquakes. Damage to these adjacent structures can also affect the operation of the CI. Among others, Pitilakis et al. (2014) present in a comprehensive way an extensive literature review of seismic fragility functions for all elements at risk, such as buildings, lifelines (e.g., energy system), transportation system (e.g., tunnels,

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embankments/cuts, slopes, retaining walls, bridges) and other critical facilities subjected to seismic shaking and ground failure (e.g., due to earthquake triggered landslide or soil liquefaction). Commonly used intensity measures are the Peak Ground Acceleration (PGA) when ground shaking is the main cause of earthquake damage or the Permanent Ground Displacement (PGD) in case of ground failure. In the following, some of the most important contributions to quantify the seismic vulnerability of the different assets per system are discussed.

Energy system

Regarding energy CI, it is vulnerable to high impact low-probability events such as earthquakes (Waseem and Manshadi 2020). An extensive framework for modelling earthquakes, seismic vulnerability analysis of electric power systems, and mitigation techniques to ensure operational resiliency is proposed in Nazemi and Dehghanian (2019). In the literature there are several studies providing seismic fragility functions of electric power system components, such as electric micro-components, substations, distribution circuits or generation plants (e.g., Hwang and Huo 1998; Hwang and Chou 1998; Anagnos 1999; Rasulo et al. 2004; Duenas-Osorio et al. 2007; Shinozuka et al. 2007; Straub and Der Kiureghian 2008; FEMA 2024b; Baghmisheh and Estekanchi 2019). In most of the studies, the fragilities are expressed in terms of PGA but in the study of Vanzi et al. (2004) for 420 kV circuit breaker, they are a function of spectral acceleration. Hwang and Chou (1998) used the event tree/fault tree technique to assess the seismic behaviour of an electric substation. A substation is considered as a combination of components (equipment and structures). Using the component fragility data, the failure probabilities of the substation at various levels of seismic shaking can be determined. In addition, using the minimum cut set technique the most vulnerable component in the substation can be identified. Duenas-Osorio et al. (2007) investigate the effect of seismic disruptions on the performance of real interdependent networks and present fragility curves related to the entire electric power grid. However, Pitilakis et al. (2014) has noted that a fragility function of the entire power grid can be considered a result of an ad hoc study for a network, rather than a "portable" function which can be used for other systems. Shinozuka et al. (2007) study seismic effects on electric power systems by identifying the possibility of sequential failures of receiving station components. Such failures progressively degrade the power network performance, and potentially lead to a system blackout. The transformers, disconnect switches, circuit breakers and buses critical to the operation of the transmission network are incorporated into the systems analysis and appropriate fragility curves are developed.

HAZUS (FEMA 2024b) proposes fragility curves for substations, distribution circuits and generation plants, resulting from a combination of expert judgement models and empirical models based on statistical analysis of damage data from previous events. Damage states describing the level of damage to each of the electric power system components are defined (i.e., minor, moderate, extensive, or complete). For instance, for generation plants, minor damage is defined by turbine tripping, or light

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damage to diesel generator, or by the building being in minor damage state; moderate damage is defined by the chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or by the building being in moderate damage state; extensive damage is defined by considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or by the building being in extensive damage state; complete damage is defined by extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or by the building being in complete damage state. The classification of these facilities is done based on voltage level for substations and power output for generation plants. Different sets of curves are also provided for facilities with anchored or unanchored components, meaning designed with special seismic tiedowns or tiebacks, and designed with manufacturer's normal requirements, respectively. When necessary (i.e., for substations, generation power plants, etc.) HAZUS fragility curves account for the probabilistic combination of subcomponent damage functions, using Boolean expressions to describe the relationship between components and subcomponents.

Moreover, Poljanšek et al. (2010) present an overview of the results obtained through the application of GIS-based probabilistic vulnerability assessment methods for Europe and how this type of information can be of use in decision-making for mitigation, preparedness, and emergency resource deployment. Buritica (2013) developed a novel methodology for seismic vulnerability assessment of power transmission systems. The analysis is carried out from the perspective of both the system's form (i.e., topological-electrical importance of elements) and system's strength (i.e., probability of failure). The form combines the electrical properties of the network (e.g., electrical distance, power flow) with the systems approach via hierarchical network decomposition. On the other hand, the strength focuses on evaluating the probability of failure by means of the physical consequences of multiple earthquakes scenarios. Therefore, the vulnerability measure presents a trade–off between strength and form. More recently, Liang et al. (2022) propose a modular quantitative assessment method to assess the seismic vulnerability of a substation. In this method, the relation between the functionality state of a substation and the damage state of its components is established through the connection matrix technique. A substation is viewed as a network system, whose topology is defined by the connections among various pieces of electrical equipment (i.e., the components), represented in the connection matrix.

Regarding gas and oil systems, the various elements composing them can be roughly classified into three categories, namely the pipelines, the storage tanks, and the different processing facilities such as compression or pumping stations. Concerning pipelines, there are two categories of fragility models for estimating potential seismic damage: empirical fragility models (e.g., Isoyama et al. 2000; American Lifelines Alliance (ALA) 2001; Eidinger 2020; FEMA 2024b; O'Rourke et al. 2014; Piccinelli and Krausmann 2013; Lanzano et al. 2013; 2014) and numerical fragility models (e.g., Lee et al. 2016; Jahangiri and Shakib 2018; Ashrafi et al. 2019; Tsinidis et al. 2020). Empirical fragility models are typically developed from data collected after past earthquakes and yield the average number of repairs per length of pipeline, while

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numerical fragility models are typically developed from finite element simulations of pipelines subjected to a range of conditions and yield probabilities of damage state exceedance. Tsinidis et al. (2019) present a thorough critical review of available fragility relations for the vulnerability assessment of buried natural gas pipelines subjected seismically-induced transient ground deformations. The ALA (2001) provides damage functions for buried water pipelines that take into consideration different damage sources (i.e., ground shaking and ground failure), materials, diameters, and joint typologies. According to HAZUS (FEMA 2024b), two damage states are considered for pipelines, i.e., leaks and breaks. If the damage is induced by ground failure, the percentage of leaks and breaks is estimated as 20 and 80%, respectively. Conversely, if the pipeline is damaged by ground shaking, the percentage of leaks and breaks is reversed to 80 and 20%, respectively. Lanzano et al. (2014) presented fragility curves as lognormal functions of peak ground velocity (PGV) and PGA for different joint typologies for ground shaking and ground failure corresponding to three damage states: DS0, corresponding to no damage; DS1, corresponding to longitudinal and circumferential cracks and potential compression joint breaks; and DS2, for tension cracks along continuous pipelines and joint loosening in segmented pipelines.

Concerning the storage tank farms, the type of European atmospheric storage tanks may be mainly on-grade steel tanks with anchored or unanchored components. The existing fragility curves cover this typology (e.g., O'Rourke and So 2000; ALA 2001; FEMA 2024b). HAZUS (FEMA 2024b) fragility curves for "tank farms" account for the complexity of the electrical and mechanical equipment. More recently, Bakalis et al. (2017) also provide seismic fragility curves for cylindrical liquid storage tanks. Nevertheless, the case of gas storage is less straightforward and the very specific features of the different storage facilities (such as LNG tanks, air-tight cylindrical or spherical tanks for special gases, underground cavities for seasonal storage) obstruct the use of generic fragility curves. Kim et al. (2019) provide specific seismic fragility curves for cylindrical base-Isolated LNG storage tanks for various target periods and friction coefficients in terms of PGA. Concerning the processing facilities (i.e., compression or reduction stations), their role is to treat the gas and oil to the required quality standards through various processes (separation of sediments and water; heating and chemical operations, etc.). Pumping / compressor stations may have the same damage states as a usual building, the loss index being defined by the percentage of failed structural elements (criterion also used in HAZUS methodology). For gas stations similar to Greek ones, which consist of low-rise masonry buildings with anchored components, the fragility curves developed from the project SRMLIFE (2003-2007) can be used. For other typologies of European gas stations that their typology is not known, the generic fragility curves of the HAZUS methodology (FEMA 2024b) can be used, as they are based only on the distinction between anchored and unanchored components. FEMA (2024b) also provide generic fragility curves for oil refineries according to their capacity (small or medium/large), for oil system pumping plants and tank farms as well as for fuel facilities with buried tanks. Finally, Karaferis et al. (2022) propose seismic fragility curves for high-rise stacks in oil refineries.

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Transportation system

Recent devastating earthquakes have shown quite dramatically the (direct and indirect) damage that earthquakes can inflict on roads, bridges, rails, ports, airports and other assets and networks of the transportation system resulting in significant socio-economic losses. El-Maissi et al. (2021) present an extended review on the seismic vulnerability assessment methods for roadway assets and networks also providing a description of the main types of roadway asset damage. They divided the methods into two main categories, i.e., physical (that are based on fragility functions and vulnerability indexes) and traffic-based approaches (that use the accessibility and link importance index).

Numerous studies have assessed the seismic vulnerability of individual transportation assets, such as embankments/cuts, tunnels, and bridges resulting in the construction of probabilistic fragility functions for different damage states (e.g., minor/slight, moderate, extensive/complete). Empirical fragility curves for road embankments have been generated by Sasaki et al. (2000), Maruyama et al. (2010) and Nakamura (2015) as a function of PGA or PGV based on damage observations in Japan. Argyroudis et al. (2013) and Argyroudis and Kaynia (2015) develop analytical fragility curves for cantilever bridge abutments-backfill system and embankments and cuts respectively due to seismic shaking considering different soil conditions. Yin et al. (2017) investigate the influence of retaining walls on embankment seismic fragility using incremental dynamic analysis while Tsubaki et al. (2016) developed fragility curves for railway embankment fill and track ballast scour based on recorded observations of railway damage in Japan and simulated overtopping water depth. HAZUS (FEMA 2024b) provide expert judgement generic seismic fragility and vulnerability functions for the main components of the road network (i.e., roadways, bridges, tunnels) and the railway network (i.e., railway bridges, fuel facilities, dispatch facilities, and urban stations and maintenance facilities) subjected to ground shaking and ground failure. Tsinidis et al. (2022) present an extended state-of-the-art review of seismic vulnerability models of tunnels and underground structures against seismic ground shaking and earthquake-induced ground failure. They highlight that studies on seismic vulnerability assessment of tunnels due to seismically induced ground failure are very limited compared to those referring to ground shaking. Many studies focus on the development of seismic fragility curves for bridge assets using analytical or empirical/expert judgement approaches (Kwon and Elnashai 2010, Ghosh and Padgett 2010, Tsionis and Fardis 2014, Billah and Alam 2015, Gidaris et al. 2017, Stefanidou et al. 2017). Soil-structure interaction (SSI) effects on fragility analysis of bridges have been considered in several studies (e.g., Stefanidou et al. 2017, Stefanidou and Kappos 2023) while liquefaction-sensitive fragility curves were constructed using the analytical approach including SSI effects (Kwon and Elnashai 2010).

Several authors have contributed towards the multi-hazard fragility assessment of transportation infrastructures. Argyroudis et al. (2019) propose a methodological framework for the development of numerical fragility functions of transport systems of assets under multiple hazards considering also hazard interactions and cascading effects. Gehl and D'Ayala (2016) developed multi-hazard fragility functions for

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bridge assets using system reliability methods and Bayesian networks. Stefanidou et al. (2022) present a methodology for the estimation of seismic and flood fragility for bridges resulting in the construction of multi-hazard fragility curves.

Various vulnerability index (VI) based methods have been proposed to assess the vulnerability of the transportation infrastructure (e.g., Elnashai et al. 2004, Zanini et al. 2013, Francini et al. 2020, Adafer and Bensaibi 2017, Djemai et al. 2019). For instance, Francini et al. (2020) use four parameters to develop a VI for urban roads: the length of the road, the width of the road, the redundancy level of the road, and various critical elements (bridges, intersections, underpasses, tunnels, and other elements that could affect the vulnerability of the system). Adafer and Bensaibi (2017) propose an index-based method, based on excessive literature review from past earthquakes worldwide, including ground motion characterization, fragility curves, and traffic analysis during earthquakes. This VI has been developed based on different factors, e.g., the number of lanes, the ground type, the embankment height, the maintenance conditions, pavement type and pavement conditions, that are weighted according to the analytical hierarchy process (AHP) method.

Concerning the vulnerability of ports and airports to earthquakes, there are also several studies in literature for their seismic vulnerability assessment. Empirical lognormally distributed fragility functions for waterfront structures, cargo handling and storage components were proposed in HAZUS (NIBS, 2004), where for the quay walls there is no distinction between the different wall typologies and the earthquake intensity measure is PGD. For the cargo handling and storage components there is a classification between anchored and unanchored cranes and the earthquake descriptors are PGA and PGD. In literature there are also several other analytical fragility curves for the assessment of direct earthquake-induced damage to gravity-type quay walls using 2D dynamic finite element analysis, considering the occurrence of liquefaction phenomena (Karafagka et al. 2022, Ichii 2003, 2004), or without the occurrence of liquefaction (Kakderi and Pitilakis 2010). Chiou et al. (2011) proposed a procedure for developing analytical fragility curves for typical pile-supported wharfs using the capacity spectrum method (CSM). Miraei and Jafarian (2013) developed analytical fragility curves for gravity quay walls. Torkamani et al. (2014) developed seismic fragility curves of an idealised pile-supported wharf with batter piles through a practical framework. Kosbab (2010) presented an analytical method for application to seismic fragility analysis of container cranes. Nonlinear dynamic analyses were performed for the three representative container cranes and pushover analyses of 2D finite element models were performed. Özcebe et al. (2002), developed fragility curves of critical port infrastructure components by modelling the soil-wharf-crane interaction. Roark et al. (2000) propose six classification criteria applied to define the seismic vulnerability of airports. The six classification criteria include general structural concerns, general non-structural concerns, life safety, cost, construction time and fragility.

Engineering practice for seismic risk assessment and the management of port facilities currently relies on the performance of specific critical components. However, the resilience of a port, i.e., its ability to

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promptly recover to a serviceable status after an earthquake, depends not only on the performance of its individual components but also on their location and physical and operational connectivity, as well as on the port system as a whole (Werner 2004). The consideration of the interactions and contributions of all components of a port, such as waterfront structures, cargo handling and storage components, buildings, utility systems, and transportation infrastructures to the seismic vulnerability assessment is the subject of many other studies in literature (e.g., Pachakis and Kiremidjian 2005, Pitilakis et al. 2014, 2019). Pitilakis et al. (2019) propose an engineering risk-based methodology for stress testing CI, which is applied to the port of Thessaloniki in Greece exposed to seismic, geotechnical and tsunami hazards. Fotopoulou et al. (2022) present a methodology for the seismic risk assessment of port facilities, which considers the combined effects of ground shaking and liquefaction as well as various interdependencies among port elements that may affect the port's operation and, consequently, the total risk impact. Conca et al. (2020) investigated the effect of interdependencies in a seismic risk analysis of ports. They compared the results for specific seismic scenarios obtained in the assessment of the seismic vulnerability of the seaport, considering and neglecting the interactions among its components, and they found that the modelling of the port system without considering interdependencies led to less conservative results.

Telecommunications

Telecommunication infrastructure provides essential services during an emergency caused by a seismic event as it can guarantee communication among users and facilitate search and rescue operations. Few efforts have been made so far to assess the vulnerability of the telecommunication network.

Cardoni et al. (2022) present a methodology for modelling and assessing the seismic vulnerability and resilience of wireless telecommunication networks, which play a critical role in providing essential services to urban communities. To capture the interdependencies between telecommunication networks and the built environment, they associate the failure of network components with the collapse of the buildings hosting them. This approach allows accounting for the impact of structural damage on network functionality. Three vulnerability indexes are defined to analyse the resilience of urban telecommunication networks. These indexes consider the failure of telecommunication towers, throughput capacity, and the number of users supported by each base station.

Jimenez and Medina (2023) conducted a study to assess the operability of the Venezuelan telecommunications network in the event of earthquakes. To achieve this, a model was developed to calculate spectral acceleration and simulate ground motion, taking into account the infrastructure's characteristics and the geographical factors. The aim was to evaluate the likelihood of surpassing pre-defined damage states (specifically light and extensive damage) and determine the marginal probability of each network component experiencing a certain level of damage. The network was tested using selected earthquakes ranging from 6 to 8 magnitude on the Richter scale. The results indicated that the

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probability of network nodes suffering slight or extensive damage was influenced by the geographic location of the earthquakes. In general, there was a higher likelihood of experiencing slight damage compared to extensive damage.

Single assets

Seismic fragility curves are commonly used to assess the seismic performance and vulnerability of single assets. In most vulnerability and risk assessment studies in the literature that concern hospitals and healthcare systems against earthquakes, the available fragility curves for residential buildings are used. However, fragility curves for residential buildings may be inappropriate for structures such as school buildings and hospitals, potentially leading either to an underestimation or an overestimation of their actual vulnerability.

Schools and hospitals encompass a range of building types, such as single-story structures, multi-story buildings, and specialised facilities (e.g., operating theatres, laboratories). Fragility curves should account for the specific characteristics of these building types. As design data, they require information such as the quality of the construction materials, the building age, the level of maintenance etc., which is not always available and, therefore, onsite surveys may be required. One of the most influencing factors that affect fragility curves is the building's typology and in particular the height. This factor is not always available and, therefore, it may be collected through inspections and surveys. The Global Human Settlement Layer (GHSL)41 project can help in this direction allowing the production of new global spatial information and tools for assessing the human presence on the planet. The developed GHSL datasets are available for open and free download. Specifically, GHS-BUILT-H-R2023A–GHS building height is a spatial raster dataset that depicts the distribution of the building heights as extracted from the filtering of a composite of global digital elevation models (DEM) and the filtering of satellite imagery using linear regression techniques generalised at the resolution of 100m and referred to the year 2018.

Romao et al. (2021) presents the new model for vulnerability assessment of the European building stock, developed as part of the 2020 European Seismic Risk Model ESRM20. Martins and Silva (2021) develop new vulnerability functions for the most common typologies of building categories globally. This model was used to estimate economic losses due to earthquakes as a key component of the global seismic risk estimation model under the support of the Global Earthquake Model (GEM). Building typologies were classified based on (i) construction material, (ii) lateral load resisting system, (iii) level of ductility and (iv) height. Vulnerability curves were extracted for different levels of damage (minor, moderate, extensive and complete damage) considering different measures of seismic intensity (PGA, SA(0.3 s), SA(0.6 s) and SA(1.0 s)).

[41] https://ghsl.jrc.ec.europa.eu/

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Borzi et al. (2008b) and Borzi et al. (2020) use SP-BELA methodology to evaluate the seismic behaviour of Italian buildings through a non-linear static analysis. In particular, this simplified pushover-based methodology allows us to estimate the structural vulnerability of buildings through the definition of fragility curves. These curves are derived by comparing estimated and observed damage levels across various seismic scenarios, considering five damage levels.

Seismic fragility curves based on direct damage observation have been recently developed, primarily focusing on residential buildings (e.g., Dolce et al. 2021). However, empirical fragility curves specifically for public buildings, such as schools, are still relatively scarce. For school buildings, empirical fragility curves can be found in Munoz et al. (2007) for Peruvian schools and in Giordano et al. (2021a, b) for Nepalese schools. These studies provide valuable insights into the vulnerability and potential damage levels of school buildings in those specific regions.

Bhakuni (2005) uses the visual assessment method to determine the vulnerability levels of school buildings. The selection of schools is based on location, size, economic levels and building types. The structural types examined were reinforced concrete and confined masonry structures, as they constitute around 90% of the total school building stock. Vulnerability levels were determined by correlating building types with the school's population.

Fotopoulou et al. (2022) conducted 3D incremental dynamic analysis (IDA) and nonlinear pushover analysis to investigate whether existing fragility curves for residential buildings are appropriate for assessing the vulnerability of individual school buildings. It was shown that the literature fragility curves may lead to significant differences in fragility and loss estimation for the case of critical buildings such as schools, highlighting the need to develop building-specific fragility functions for the most common typologies of strategic and important structures.

Ludovico et al. (2023) construct fragility curves of Italian reinforced concrete and unreinforced masonry public school buildings based on observational and heuristic approaches. The main characteristics of the school buildings were analysed in terms of frequency distribution of the construction age, number of stories above ground and average surface area. Three different approaches (i.e., empirical, empirical-binomial, heuristic) were considered in order to derive the fragility curves, which were discussed and compared with other fragility curves available in the literature for the Italian residential building stock.

Lang et al. (2009) conducted a questionnaire survey for the seismic vulnerability assessment of hospitals and schools. These questionnaires provide the user with a powerful and quick tool in order to identify weak structural and non-structural features of the structure which are important in case of an earthquake disaster. The questions are intended to find out the primary structural system.

Infrastructure systems are essential to the operation of healthcare facilities and do not exist in isolation of one another - telecommunications networks require electricity, transportation networks require systems information to operate, emergency systems require transportation networks, and so forth. During a disaster event, health care facilities are expected to operate efficiently to provide sufficient

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care to injured patients. Physical damage to critical facilities or disruption of their operations or supply chain could prevent a full, effective response and aggravate the consequences of an emergency. Therefore, an essential component in the vulnerability assessment of critical facilities (i.e., hospitals) is the analysis of interdependencies between the different infrastructure systems that supply resources for the operation of the facility (Arboleda et al. 2009).

The seismic assessment of a single hospital facility is studied in Lupoi et al. (2008) through a probabilistic methodology. Hospital is a complex system made of several components such as human, organizational, physical, environmental, and medical services, each including a large variety of elements. Their behaviour has been studied, but capacity models and fragility curves are not available for all of them. A general methodology for the evaluation of the ''probability of failure'' of hospital systems is the fault-tree technique (Pitilakis et al. 2014). Fault-tree analysis concerns CI, where multiple conditions are necessary for the systems to ensure its function. This approach aims to evaluate the remaining operating capacity of objects such as health-care facilities. The system is broken down into structural, non-structural or human components and is generally used for the derivation of fragility curves for specific components that comprise a set of sub-components (e.g., health care facilities, water treatment plants).
Karapetrou et al. (2016) assess the seismic vulnerability of an eight-story RC hospital building. Ambient noise measurements were utilised to assess the dynamic characteristics. These measurements were obtained by a temporary seismic network that was installed within the hospital. The methodology resulted in the construction of time- and building-specific fragility functions based on incremental dynamic analysis of the updated finite element models.

4.3 Landslides

Landslides represent one of the most devastating natural hazards, as they may result in significant direct and indirect losses to the population and built environment (Shano et al. 2020). A lot of researchers have explored the landslide impacts including human losses, property damage, and infrastructure damages (e.g., Davies 2022, Spegel and Ek 2022). CIs can be vulnerable to landslides, depending on their **location, their specific structural characteristics,** and the **surrounding topography**. More specifically, CIs that are located on or near steep slopes may be vulnerable to landslides if the slopes are unstable. Unstable slopes can be caused by a variety of factors, including geological conditions, erosion, and human activity such as excavations or construction. Heavy rainfall or snowmelt can increase the likelihood of landslides, particularly in areas with steep slopes or poor drainage. Prolonged periods of rainfall or rapid snowmelt can saturate the soil and increase the weight of the slope, making it more likely to fail. Seismic activity, such as earthquakes, can trigger landslides in susceptible areas. Earthquakes can cause ground shaking, liquefaction, or slope failure, leading to landslides in nearby areas. In many cases CIs are located near water bodies such as rivers or lakes and may be vulnerable to landslides if the slopes adjacent to these water bodies are unstable. The water can erode the slope, increasing its instability and the likelihood

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of landslides. Finally, infrastructure subject to the same landslide event may exhibit different levels of damage owing to their differing structural characteristics (e.g., typology, construction quality and material, foundation type, state of maintenance and use). Overall, the vulnerability of CI to landslides is influenced by a combination of factors related to the **location, structural characteristics, topography, and climate of the area**. Mitigating the risk of landslides requires careful consideration of these factors and implementation of measures such as slope stabilisation, drainage systems, and early warning systems to reduce the risk of damage and disruption due to landslides.

Energy system

Regarding the electric power network, landslide hazards may cause serious threats to the safe operation of the power transmission system, as it has a long transmission span and passes through wide areas with complex topography settings and various human engineering activities (Liu et al. 2021). However, most of the available literature is concentrated on other natural hazards and does not address landslide hazards. To the author’s knowledge, only Ghorani et al. (2021) present a novel approach that quantifies the landslide hazard, its damage to power system components, and the impacts on the overall system performance to prioritise reinforcement activities and mitigate the landslide vulnerability.

Regarding natural gas and oil networks, landslides constitute a significant threat for pipelines because they can generate permanent ground displacements along or across the pipeline alignment (Marinos et al. 2019). However, although there is some literature related to the assessment of landslide hazard or susceptibility along or across a pipeline, there are not many studies related to the vulnerability. According to Marinos et al. (2019), vulnerability due to landslides constitutes a difficult expression to represent quantitatively as it cannot be measured objectively, although there are various approaches to assess landslide vulnerability. In general, fragility curves can be calculated using empirical or numerical methods. According to Pengpeng et al. (2022) empirical fragility curves for the landslide-pipeline interaction problem are not available due to the lack of field data. In the available literature, Feris et al. (2016) is found to present the development of a statistical and judgment-based screening level vulnerability model for pipeline crossings of slopes that are subject to landslides that can be used to provide an estimate, of the relative importance of slope crossing sites based on parameters that can be obtained without detailed site-specific studies. When vulnerability is combined with probability of landslide impact, it can be used to give an estimate of the probability of pipeline failure. Numerically, Pengpeng et al. (2022) is only found to suggest a simplified approach to generate parameterized fragility curves of buried continuous pipelines against landslides and assess the relative importance of the soil friction angle, pipe burial depth, diameter, and wall thickness on their vulnerability.

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Transportation system

The vulnerability of a road or railway system to landslide may be attributed to both the partial or complete blockage of the road or track as well as structural damage, including damage to the surfacing, which is associated with the level of serviceability (Corominas et al. 2014). Information regarding the type (e.g., highway, main road, or unpaved road), width, and traffic volume is important to accurately assess the vulnerability of transportation infrastructure to landslide hazard. While there has been extensive research into quantifying landslide susceptibility, research into vulnerability assessment of different assets due to landslides has been limited and it has been mainly based on empirical data and judgment. In the following, we present the existing methods to assess the vulnerability of the transportation system to landslides.

Bell and Glade (2004) establish fixed vulnerability values for buildings, roads and infrastructure in a given area principally based on expert judgment, as a function of the return period of debris flow and rockfalls. Winter et al. (2014) determined the physical vulnerability for roads exposed to debris flow based on the statistical manipulation of questionnaires filled by experts regarding the probability of exceeding different damage states (limited damage, serious damage and destruction) as a function of the volume of debris. Fragility curves have been proposed for both low-speed and high-speed roads subjected to debris flows. Argyroudis et al. (2013) propose a semi-empirical methodology to estimate the physical vulnerability of roads subjected to earthquake induced landslide hazards. It is based on a modification of the existing judgmental HAZUS fragility curves using a semi-empirical model that relates the seismic PGD with the PGA for the Newmark rigid sliding block case. In this regard, it is possible to account for the specific characteristics of soil and local topography within the estimation of road vulnerability. Various sets of fragility curves have been constructed as a function of PGA, considering the characteristics of the slope (i.e., yield coefficient, ky) and the earthquake magnitude. Specific focus on vulnerability models for landslides at ports and airports is limited. However, the above studies offer valuable insights into the broader topic of landslide vulnerability assessment for transportation infrastructure. They provide methodologies and case studies that can be adapted and applied also to ports and airports.

Single assets

Corominas et al. (2014) present recommended methodologies for the quantitative risk analysis (QRA) for landslide risk. Experience indicates that the extent of damage to buildings due to landslides varies considerably according to the characteristics of the building, the landslide mechanism, and the magnitude and intensity. The vulnerability may be expressed in terms of damage states varying from nonstructural damage to extensive collapse. Damage may be structural or nonstructural with damage caused to utility systems. Typical typological parameters which determine the capacity of buildings to withstand landslide actions are the following: the structural system, geometry, levels of design codes, foundation and

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superstructure, details, number of floors, etc. An additional important factor is the geographic location of the exposed elements within the landslide body (crest, transport zone, toe, runout zone, etc.), given the variation of the movement and the consequent interaction with the structures and infrastructure. While damage to the built environment resulting from the occurrence of rapid landslides such as debris flow and rockfalls is generally the greatest and most severe, as it may lead to the complete destruction of any structure within the affected area, slow-moving slides also have adverse effects on affected facilities (Mansour et al. 2011).

Fotopoulou and Pitilakis (2013) developed an analytical methodology for assessing the vulnerability of reinforced concrete buildings subjected to earthquake triggered slow-moving slides. The fragility curves were estimated by determining the peak ground acceleration or permanent ground displacement at the seismic bedrock and the probability of exceeding each limit state, based on a two-step uncoupled numerical modelling approach. The developed method is applicable to different soil types, slope geometries and building configurations, allowing explicit consideration of various sources of uncertainty. Negulescu and Foerster (2010) also calculated vulnerability curves as a function of the differential settlements of a reinforced concrete frame building.

4.4 Wildfires

Wildfires can be triggered by natural circumstances, such as volcanic eruption, lightning strike, spontaneous ignition due to local heating, or human actions. In Europe, human actions, such as arson, are the primary cause of wildfires. However, climate change has exacerbated the intensity and duration of these fires. For instance, El Garroussi et al. (2024) has shown that areas in southern Europe could experience a tenfold increase in the probability of catastrophic fires occurring in any given year under a moderate climate change scenario.

Wildfires can cause very high temperatures. The probability of dielectric failure increases with the increase in temperature (Fu et al. 2001). Bagchi et al (2013) propose an overall methodology for modelling and quantifying the damage caused by fire to the electrical distribution network of a city where they introduce the Load Loss Damage Index (LLDI). In addition, a very interesting study is that of Guo et al. (2018) that propose a method based on Weibull distribution and dynamic heat balance equation to evaluate the impact of forest fire on the ageing degree of power transmission lines. Forest fire accelerates the ageing degree of power transmission line by thermal radiation. By knowing the rise in temperature, the fire impact on lines can be estimated. Yao et al. (2018) also propose an effective process for transmission line temperature evolution using the numerical weather prediction and analytical solution. Finally, Randaxhe et al. (2020) propose a methodology to build a probabilistic fire demand model to investigate the structural behaviour of steel pipe-racks located within industrial and petrochemical plants used to transport flammable material, liquid, or gas fuel, on long distances. They propose fire fragility

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functions in terms of the maximum average heat flux impinging the structure HF_{avg} and the ratio between fire position and fire diameter L/D, for two structural ultimate limit states, near collapse and life safety, using the maximum transversal inter-storey drift ratio as the engineering demand parameter.

Regarding the transportation infrastructure, Zhu et al. (2023) have recently developed a framework to assess the vulnerability for a fire-exposed simple-span overpass bridge prototype with composite steel plate girders. The damage from each fire scenario was correlated to two measures of fire hazard intensity, namely the peak heat release rate, and the total thermal energy imparted along the girder span. Bivariate fragility curves that correlate the two intensity measures to each damage level via a cumulative normal distribution function were finally obtained for the prototype bridge. Thompson M.P. et al. (2020) focus on mapping wildfire exposure to assess the risk to infrastructure, including buildings and transportation networks.

Wildfires are an important consequence of climate change (Schoennagel et al. 2017) as the global temperature is rising rapidly, with a significant impact on single buildings as well. Schulze et al. (2020) investigate fire impacts to schools and healthcare facilities in Paradise, CA. Photographs, light detection and ranging (LiDAR) scans of damaged buildings, drone aerial images, and interviews with key school and healthcare stakeholders used to document the structural and nonstructural damages to infrastructure. Nonstructural damage to schools and hospitals, such as damage to electrical systems or other utilities, significantly impacted the functionality of these facilities.

4.5 Hurricanes

Hurricanes are severe weather events able to cause massive blackouts as well as dramatic social, economic, and environmental losses. Gil and McCalley (2011) studied the general impacts of hurricanes on natural gas and electricity. A variety of vulnerability methods and fragility curves have been developed for energy system infrastructure during adverse weather events to identify recurrent patterns in the power outage data in order to understand the vulnerability of the existing power grid. For example, Allen et al. (2014) developed fragility curves to characterise the relationship between wind speed and resulting power outages during hurricanes, using real-time power outage data and wind speed data to derive statistical relationships. Panteli et al. (2017) also represent the physical response of towers and power lines to high winds as a function of line failure probability in response to wind speed. In addition, Xue et al. (2020) investigated the consequences of transmission tower failure and damage on the performance of the power transmission network during a hurricane. They developed a fragility model of the transmission tower-line system to probabilistically describe the power system component's failure and damage state. The developed fragility curves are in terms of wind velocity in meters per second (m/s). Moreover, Ma et al. (2020) present a probabilistic framework for the development of fragility curves of electrical conductors in power transmission networks subjected to hurricane hazards. The derived fragility

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functions are in terms of maximum sustained wind speed (in m/s) and wind angle of yaw (in degrees). They prove that the failure probability of the conductors increases substantially once the wind speed reaches a certain critical value, and that it is largely affected by the wind direction and span length. Thus, the variability of span lengths over the transmission network significantly influences the overall system failure. Ma et al. (2021) also propose a component-based fragility modelling framework for transmission towers subjected to hurricanes. The intensity measure is the maximum sustained wind speed. A novel method is introduced to directly simulate the load transferred from the cables to the tower using the modal superposition method and the spectral representation technique. Additionally, Sang et al. (2020) propose an integrated framework to convert weather forecasts into appropriate information for preventive operation during hurricanes so that the power outages induced by hurricanes can be reduced. Wind fragility curves for transmission towers in terms of wind speed are derived for four limit states. These are defined as the transmission tower's top displacement over tower height at 1.5%, 2%, 2.5%, and 3%. Weather data is used as input to calculate the failure probability of the transmission lines. Watson and Etemadi (2020) also develop models for hurricane exposure and fragility curve-based damage to electrical transmission grid components. They use fragility curves from the literature for transmission lines/towers (Quanta Technology 2009) and substations (FEMA 2022), and coal, gas and nuclear power generating plants (Vickery et al. 2006; Twisdale et al. 2015). Finally, Bennett et al. (2021) propose an energy system optimization model that accounts for hurricane risks by combining infrastructure fragility curves and hurricane probabilities.

Only little research has been done on the vulnerability assessment of transportation infrastructure to hurricanes. Gazzea et al. (2023) proposed a framework for rapid, scalable, and low-cost vulnerability assessment along roadways using high-resolution satellite images. The framework was implemented in a portion of the City of Tallahassee, the capital of Florida, U.S., in September 2018, before Hurricane Michael. Specifically, the vegetation exposure of roadways has been initially assessed based on tree parameters estimated via satellite imagery, such as height, distance to the roadway, health, and density. A vulnerability index which combines the vegetation exposure with road importance, has been finally calculated based on the consequences that such closures have on the transportation network, such as mobility and number of buildings affected. Abdelhafez et al. (2021) studied the vulnerability of seaports to hurricanes and sea level rise in a changing climate. They proposed a new model for quantifying the functionality of seaports subjected to multi-hazards using a fault tree analysis. The methodology is validated using data from Hurricane Katrina. A case study of the Port of Mobile, AL revealed that if a Katrina-like hurricane were to occur late in the 21st Century, damages to the Port of Mobile would increase by a factor of nearly 7 under an RCP 8.5 scenario when compared to the damages caused by Hurricane Katrina alone. Some other studies have considered the impact of hurricanes on seaport operational losses from a wind engineering perspective without addressing the impact due to hurricane's storm surge (Zhang and Lam 2015; Cao and Lam 2018). Others have modelled the hurricane's storm surge and showed the

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level of inundation of a port due to see lever rise and other climate-driven effects without calculating the damage to the built environment (Becker et al. 2012; Chhetri et al. 2015; Ng et al. 2016; Sanchez-Arcilla et al. 2016). Another study (Izaguirre et al. 2020) addressed the port operations including some essential components using an operational threshold approach and a semi-empirical formulation to determine the main climate driver for the vulnerability of the studied ports. The functionality and recovery of other port components and interconnected systems have not been addressed in depth. Only Balbi et al. (2018) have addressed the resilience of each component of the seaport, which is necessary to deconstruct the various factors that impair port performance and lay a foundation for evaluating the reliability of port's components following a hurricane and its capability to recover from a natural disaster quantitatively. However, the Balbi study did not provide either a theoretical or logical model of port operations or functionality; nor did it address the interdependencies between port components and systems.

The HAZUS-MH Hurricane Model has been developed to estimate the economic and social damages and losses to buildings due to windstorms. The model uses an existing peer reviewed hurricane hazard model that models the entire track and wind field of a hurricane or tropical storm (Vickery et al. 2000a,b). The HAZUS-MH Hurricane Model contains the hurricane hazard, terrain model, wind pressure, and windborne debris models. The hurricane wind field model has been extended to allow estimating rainfall rates used to assess the amount of water entering buildings through broken windows and doors and is a significant component of building damage. The terrain model was developed using existing information on land use land cover combined with estimates of surface roughness for each land use type. The wind load model used in HAZUS reproduces the variation of wind loads with wind direction and has been validated through comparisons with wind tunnel tests. When coupled with the windborne debris models described herein, the wind load models also provide the necessary inputs to estimate wind induced damage and loss.

4.6 Windstorms

Windstorms are among the most destructive hazards with regard to the infrastructure damage and economic losses within Europe. They can affect power/communication, transportation networks and buildings. Regarding energy infrastructure, they can cause equipment failure when hitting the transmission and distribution lines. The direct losses to critical energy infrastructure are evaluated as the repair cost of the damaged power grid assets. The costs of repairing can be estimated from the replacement value of the assets and the potential for asset failure. The latter can be calculated from the exposure of assets to the projected peak wind speed using appropriate fragility functions (Veeramany et al. 2015). Several fragility functions have been developed for towers and transmission lines due to windstorms (e.g., Winkler et al. 2010; Prahl et al. 2015; Prahl et al. 2016; Fu et al. 2017; Panteli and Mancarella 2017; Dunn et al. 2018; Karagiannis et al. 2019). However, the fragility functions for

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windstorms are less mature compared to those for other natural hazards, such as earthquakes or floods. For instance, Winkler et al. (2010) use building fragility functions to estimate the potential losses to transmission substations. Panteli et al. (2017) also highlight the relative lack of empirical fragility functions and the high costs associated with the development of experimental fragility curves for transmission towers and overhead lines. Finally, more recently, Karagiannis et al. (2019) elucidate the vulnerability of CI to windstorms, especially in light of climate change, with focus on critical energy infrastructure. Regarding the natural gas and oil networks, Cruz and Krausmann (2013) assess their vulnerability to climate change and extreme weather events and discuss the options available for mitigation and adaptation.

Telecommunication towers are usually tall steel lattice structures, which are mainly affected by severe weather conditions such as low temperatures, high winds and snow. Especially, storm events may lead to significant damage of steel lattice towers of a network resulting in total collapses with adverse impact for the whole operation of the network. The above effect of strong winds is further enhanced when ice has accumulated on the exposed members of the structure due to low temperature and/or precipitation (Klinger et al. 2011, Makkonen et al. 2014). Bilionis & Vamvatsikos (2019) conducted non-linear dynamic analyses in order to estimate the fragility of steel telecommunication towers in Greece under possible combinations of wind speed and icing conditions. To evaluate the impact of ice, various uniformly thick layers of ice were taken into account, which not only increased the weight but also the cross-sectional area of all structural components and surfaces. Wind's speed was used as the intensity measure (IM) of wind for the estimation of fragility functions. Depina et al. (2021) implement the Performance-Based Wind Engineering (PBWE) methodology to the risk assessment of the critical telecommunication infrastructure subjected to the Bora wind along the Croatian coastline. Typical steel lattice frame telecommunication towers were used for the simulation while the wind hazard was expressed in terms of the parameters of the wind velocity field. The uncertainties in the wind hazard and the structural parameters were propagated to the structural response (e.g., displacements, internal forces) through a set of Monte Carlo analyses. Gao and Wang (2017) conducted non-linear dynamic analysis on typical lattice telecommunication tripole tower and angle tower. A dynamic sensitivity index and a collapse probability are both proposed to identify the most unfavourable wind direction for the two towers. The progressive collapse of fragile curves of the towers was described by the lognormal distribution function.

4.7 Tornadoes

Tornadoes have the potential to cause severe destruction or damage to physical infrastructure, including buildings within a community. This not only leads to direct losses but also indirect losses, such as the closure of vital social institutions that have a cascading impact on the entire community, such as schools. Historically, building codes and standards did not incorporate tornado hazards extensively due to

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the relatively low probability of a direct tornado strike. However, the recently issued ASCE 7-22 standard addresses tornadoes for Risk Category 3 and 4 buildings, encompassing schools and critical facilities. Wang et al. (2022) proposed a range of design combinations for a reinforced masonry school building with different performance objectives aimed at facilitating faster reopening of schools. Tornado fragilities specific to the improved designs of a school building were developed, utilizing tornado loads derived from the new tornado chapter in ASCE 7-22. These fragilities were then integrated into a community-level model, considering school attendance zones, to assess their impact.

4.8 Heatwaves

Heatwaves that represent a period of several days to weeks of abnormally hot weather, often with high humidity, have generally become more frequent and intense across Europe.

Heatwaves can potentially cause physical damage to electricity generators above a certain temperature threshold or force curtailment to avoid safety hazards. They can also lead to abrupt failure and shorter lifetimes of power lines and transformers, while they also increase transmission and distribution line losses and reduce their carrying capacity (Dumas et al. 2019). Bollinger and Dijkema (2016) propose an approach for assessing generator vulnerabilities to heat waves. More specifically, a heat wave vulnerability level is assigned to each generator based on the type of generator (thermal or other), its geographic location (inland or coastal), and the cooling method (presence of a cooling tower). In addition, Csanyi (2021) reviews the most common failure patterns of electrical equipment in distribution networks. This paper describes the damages of certain components of a given power grid (i.e., distribution transformers, underground cables, overhead lines, circuit breakers, surge arresters, and insulators and bushings) under various hazards. Csanyi (2021) supports that heat can cause a transformer's loss of life because it damages the insulation polymers that protect the equipment. Additionally, heatwaves are particularly a concern for natural gas power plants. The operation of this type of power plants requires ambient air for compressor intake, which is then pumped into the burning chamber. The higher the air ambient temperature, the lower the air density and, hence, the burning efficiency, which then reduces power outputs (Handayani et al. 2019). However, no vulnerability approaches have been identified in the existing literature.

Heatwaves can also cause damage to structures due to thermal expansion, for example, Nguyen and Wang (2011) propose and exemplify the use of thermal compression load and critical load of a rail section to estimate failure probability.

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4.9 Drought

Drought is a slow-onset natural disaster often referred to as a creeping phenomenon (Wilhite 2003) that causes inevitable damage to water resources and to farm life (Zarafshani et al. 2016). Drought vulnerability may be defined as the susceptibility of individuals, groups and/or nations to suffer adverse effects when impacted by a drought event. To assess the drought vulnerability various indicators may be adopted related to social, economic and Infrastructural factors (Dabanli 2018). Some of the widely used drought indices include Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), Standardized Precipitation Index (SPI), and Surface Water Supply Index (SWSI) (Hayes 2012). Dabanli (2018) developed a set of drought hazard, vulnerability, and composite risk maps, in order to investigate provinces located in Turkey. The drought vulnerability analysis was conducted using four socio-economic indicators related to water demand and supply and based on DHI, DVI and DRI indexes. According to Zarafshani et al. (2016) differences in drought vulnerability are due to different individual (e.g., gender, age, education, attitude), socio-economic (e.g., social class, religion, ethnicity, social networks, access to resources and power, political structures, income diversification, infrastructural constraints, poor technology, lack of market access and capital, land size), biophysical attributes (e.g., irrigation, type of product, type of irrigation), and access to infrastructural and information sources. Hagenlocher et al. (2019) present an extended literature review of the state of the art of people-centered drought vulnerability and risk conceptualization and assessments. They revealed that factors related to poverty and income (49%), technology (47%), education levels (34%), or the availability and quality of infrastructure (34%) were deemed important drivers of vulnerability and risk by almost one third of all reviewed assessments. Recently, Sahana and Mondal (2023) studied the evolution in drought hazard, vulnerability and risk under climate change. Therein, drought vulnerability assessment was performed combining exposure, adaptive capacity and sensitivity indicators (i.e., irrigation index, waterbody fraction, groundwater availability, population density and GDP), using a multi-criteria decision-making method.

Droughts can cause water levels to drop below the level of intake valves that supply cooling water to power plants, causing plants to stop or reduce power production. In general, threshold impacts such as water levels falling below the level of intake valves depend on plant-specific features, making general response functions or fragility curves challenging to develop (Dumas et al. 2019). The U.S. Electric Power Research Institute (EPRI 2011) has developed a water supply sustainability risk index to identify power plants in counties with “at risk” water supplies, using a set of five criteria, namely the region’s susceptibility to drought, water storage limitations, groundwater use, historical precipitation and growth in water demand.

Drought can also limit or impede navigation through inland waterways due to reduced water depth for potentially extended periods. A general model on the effect of low water on deadweight and payload of inland ships is presented by van Dorsser et al. (2020) based on field observations and ship data.

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4.10 Climate-change related hazards

Climate change is associated with rising global temperature and sea level and, consequently, with increasing frequency, intensity, extent and duration of extreme weather and climate events throughout Europe and the world (Sousa et al. 2020). Climate-change related hazards can generally be divided into two main categories: those caused by extreme weather events and those resulting from gradual onset conditions (e.g., sea level rise, corrosion of structures accelerated by climate change).

There are several reports that refer to the vulnerability of various climate-change related hazards in general. It is worth mentioning that of Dumas et al. (2019) which highlights the available analytical resources for electrical grid components under extreme weather and climate as well as that of Kabre and Weimar (2022) which provides a synopsis of identified resources for fragility curves for electricity and briefly documents their content with a summary of the hazards and assets examined and any other aspects of the resource. The multiple climate hazards associated with e.g., sea level rise, changes in the frequency and intensity of extreme weather events, including hurricanes and tropical storms, greater variability in precipitation, warmer temperatures etc. can have specific deleterious impacts as well on a coastal transport system (including ports, airports, and their access roads and rails), leading to direct and indirect damages and system disruptions (UNCTAD 2017). For instance, daily port operations may be slowed or halted, in both the long- and short-term, and seaport and airport infrastructure will be exposed to serious impacts as well (UNCTAD 2014). Increases in the frequency of heavy downpours can cause flooding of critical road, port, and airport facilities and can deposit debris on roads, blocking access for employees or travelers. Heat events can cause asphalt to soften and rut, cause rail lines to buckle, and affect air operations by reducing payloads and limiting the potential for large plane landings and take-offs. Increased precipitation can cause long-term effects on the structural integrity of roads, bridges, drainage systems and telecommunication systems, necessitating more frequent maintenance and repairs (Oxford Economics 2011). Regarding the issue of corrosion due to chancing climate conditions, Sousa et al. (2020) is one of the noteworthy European efforts. Specifically, they evaluated the expected variations in climatic factors (the changes in temperature, concentration of pollutants, rainfall patterns, etc. induced by climate change) causing corrosion and carried out a literature review on the implications of climate-induced corrosion on the deterioration of concrete and steel structures, and on their seismic resistance as well.

4.11 Discussion and gaps

Although studies to quantify the vulnerability of CI assets have increased substantially in recent years, significant gaps on vulnerability data and models still exist depending on the considered network (electric

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power, gas, oil, road, port, etc.) or asset. Generally, more vulnerability models are available for hazards such as earthquake or floods while for other hazards the available models are primarily based on empirical data and judgement. This section could be regarded as a starting point towards the development of a more common terminology and standardised frameworks that will pave the way for the development of the MIRACA risk assessment framework (D3.2) and the harmonised vulnerability database (D1.5).

Regarding CI networks subjected to floods, it is observed that few vulnerability data are available depending on the network component. In addition, even if data are available, they may not be accessible due to strategic or safety reasons, as also highlighted by Merz et al. (2010), or even if accessible, they rarely correspond to the level of detail required for analyses. Especially for **transportation CI**, while vulnerability models to floods have advanced in recent years, there are still several notable gaps that exist in current research. These gaps could be related to the general lack of empirical damage data (commonly used to define damage functions) (Bubeck et al. 2019). If the final goal is to assess flood risk of the transportation infrastructure, gaps should also be related to general lack of exposure data considering that information about public infrastructure elements is often sensitive given their criticality. Moreover, because of their line features, elements such as roads or railway tracks, are substantially underrepresented in gridded land cover data, typically used for regional or global assessments (Hirabayashi et al. 2013; Jongman et al. 2014; Winsemius et al. 2016). In addition, in the latter case the availability of reliable climate related hazard data is also particularly important.

Generally, most vulnerability models focus on assessing the direct impacts of floods on CI, such as infrastructure damage and route disruptions. However, there is a need for more comprehensive models that consider indirect impacts and the cascading effects and interdependencies between different components within each system (see also Deliverable 2.1 and Deliverable 3.1). There is currently a lack of standardised methodologies for assessing vulnerability to floods in CI. Different studies use varying approaches, indicators, and data sources, making it challenging to compare and integrate findings across different locations. The development of standardised methodologies would enhance consistency and comparability in vulnerability assessments. While many vulnerability models consider current flood risks, there is often a lack of consideration for future climate scenarios and the potential changes in flood characteristics. Incorporating projections of sea level rise, changes in precipitation patterns, and increased frequency of extreme weather events would provide a more robust assessment of future vulnerability. Existing vulnerability models often focus on the physical infrastructure and operational aspects of CI, neglecting the social and economic dimensions. Considering the vulnerability of communities and the economic consequences of flood-related disruptions is crucial for a comprehensive understanding of the overall vulnerability and effective decision-making. The accuracy and availability of data play a crucial role in vulnerability assessments. However, there are often data limitations, including the lack of detailed information on infrastructure characteristics, historical flood events, and socio-economic factors. Addressing these data gaps and improving data quality would contribute to more robust vulnerability

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models. Closing these gaps would require further research and collaboration among researchers, practitioners, and policymakers. It is important to enhance interdisciplinary approaches, improve data collection and sharing, and develop standardised frameworks that integrate physical, social, and economic dimensions to provide more accurate and comprehensive vulnerability assessments for CI facing flood risks.

Regarding **CI subjected to earthquakes**, various fragility curves have been developed for most of the assets but not for all. More specifically, regarding **energy systems** subjected to earthquakes, various fragility curves have been developed for most of the electric power grid. On the contrary, regarding gas and oil networks subjected to earthquakes, there are fragility curves that can be used but with some limitations, e.g., they are applicable only to the specific conditions for which the model was developed and/or they cannot directly distinguish between different damage states. As regards the **transportation sector**, seismic fragility functions for transportation assets are mostly based on empirical and expert-judgement approaches while the available hybrid and analytical based fragility models are generally limited, and they are mainly due to seismic ground shaking only ignoring the impact of ground failure. Moreover, the variability of data regarding the vulnerability parameters and their weighting scores makes it difficult to formulate a coherent vulnerability index approach. Regarding **telecommunication systems**, although many strategies to improve the seismic performance and resilience of this infrastructure can be found in the literature, methods to model the vulnerability and quantify the resilience at the urban level are still lacking. Heterogeneity of telecommunication networks, limited research focus compared to other CIs and limited damage data (e.g., lack of data on the performance of telecommunication networks during past seismic events) result in gaps and uncertainties in the understanding of network vulnerabilities. Addressing these gaps requires concerted efforts from researchers, industry professionals, and policymakers. Collecting more data on the performance of telecommunication networks during seismic events, standardising testing procedures, and incorporating the latest technology and infrastructure advancements into seismic fragility curve development are essential steps. When it comes to seismic fragility curves for **critical single assets** and their vulnerability to different hazards, there are several information gaps that need to be addressed. Although a significant amount of work has been done in developing seismic fragility curves for the residential building stock, only few contributions clearly refer to **school buildings or healthcare facilities**, and their use may be inappropriate for these types of structures, potentially leading either to an underestimation or an overestimation of their actual vulnerability. Critical single assets may vary significantly in terms of their design, materials, age, and maintenance practices that can influence their seismic vulnerability and performance. However, there is a lack of data and specific seismic fragility curves that account for these variations in age and construction types. Schools and hospitals are complex systems that rely on various interdependent components for their functionality. Understanding the interdependencies and functionality of these facilities under different seismic hazard scenarios is essential but often lacks comprehensive data.

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In general, seismic vulnerability models may focus on specific types of infrastructure or hazards, such as buildings or ground shaking, and may not consider the full range of possible hazards and vulnerabilities (e.g., secondary hazards, such as fires or liquefaction). Seismic vulnerability models are subject to uncertainties and variability in the data and modelling assumptions, as well as the inherent variability in earthquake hazard and infrastructure response. These uncertainties may not be fully quantified or considered in the models, leading to limitations in their accuracy and reliability. Seismic vulnerability models should be validated using data from past earthquakes, although these may be limited, particularly for rare or extreme events.

For most of the hazards, except for earthquakes and floods, it is observed that although many CI component vulnerability quantifications are available in the literature, they are primarily empirical and single-event driven, as also noted by Dumas et al. (2019). Moreover, a lack of comprehensive vulnerability assessment studies to climate-change related extreme weather hazards for specific CI network components, such as underground power lines, or whole networks is noted. The impacts of climate change, such as rising temperatures, extreme weather events, and sea-level rise, pose additional challenges to the vulnerability of CI. However, there are information gaps in incorporating climate change considerations into vulnerability assessments for the CI. More data and research are needed to understand the specific climate-related vulnerabilities and develop strategies to mitigate them. This includes considering the potential changes in intensity, frequency, and spatial distribution of hazards over time. As the intensity and frequency of climate-change related extreme weather hazards are expected to increase in the near future, it is deemed necessary to study and understand the vulnerability of all CI networks components, which is crucial for disaster risk management and long-term planning.

Finally, **all systems and single assets** can be exposed to various hazards, including floods, earthquakes, landslides, hurricanes, severe storms, etc. However, fragility curves are often developed for specific hazards in isolation, and there is a lack of multi-hazard fragility curves, as testing the vulnerability of CI to different hazards is complex and resource-intensive. The interaction between different hazards and their cumulative effects is not fully captured, leading to gaps in assessing the overall vulnerability of CI.

Next chapter presents some efforts where frameworks and tools were developed to assess vulnerability and losses of CI in a multi-hazard environment.

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5. State-of-the-art frameworks and tools to assess vulnerability and losses of CI in a multi-hazard environment

Effective risk reduction poses the need for the development of multi-hazard models and tools to accurately assess the vulnerability and risk of CI. However, when dealing with multiple hazards a range of additional challenges (e.g., due to the differing characteristics of processes and cascading effects) should be considered. Below are some large, concerted efforts to come up with frameworks and tools for carrying out vulnerability and loss assessment in a multi-hazard environment.

The National Institute for Building Sciences (NIBS) originally developed HAZUS (Hazard U.S.) on behalf of the Federal Emergency Management Agency (FEMA) back in the 1990 as a closed system, limited to seismic hazard and to U.S.A. scenarios. The current version, called HAZUS 6.1 includes multiple hazards (earthquakes, hurricanes and floods), up to date inventory data and hazard characterization. The main merit of the HAZUS platform is that of having provided for the first time an unparalleled set of fragility models for basically every component in every system in which the built environment can be subdivided. It must be recognized, however, that many of these models have been derived based solely on expert judgement and overall, the consistency of derivation is limited. One effect of the sheer size of the HAZUS framework and set of tools is that it established itself very soon as the reference for all studies in the sector. For instance, many researchers have adopted as a default choice, somewhat uncritically, the five damage states/levels introduced by HAZUS. Most fragility studies published after its appearance employed this discretization of damage that, in many cases, can be too refined for the considered component. Also, HAZUS has basically introduced the lognormal distribution for fragility functions, rapidly becoming the de facto standard.

Syner-G was a European Collaborative Research Project (November 2009 – 2012) focusing on systemic seismic vulnerability and risk analysis of buildings, lifelines, and infrastructures. SYNER-G developed an innovative methodological framework for the assessment of physical as well as socio-economic seismic vulnerability at the urban/regional level. A systemic analysis methodology and tool is developed for buildings, water supply system, waste-water network, electrical power network, oil and gas networks, transportation network, health care system and harbours. Each system is specified with: (i) the taxonomy describing the components within the system, (ii) the solving algorithms that are used to evaluate the system's performance and (iii) the nature of the interdependencies with components from other systems.

The Central American Probabilistic Risk Assessment (CAPRA) platform was developed in partnership with Central American governments, the support of the Central American Coordination Centre for Disaster Prevention (CEPREDENAC), the Inter-American Development Bank (IDB) and the International Strategy of

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United Nations for Disaster Reduction (UN-ISDR) and the World Bank. It is a free, modular, extensible platform aimed at risk analysis and decision making. Hazard information is combined with exposure and physical vulnerability data, allowing the user to determine conjoint or cascade risk on an inter-related multi-hazard basis. The CAPRA suite of software includes hazard mapping (including geologic and hydrogeological hazards and a special module of Climate Change hazard assessment), risk assessment (probabilistic risk calculations) and cost-benefit analysis tools to support proactive risk management. CAPRA can also be used to design risk-financing strategies.

INFRARISK project (October 2013 - September 2016) developed a reliable stress test framework for critical European transport infrastructure to analyse the response of networks to extreme hazard events. The project considers the spatio-temporal processes associated with multi-hazard and cascading extreme events (e.g., earthquakes, floods, landslides) and their impacts on road and rail transport infrastructure networks.

STREST project[42] (October 2013 - September 2016), proposed a new engineering risk based multi-level framework for stress tests for non-nuclear CIs of different classes. The methodology is based on a common CI taxonomy and rigorous models for the hazard, vulnerability, performance and resilience assessment under different natural hazards considering interdependencies between CIs and cascading failures. Different levels of stress tests are proposed, based on the complexity of the analysis (e.g., quantification of epistemic uncertainty, expert elicitation) and the risk assessment approaches (single or multi-hazard, probabilistic or scenario based).

Global Earthquake Model (GEM) was founded in 2009 with the purpose of improving the global knowledge of earthquake risk and contributing to the reduction of risk worldwide. In 14 years, GEM has become widely known for its global effort to improve the state of practice of earthquake hazard and risk assessment and for its contribution to improving the state of knowledge of earthquake risk. GEM has also contributed substantially to the broader objectives of the disaster risk reduction community through its public-private partnership, global collaboration network and development of open, global databases and software for application to earthquake and multi-hazard risk assessment. At the same time, catastrophe risks continue to increase, as does the demand for open and credible risk information to inform risk reduction. GED4ALL Building Taxonomy (Silva et al. 2018) is a classification system specifically designed for multi-hazard applications developed as part of the GEM initiative that considers various natural hazards (earthquakes, floods, strong winds, tsunamis, drought) as well as different assets (e.g., buildings, lifelines, critical facilities, crops, livestock, and forestry).

RiskScape is a GIS-based software tool developed by the National Institute of Water and Atmospheric Research (NIWA) in New Zealand. It allows for the assessment of risks to natural and built environments from multiple hazards. RiskScape incorporates spatial analysis, exposure modelling, vulnerability

[42] www.strest-eu.org

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assessment, and loss estimation to evaluate the vulnerability and potential losses of CI systems. The framework provides insights into the vulnerability of CI systems, allowing for the prioritisation of mitigation efforts and the development of resilience strategies.

NIST Community Resilience Planning Guide for Buildings and Infrastructure Systems (CPG) is a framework developed by the National Institute of Standards and Technology (NIST) in the United States. It provides a structured approach for assessing the vulnerability of buildings and infrastructure systems to multiple hazards.

The **Critical Infrastructure Resilience Platform (CIRP)** in the frame of the EU Research project **EU-CIRCLE**[43] (June 2015 – May 2018), aims to enhance the resilience of interconnected CI in Europe against climate-related challenges. The main objective of CIRP is to offer a web-based software accessible to multiple users, enabling the analysis of CI vulnerabilities and their impacts resulting from climate change. These impacts encompass not only physical damages but also service disruptions, societal costs, environmental effects, and economic costs due to suspended activities.

IN-CORE (Interdependent Networked Community Resilience Modeling Environment) is a framework developed by the University of Southern California. It provides a suite of tools to assess the interdependencies among CI systems, simulate hazards, and estimate infrastructure vulnerability and cascading impacts. IN-CORE supports multi-hazard analysis, which involves considering the simultaneous or sequential occurrence of multiple hazards and their interactions.

Koks et al. (2019) present a global multi-hazard risk assessment framework and associated tools for road and railway infrastructure assets. They considered several natural hazards, i.e., tropical cyclones (wind speed only), earthquakes, surface flooding, river flooding, and coastal flooding. The annual cost of repairing transport infrastructure globally and by country damaged by the different hazards are presented. The direct economic benefits of improving infrastructure standards against flooding are also assessed.

INFRARES project (2020 - 2023)[44] developed an innovative and user-friendly software for multi-hazard risk and resilience assessment of transportation infrastructure (bridges and tunnels), for an easy application by Stakeholders, Operators and Public Authorities.

The above frameworks and tools to assess vulnerability and losses of CI in a multi-hazard environment, are just some of the available tools. Most of them have been developed at a research level and could be used in the future by the relevant bodies. It should be noted that despite the fact that a lot of relevant work has been done, there is still a lack of tools that can be easily used at European level considering also systemic effects and cascading failures.

[43] https://www.eu-circle.eu/

[44] https://www.infrares.gr/about/

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6. Concluding remarks

Within the framework of this deliverable, we conducted **an extensive literature review on existing exposure and vulnerability data and models on different CI assets**. We also reviewed the available frameworks and tools to assess vulnerability and losses of CI in a single and multi-hazard environment. The aim was to identify gaps in CI exposure and vulnerability data and models and create the basis for a pan-European harmonised exposure and vulnerability database (D1.4 and D1.5). In general, it has been concluded that although several efforts have been made to develop exposure datasets for the various CIs, a pan-European harmonised, accessible, and complete database of the different CI assets also containing the appropriate attributes to be used within a risk assessment study is not available.

Regarding exposure data, it is found that some datasets, such as OSM, are based on Voluntary Geographic Information collected data. Thus, issues related to data accuracy, completeness, and quality are raised. Despite these limitations, OSM data seems to be the most complete and is directly usable for analysis of the transport network (road and rail networks). In contrast, OSM data seems insufficient for an analysis of the energy systems: for electrical power, natural gas and oil pipelines many attributes are insufficient or completely missing for their detailed use in a vulnerability or risk assessment study. This also holds true for the telecommunication system as well as for single critical assets such as schools and hospitals. The existing information gaps on exposure data make it difficult to assess in detail their vulnerability and losses both in a single- and multi-hazard environment. In general, the lack of standardised data collection methods and reporting frameworks seem to be the main information gap, as there are no globally agreed-upon standards for collecting and reporting exposure data. This makes it challenging to analyse and compare data across different locations, and it limits the ability to make risk data-driven decisions. Additionally, the limited availability of long-term exposure data constitutes another significant gap, as most existing exposure data are received during specific events or in response to specific concerns. Long-term exposure data are necessary to better understand the chronic effects of exposure to natural hazards and climate change. The above gaps pose significant challenges to understanding and mitigating the various risks. A collaborative effort is required from governments, industry, and research institutions to develop standardised data collection methods and reporting frameworks. We also note that not all data sources are comprehensive or up-to-date, and users should exercise caution when interpreting and using the data.

Regarding vulnerability data and methods for the different natural hazards, although there is a substantial increase of the studies quantifying the vulnerability of CI assets the recent years, significant gaps on vulnerability data and models still exist depending on the considered network (electric power, gas, oil, road, port, etc.) or single asset as well as on the considered hazards. Regarding CI subjected to floods, it is observed that few vulnerability data are available depending on the network component. In addition, even if data are available, they may not be accessible due to strategic or safety reasons. As

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regards for CI subjected to earthquakes, various seismic fragility curves have been developed for most of them but not for all. In addition, empirical models do not directly distinguish between different damage states while numerical ones may not be directly applicable to regional seismic risk assessments. Methods to model the vulnerability and quantify the resilience at the urban level are also lacking, even if there are many strategies in the available literature to improve the seismic performance and resilience of CI. In addition, seismic vulnerability models may focus on specific types of infrastructure or hazards and may not consider the full range of possible hazards (such as secondary hazards) and vulnerabilities. Generally, most vulnerability models focus on assessing the direct impacts of hazards on CI, such as infrastructure damage and disruptions to operations. However, there is a need for more comprehensive models that consider the cascading effects and interdependencies between different components within each system. **There is currently a lack of standardised methodologies for assessing vulnerability of CI to natural hazards**. The accuracy and availability of data also play a crucial role in vulnerability assessments. For most of the hazards, it is observed that although many CI component vulnerability quantifications are available in the literature, they are primarily empirical and single event driven. Moreover, a lack of comprehensive vulnerability assessment studies to climate-change related extreme weather hazards for specific CI network components is noted. As the intensity and frequency of climate-change related extreme weather hazards are expected to increase in the near future, it is deemed necessary to study and understand the vulnerability of all CI networks components, which is crucial for disaster risk management and long-term planning. A lack of multi-hazard fragility curves has also been identified in the literature, probably because testing the vulnerability of CI to different hazards is complex and resource intensive. However, not fully capturing the interaction between different hazards and their cumulative effects lead to gaps in assessing the overall vulnerability of CI.

Finally, we summarise some of the most important frameworks and tools towards multi-hazard risk assessment and we conclude that there is **an urgent need for the development of a common Pan-European harmonised platform that has all the required features to assess CI multi-hazard risk under climate change** considering also systemic and cascading effects.

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