Reviewing and informing the existing gaps for Critical Infrastructure interdependencies

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Executive Summary

This document provides a review of existing information and gaps in Critical Infrastructure (CI) interdependency data and modelling. It satisfies the remit of Task 2.1 within the Work Package 2 (WP2) Multi-hazard Infrastructure Risk Assessment for Climate Adaptation (MIRACA) project. The focus of this document is to: (1) Provide a literature review of existing CI interdependency frameworks; (2) Identify the most useful CI interdependency modelling approaches for demonstrating the effects of service disruptions across multiple CI systems; (3) Examine existing state-of-the-art data in Europe that could be used in MIRACA; and (4) Identify gaps and opportunities for improved CI interdependency focussed modelling, data creation and policy outcomes that would enhance the next steps of MIRACA.

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1. Introduction

Critical Infrastructures (CIs) such as energy (electricity, gas, oil), transport (roads, railways, maritime and inland waterways, airports), telecommunications (telecom in short), education and healthcare facilities, provide essential services that sustain social and economic well-being of societies (Hall et al., 2016a). CIs operate under continuous stress because they are built under design and capacity constraints, while the demands and external perturbations imposed upon them are constantly changing (Pant et al., 2016). These stresses are particularly magnified under extreme weather events that induce damages causing widespread disruptions due to CI failures. CI disruptions, especially in energy, transport and telecommunications, lead to far-reaching consequences of socio-economic losses because of the networked behaviour of their assets and service provisions (Thacker et al., 2017a; Koks et al., 2019a; Oughton et al., 2019).

This document focuses on CI interdependencies that trigger cascading failures across multiple systems, the study of which is an objective of the Multi-hazard Infrastructure Risk Assessment for Climate Adaptation (MIRACA) project. In particular, Work Package 2 (WP2) within MIRACA aims to *develop and demonstrate a complete framework for interdependent CI network use and failure propagation modelling*. The framework will lead to the: (1) creation of improved models and data to represent interdependencies across CI networks; (2) representation of service delivery from these networks to other CI and to customers, businesses and wider economic sectors; and (3) development of methods to assess cascading failures and interdependencies between CI networks at the pan-European scale.

Towards building the WP2 framework, the first Task 2.1 delivers (through this report) a review of current literature towards identifying the existing data needs and gaps that need to be addressed for creating harmonised interdependent network models at large scales. This involves:

1. A literature review of frameworks that identify the different types of interdependencies between CI networks.
2. Identifying the current state of research to identify CI interdependency models that would be most useful for modelling service disruptions across multiple CI systems.
3. Reviewing the existing state-of-the-art data in Europe that could be used in MIRACA.

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4. Identifying gaps and opportunities for improved CI interdependency-focused modelling, data creation and policy outcomes that would enhance the next steps of MIRACA.

The next sections of the report are organised as follows. Section 2 discusses the relevance of incorporating CI interdependencies in risk assessments. Section 3 explores the definitions of CI interdependencies proposed in literature and the most relevant modelling approaches for MIRACA to be able to quantify those interdependencies. Section 4 presents the existing state-of-the-art datasets at the EU scale that will be useful for CI modelling and identifies the gaps that MIRACA can address and improve. Section 5 concludes this review with the key lessons and opportunities for CI interdependency modelling in the next steps of MIRACA.

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2. Relevance of CI interdependence

2.1. Impacts of infrastructure interdependency

There is consensus in academic research and public policy that CIs have evolved to be highly interdependent systems (Ouyang, 2014; Hall et al., 2016b; CISA, 2019; OECD, 2019). The term *interdependence* is widely used in literature to characterise the bi-directional relationship between two infrastructure assets where each asset affects the operations of the other (Rinaldi et al., 2001; Pederson et al, 2006). Interdependencies across multiple CIs are highly desirable because they enable the smooth functioning of society and businesses (Grafius et al., 2020), provide economic benefits (Zavadskas et al., 2018) and enable the growth of CI systems at economies of scale (Henckel & McKibbin, 2017). These interdependencies are becoming more extensive in modern infrastructure networks for two technological reasons: (i) the transition towards electrification of all infrastructures that were previously powered by fossil fuels (notably transport and heating) in order to cut harmful carbon emissions; and (ii) the digitisation of all forms of infrastructure in order to enhance efficiency. However, interdependencies lead to undesirable outcomes of widespread disruption propagation across multiple CI systems that escalate the consequences of localised failures (Pant et al., 2022). It is widely accepted that networked CIs such as electricity, transport and telecom systems are highly susceptible to *cascading failures*, which is defined as the "uncontrolled successive loss of system elements triggered by an incident at any location" (Vaiman et al., 2011).

Several examples of cascading failures across CIs have been documented in Europe, with the most prominent examples being the power network failure originating in Italy in 2003 and Germany in 2006 that respectively resulted in large-scale blackouts for about 57 and 45 million people across several European countries (Guo et al., 2017). These incidents prompted an improvement in the policy governing the security of transmission of electricity across Europe (Van der Vleuten & Lagendijk, 2010). Empirical evidence of 1,749 documented cascading failure events across 12 CI and industry sectors in Europe showed that 60% of power failures and 24% of telecom failures caused outages in other sectors (Luiijf et al., 2008). The ongoing war in Ukraine has very strongly demonstrated that Russian attacks on energy and telecom CI assets have caused cascading failures that have severely affected millions of people in Ukraine and impacted global energy and food security (Zwijnenburg & Nikolaieva, 2022; Zhou et al., 2023).

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In the context of the MIRACA project, the particular focus is on CI failures due to multi-hazard natural events such as extreme floods (pluvial/fluvial/coastal), windstorms, droughts, heatwaves, wildfires, earthquakes and landslides. For such hazards, the combination of compounding and cascading events (Wells et al., 2022) can also introduce *common cause failures* (where multiple CI assets are damaged at the same time by the hazard) and *escalating failures* (where one CI failure impedes the recovery of another) (Rinaldi et al, 2001; Rehak et al., 2018). Extreme floods in Germany in 2021 caused an estimated €700 million – €1.2 billion damages to roads, bridges and railway networks, disconnected 200,000 people from the power networks, created telecom outages in flooded regions, caused severe damages to several hospitals and schools, and most of these impacts lasted for several weeks (Koks et al., 2021). Flood losses to the United Kingdom's economy in 2015/16 were estimated to be €1.7 billion, and €360 million from compounding events between November 2019 and March 2020 (FCERM, 2021), while multiple storm events in 2021-2022 caused electricity disruptions for over 1 million customers and major transport disruptions (BEIS, 2022; Met Office, 2022). Evidence from the UK Environment Agency (EA) showed that two-thirds of properties in England obtained services from CI assets directly or indirectly exposed to floods, which meant that for every person affected during a large flood, about sixteen more suffered knock-on effects from losses of CI services (EA, 2021).

2.2. Efforts to understand the impacts of infrastructure interdependency.

With the backdrop of increasing evidence of the CI cascading failures, interdependencies are increasingly considered to be an issue of national security and protection against risks in Europe and other countries (CISA, 2019; Lewis & Petit, 2019; OECD, 2019; Chouinard & Hales, 2020). Over the years many policy frameworks and directives, at the European Union level, have been introduced, including the Critical Entities Resilience Directive (CER) (EU, 2022), which replaced the European Critical Infrastructure Directive (EU, 2008). CER aims to improve the resilience of 11 CI sectors (including the ones of interest in MIRACA): energy, transport, banking, financial market infrastructures, health, drinking water, wastewater, digital infrastructure, public administration, space and food. Previously, the European Programme for Critical Infrastructure Protection (EPCIP) also stressed the need to improve CI preparedness against attacks (EU, 2006).

With increasing extreme weather events happening due to climate change, CI assets are more vulnerable to damages that could lead to cascading failures (Mikellidou et al.,

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2018). A study, on direct physical damage to CI assets (energy, transport, education, health, and industry) losses from multiple hazards (heatwaves, cold waves, floods, droughts, windstorms, wildfires) under future climate scenarios, has estimated asset damage losses amounted to around €3.4 billion per year at present and could increase six-fold by 2050s to 10-fold by the end of the century with the largest concentration of estimated risks in Italy, Slovenia, Portugal, Spain, Greece and Croatia (Forzieri et al., 2018). It could be argued that these estimates would be much higher and magnified in future climate scenarios if the indirect economic losses from CI interdependencies and their cascading impacts were also accounted for in the analysis. However, till date such an assessment has not been undertaken.

A number of European Commission funded projects have sought to understand and model the impacts of infrastructure interdependency at the pan-European level. For transportation, projects such as TRUST (TRansport eUropean Simulation Tool) and ETISPlus (Speth et al. 2022) have developed multimodal transport models at varying spatial scales to map passenger and freight flows from which economic impacts of disruptions could be estimated. TRUST focused on origin-destination flows at the NUTS3 level and ETISPlus on flows along the asset level for long-distance transport links (e.g. motorways and highways only). However, TRUST is not an open-source model, though the methodology has been shared (TRT, 2024). ETISPlus data was created in 2010, though an update synthetic model of flows for 2019 and 2030 was recently created (Speth et al., 2022). Projects like CASCADes and RESIST specifically address climate-induced disruptions, evaluating how extreme weather events cascade across critical infrastructure sectors, especially transportation, energy, and ICT, and offering resilience strategies. However, these projects develop solutions at macro-scales and digital twins models for high-level stakeholder engagement. INFRARISK and IMPRESS develop risk assessment tools for transportation under natural hazards, while also examining interconnected vulnerabilities with energy and water systems.

Gaps remain, particularly in the assembly and creation of data for modelling cross-sectoral interdependencies between transportation, energy, water, and ICT systems. Although some projects (e.g., CASCADes) move in this direction at the macro-scale, further research is necessary to deepen cross-sectoral analyses, especially in mapping essential lifeline infrastructure and critical interdependencies at the asset level across Europe. Addressing these gaps will be critical for understanding resilience needs across the European infrastructure network and developing tools for coordinated, sector-wide responses to both natural and anthropogenic threats.

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Various policy directives have consistently noted that the silo-ed approach of CI owners to manage and operate their CIs and a lack of understanding of CI interdependence remains a major challenge in estimating and tackling climate risks (OECD, 2019; NIC, 2021; Sonesson et al., 2021). This leads to additional challenges of lack of coherent data for modelling infrastructure interactions and inconsistent risk measures that make it difficult to compare resilience outcomes across different sectors (NIC, 2020; HM Government, 2022).

Based on all the above, the case for building models in MIRACA to quantify CI interdependencies for estimating wider socio-economic losses is quite clear and relevant. Next, we examine the state of current CI modelling that is relevant for our project.

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3. Interdependency modelling principles

3.1. Interdependency typology

Since it has been well established that CIs function as interdependent systems, a large amount of research has now focussed on conceptualising, modelling and quantifying interdependence across CIs (Ouyang, 2014; Hickford et al., 2018; Saidi et al., 2018). This has led to defining CIs as *system-of-systems* which is the "collection and interconnection of all physical facilities and human systems that are operated in a coordinated way to provide a particular infrastructure service" (Hall et al., 2016b). From a risk assessment perspective, this definition is relevant for MIRACA because it lays emphasis on the physical facilities embedded in space, which are exposed to spatial hazards, and also focuses on the role of CI assets in providing infrastructure services that determine the extent of cascading failure impacts. The system-of-systems of CIs is further conceptualised as a combination of systems embedded in networks at multiple levels that evolve over time (Eusgeld & Nan, 2009), exhibiting multi-scale hierarchical structures (Thacker et al., 2017b; Verschuur et al., 2022b). This evolution of the CI over space and time is relevant in the assessment of changing risks and considering adaptation options for existing CI assets or for new CI investments in the future, both of which are a focus of the MIRACA project.

Various classifications of interdependencies in the system-of-systems modelling of CIs have been proposed and reviewed in great detail (Ouyang 2014; Saidi et al., 2018). Table 1 describes useful interdependency typologies defined over the years in the academic literature with MIRACA-relevant practical applications (Rinaldi et al., 2001; Zimmerman, 2001; Dudenhoeffer et al., 2006; Lee II et al., 2007; Zhang & Peeta, 2011). It is noted that these examples show a *directional dependency* in terms of the initiation of the failures, which can lead to further interdependent failures that cascade back to the original CI (Pant et al., 2020). Two empirical examples of cascading failures enabled by CI interdependence are described below (Bloomfield et al., 2009; Ferrari & Santagata, 2023):

1. An explosion at the Buncefield Oil Depot in the UK in 2005 highlighted the geographic interdependencies by propagating disruptions to the adjacent road network, causing €77m of damage to energy and adjacent businesses, including a major Information Technology Company's headquarters. This further triggered cyber/informational interdependencies where five hospitals lost access to

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servers hosting patient records for a week, and the national payroll scheme worth €1.5 billion was disabled for a while before being recovered.

2. The collapse of the Genoa bridge in Italy due to floods in 2018 emphasised the geographic interdependencies where part of the collapsed building fell and broke the railway lines going under it and also damaged warehouses of an energy company. This further created functional, social, market and economic interdependencies by drastically disrupting the mobility of people and goods from the Port of Genoa, one of the largest in the Mediterranean. The issue also highlighted budgetary interdependency in terms of the lack of spending on infrastructure maintenance in the region.

Table 1: *Descriptions of different types of interdependencies defined in literature, supported with their practical applications in the MIRACA project.*

Interdependency type	Definition	Practical applications in MIRACA
Physical	Different CI assets are physically connected and share inputs and outputs with each other.	Electricity network CI asset failures shutting down directly connected CI assets: transport, telecom, schools and hospitals.
Geographic/Geo-located/Spatial	CI assets are exposed to the same local environment or spatial footprint.	A large flood hazard destroying road bridges, which might also have electricity and telecom cables going under them.
Cyber/Informational	There is an exchange of information between CI assets, underpinned by an information infrastructure.	Telecom data centre failures shutting down operations of electricity networks, emergency health services, and road and railway signalling.
Functional (combination of physical and cyber)	The operation of CI assets of two infrastructures are contingent on the supply of resources and services from each other.	Electricity and telecom CI asset failure shutting down both networks and affecting operations for transport, education and health CI assets.
Social	The operations of CI assets are co-dependent upon social	A post-disaster surge in demand for emergency services and schools as shelters putting

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	perceptions and demands for CI services.	transport, electricity and telecommunication CI assets under stress, leading to road closures, electricity load shedding and telecom towers losing signals.
Market and Economic	The economic and market supply and demand affect CI assets	A post-disaster decline in manufacturing, agriculture, mining production reducing critical transport goods and services delivery to others CI assets.
Budgetary	The investments into new or existing CI assets of different infrastructures depend on the same public financing constraints	Limited centralised budgetary constraints governing the prioritisation of building resilience to electricity or telecom CI assets over others CI assets, thereby ignoring some localised cases where investing in other CI asset resilience might be more beneficial.
Policy and Procedural	There are set of binding policies that govern CI assets of all types	Short-term post-disaster sequencing of CI restoration enabling or hampering recovery. Long-term climate emission commitments governing the evolution of centralised or de-centralised CI networks, altering the nature of interdependencies.
Culture and Norm	The utilisation of various critical infrastructure assets and services is contingent upon and will influence urban transitions by interacting with societal norms and cultural values.	Cultural norms that emphasise public transportation may place less strain on road networks; cultural norms shape how communities respond to infrastructure failures or crises (community and mutual assistance or individualism), impacting how quickly repairs

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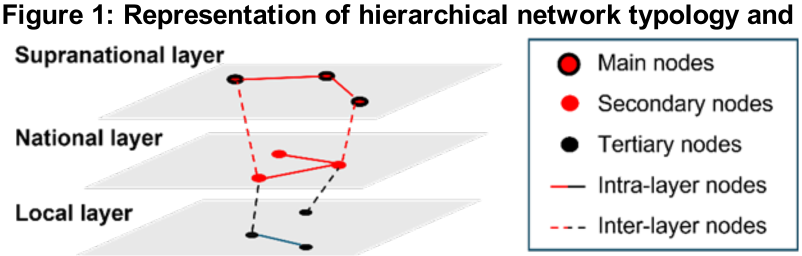
		and recovery efforts are coordinated; cultural norms can also influence how resources or investments are allocated and prioritised in society.

3.2. Interdependency modelling approaches

To model and quantify the different types of CI interdependencies, the most common approaches have utilised spatial network-based methods (Murray et al., 2008; Barthélemy, 2011). The most useful network models are those that capture the multi-layered hierarchical nature of CIs showing (Thacker et al., 2017a-b): (1) The ability of the CI assets to provide a service through *source nodes* that generate services; (2) The interdependence or directed dependence between CI assets through *intermediary nodes and links* that transmit services from generation towards locations of demand; (3) The interface between CI assets and socio-economic entities through *sink nodes* that deliver the services to customers and business who have the demand for the service. Such models are able to capture the heterogeneity, scale, and dimensionality of multiple CIs at large scales (Zio, 2016). Several network-based representations of CIs have focussed specifically on characterising topology (Barabási, 2009) – the physical, geographic and logical arrangement of nodes and their connecting links – and its implications on CI vulnerability (Barthélemy, 2011; Hines et al., 2010; Dunn & Wilkinson, 2013; Freitas et al., 2022).

Multi-layered infrastructure networks are often conceptualized as layered hierarchies, with large, high-impact nodes at the top (with supranational influence) and progressively smaller, locally influential nodes at the lower layers. Interdependencies between these networks are represented as directed links, indicating the flow of passengers, freight, and resources, as depicted in Figure 1.

Figure 1: Representation of hierarchical network typology and dependencies



A robust interdependency analysis model would represent the bidirectional relationships between cross-sectoral critical infrastructure (CI) networks. Specifically,

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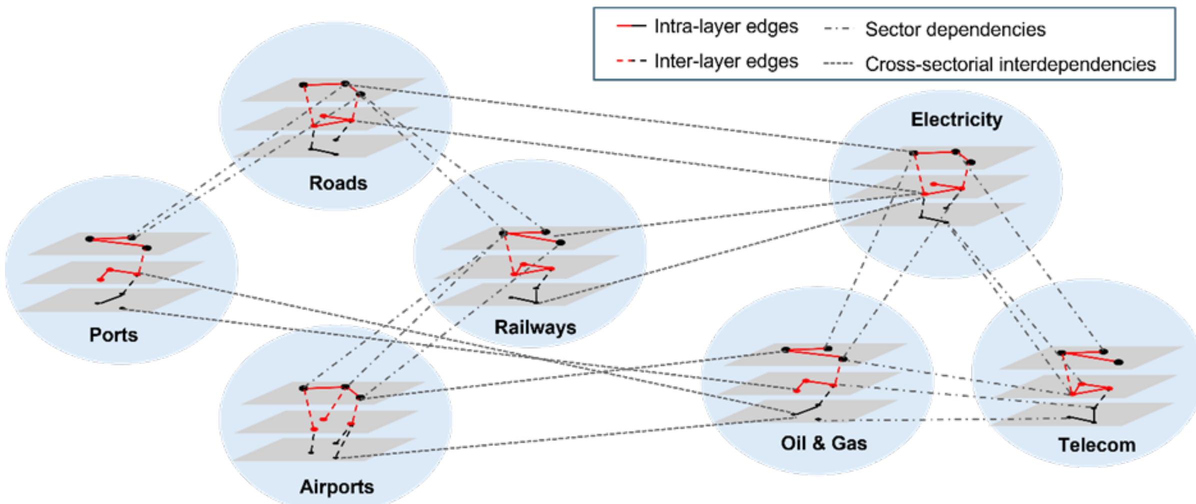
how resource networks (e.g. energy, telecoms) disruptions impact system operability and how transportation network disruptions affect accessibility. To achieve this, mapping connections between all the sectors, as illustrated in Figure 2, provides a comprehensive view of passenger, material, and energy flows within and across networks. This mapping enables a foundational assessment of cascading impacts resulting from the failure of individual nodes, offering insight into resilience strategies that can mitigate potential disruptions across critical infrastructure sectors.

Figure 2: Representation of multi-modal and cross-sectorial network typologies and dependencies



Interdependency network methods that are only topology-based do not provide an understanding of the disruptions of services, which has led to the development of several multi-layers network methods that integrate the topology with the functional characteristics of CI assets through simplified flow-based network models (Pant et al, 2016; Thacker et al., 2017b; Zhao et al., 2018; Ganguly & Mukherjee, 2023) and more complex representations of flow dynamics (Goldbeck et al, 2019; Galbusera et al., 2020). Apart from network modelling approaches, several other modelling approaches have been employed for CI system-of-systems modelling, including, amongst others, expert scenario-based methods (Laugé et al., 2015; Seppänen et al, 2018), empirical evidence-based and historical data-driven methods (Zimmerman 2004; Luiijf et al., 2008; Mottahedi et al., 2021), macroeconomic input-output (IO) and its inoperability-based models (Koks et al., 2019b), economic computational-general equilibrium (CGE)-based methods (Rose, 2019), aggregated systems dynamics-based models of stocks and flows (Min et al., 2007; Papachristos, 2019), agent-based models (Eusgeld et al., 2011), Bayesian

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network-based approaches (Johansen & Tien, 2018), and population mobility models (Barbosa et al., 2018).

Detailed reviews of all the above models have discussed the limitations of each approach (Ouyang 2014; Sun et al, 2022), highlighting that: (1) Network models require detailed data on CI assets locations, connectivity and attributes and can be computationally expensive at large scales; (2) Models derived from expert scenarios, empirical evidence, and systems dynamics generally require highly trained professionals with experience of CI interdependencies, which can be limited and also introduce expert biases; (3) Historical data-driven analyses and population mobility models utilise field survey data and will introduce stationarity in modelling CI interdependencies and ignore future evolutions of interdependencies; (4) Economic IO and CGE models do not capture the spatial locations and connectivity between CI assets but rather focus on the aggregated presentations of the CI as economic sectors. While the spatial extension of CGE, represented by Spatial Computable General Equilibrium (SCGE) models, significantly enhances the analysis by explicitly incorporating regions, network flows, costs, and the spatial characteristics of infrastructure systems and their interrelations (Zhang & Peeta, 2011). Despite these advantages, SCGE models are not without their challenges, notably the substantial data requirements essential for in-depth spatial network analysis. Acquiring such data can pose significant logistical and technological hurdles, thereby adding complexity to the model development process; (5) For the case of the Agent-based Model, the explored emergent behaviours might not have been observed or occurred, which limits the model calibration and validation through such an approach. Instead, expert engagement is beneficial to validate the patterns of agent and system behaviour (Voinov et al., 2018); and (6) similar to agent-based models, Bayesian network models require lots of data for calibration and are difficult to scale.

As no single CI modelling approach can provide a comprehensive understanding of CI interdependencies and cascading failures, combining two or more CI modelling approaches would be most suitable (Zio, 2016; Barker et al., 2017; Sun et al, 2022). For the purposes of the MIRACA project, the most relevant approaches would be the ones that combine changing extreme hazards with spatial networks service flow models, population estimations, business locations, macroeconomic IO models and adaptation prioritisation decisions to capture geographic, functional (physical and cyber), market and economic, budgetary and policy interdependencies. While such models have not been built yet at the pan-European scale, some country-specific models for multi-modal road, rail, port and airport networks have been demonstrated in Vietnam (Oh et al., 2019)

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and Argentina (Kesete et al., 2020). To achieve the implementation of the interdependent CI failure propagation analysis, a key challenge is the collection and creation of datasets. This is discussed in Section 4.

3.3 Flow modelling approaches

Flow modelling, as a medium, assists in analysing and optimising the intricate interdependency of CI networks, encompassing energy, transportation, and telecom infrastructures in the context of MIRACA project. Diverse mathematical and analytical models have been established that are applicable to each sector. In the realm of transportation flow modelling, traffic flow models, ranging from microscopic, mesoscopic to macroscopic, have been applied to simulate traffic dynamics at distinct levels of detail (Dorokhin et al., 2020; Gora et al., 2020; Khan & Gulliver, 2018; Y. Wang & He, 2018). Yet, these conventional models are primarily designed to elucidate traffic conditions, congestion patterns, and the overall network performance, leaving a gap in the exploration of spatial flow modelling to unveil the underlying network interdependencies. To fill this gap, gravity and radiation models are emerging as two valuable tools for modelling the spatial flow distribution (Masucci et al., 2013; Piovani et al., 2018). These models hinge on the concept of location attractiveness (typically measured by population density, employment opportunity, and economic activities) and the required transporting distance. Research (Masucci et al., 2013) has shown that the gravity model outperforms the radiation model in predicting flows over short and moderate distances where most flows occur, and vice versa. However, it is essential to notice that both models are specific to transport passenger and trade modelling and may not work as well for non-physical flows (e.g., information and energy flows). Alternative flow modelling approaches that could be generalisable at the pan-European scale for studying the interdependent CI across different infrastructure systems are needed.

As discussed previously in Section 3.2, with network-based (or graph-based) methods increasingly used as a means to represent interdependent CI networks (Guldmann, n.d.; Yodo & Arfin, 2021), process-based methods emerge as a promising tool to model the flows originating from diverse sources (e.g., energy, transportation, and telecom). These models operate under the assumption that the observed flow pattern adheres to a predefined proportional assignment (i.e., fixed O-D flow matrices). Building

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on these principles, multi-layered hierarchical network service flow models, of relevance to the MIRACA project, have been developed and demonstrated through several case studies on spatially interdependent energy, transport and telecom vulnerability and risks assessments for Europe (Poljanšek et al., 2012), Sweden (Johansson & Hassel, 2010; Johansson et al., 2011), Great Britain (Thacker et al, 2017a; Oughton et al., 2019; Pant et al., 2020; Ilalokhoin et al., 2023), New Zealand (Zorn et al., 2020), United States (Dueñas-Osorio et al., 2007; Hernandez-Fajardo & Dueñas-Osorio, 2013; Almoghathawi et al., 2021) and China (Hu et al., 2014; Wang et al., 2018).

To further enhance the accuracy and robustness of process-based methods in modelling flows of various sources within integrated-interdependent networks, the MIRACA project recognises the necessity of accounting for the dynamics and uncertainties in flow modelling by incorporating variable O-D flow matrices. To achieve this, the following strategies could be employed in this project, including:

1. **Elastic demand modelling for flow diversion.** Elastic demand modelling can describe how demand for travel between different O-D pairs changes in response to the changes in the travel cost. Elasticity measures the percentage change in demand for a given percentage change in cost (Xie et al., 2011). A negative elasticity indicates that demand decreases as costs increase. Using this approach, the simulation can show how changes in cost or other factors affect the traffic flow by analysing the extent to which people divert from the original service or route to alternatives. Flow diversion may involve choosing different routes and modes of transportation. This approach is also valuable for scenario planning to understand the potential consequences of infrastructure failures, helping to make informed decisions and prompt responses.
2. **Set constraints on maximum flow rates for subpaths/subnetworks.** To model flow diversions effectively, constraints can be strategically introduced at diversion points within the network. Two primary methods include imposing capacity limits on edges to define the maximum number of units each edge can accommodate; and implementing constraints related to the cost or travel time associated with each edge (Elalouf et al., 2012; Karsten et al., 2015). These measures shape and guide traffic flow rates, allowing for a more accurate representation of diversion dynamics.
3. **Incorporate uncertainties into flow modelling.** This entails the incorporation of various sources of uncertainty, including demand fluctuations on the human side (e.g., unbounded rationality in decision-making), variations in traffic conditions

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(e.g., travel costs), and unforeseen disruptions in the environment (e.g., natural disasters, random network failures, etc.) (Dewar & Wachs, n.d.; Ottomanelli & Wong, 2011). Monte Carlo simulation method has been identified as a popular approach to quantify uncertainties in traffic flows on a transport network by (Seger & Kisgyörgy, 2018). By integrating uncertainties into the flow modelling process, our project aims to enhance the robustness of its predictions and provide more reliable insights into flow simulation under uncertain circumstances.

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3.4 Interdependency dynamics

Critical Infrastructure (CI) disruption involves the removal or loss of functionality of specific nodes or links across hierarchical network layers. When disruptions occur, these initial "first-order disruptions" directly affect the infrastructure targeted by the disruption, such as a damaged bridge or flooded railway segment. This initial impact leads to an immediate rearrangement of transportation, energy, or other flows within the affected network layer.

However, the interdependency structure of CI networks is dynamic, adjusting to the loss of operability in interconnected sectors and regions. Disruptions often extend beyond first-order impacts into "second-order disruptions", affecting sectors that depend on the disrupted infrastructure. For example, if a critical railway hub is down, not only are the primary rail routes impacted, but also dependent sectors like logistics and manufacturing may experience delays in their supply chains, as their flow of goods is rerouted or delayed.

Beyond second-order impacts, "third-order (and higher) disruptions" may emerge, where failures cascade across both sectors and geographic boundaries. For instance, a delayed cargo supply chain might eventually disrupt manufacturing, which in turn affects energy consumption patterns across regions as factories and facilities adjust operations. These higher-order disruptions introduce long-term, cross-sectoral consequences that complicate recovery, often affecting regions and networks far from the initial disruption.

This methodology has been applied at national and international scales (e.g., Thacker et al., 2017; Thompson et al., 2024; Muhlhofer et al., 2024), demonstrating that mapping disruptions by orders is essential for capturing the complex dynamics of CI interdependencies. Differentiating these orders of disruption clarifies how failure can propagate through dependent sectors and timeframes, from immediate impacts to effects at three temporal phases - during disruption, post-disruption, and throughout the recovery phase. This approach provides critical insights for establishing resilience metrics, and would help in pinpointing vulnerable nodes and "lifelines" that uphold the pan-European CI network.

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4. State of data and gaps

Spatially explicit CI interdependency data are generally scarce due to issues of national security and privacy, commercial sensitivity and competitiveness, issues surrounding ethical aspects of creating and using such data, data ownership and proprietary issues with sharing information (Sun et al, 2022). It is also not realistic to create detailed data that map the connectivity and service flows between sets of all CI assets over space and time. For the creation of a generalisable CI method and analysis at the pan-European scale, the best option is to rely on global and European open databases that provide very good quality information on CIs in a standardised form.

Table 2 provides a list of state-of-the-art and current CI spatial datasets, which have been identified as being useful for further interdependent network modelling in MIRACA. The selection of these datasets is based on the following criteria:

1. Do they provide a spatially explicit representation of CI point, polygon and line assets?
2. Can they be used for creating CI network topology that captures connectivity within or across CIs?
3. Do they provide information to create service flows across networks?
4. Do they provide information on future CI planning?

It is noted that a detailed review of multi-hazard data, CI asset data, macroeconomic data, and adaptation options data has also been compiled in other reports under Tasks 1.1, 3.1 and 4.1 of the MIRACA project, and the purpose of this review is not to repeat those works but to complement them by focussing specifically on useful data that will help build a better understanding of CI (inter)dependencies and service usage within and across sectors.

Table 2: *List of sector-specific data sources and their usefulness for CI interdependency modelling in MIRACA.*

Sector type	Source	Usefulness for CI systems modelling

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Electricity flow network	PyPSA-Eur (Hörsch et al., 2018), ENTSO-E (Hirth et al., 2018)	Location, connectivity and operational data on power plants, substations, transmission overhead lines to infer electricity supply and demand.
Oil and Gas network and flows	SciGRID Gas (Pluta & Lünsdorf, 2020), ENTSOG Transparency platform (Lustenberger et al., 2019), GIE's AGSI Transparency Platform (Fernández-Blanco Carramolino et al, 2022)	Location and connectivity of European gas pipeline network between production sites, gas terminals, storage, and compressors. Data on daily storage, supply, flow and consumption of gas.
Future energy network	PCI Transparency Platform (Hirth et al., 2018), ENTSO-E TYNDP (EC, 2021), Offshore Energy Structures (Martins et al, 2023)ENTSO-E TYNDPOffshore Energy Structures	Location, operational and connectivity information on future energy projects and assets.
Road network and flows	TEN-T Corridor (CEDR, 2020), OpenStreetMap (Koks et al., 2023), ETISplus (Speth et al, 2022), Eurostat (Lahti et al., 2017), UNECE E-Roads Census (UNECE, 2010)	Location and connectivity of roads and bridges across Europe. Statistics and estimates on vehicle numbers, freight tons and truck volumes, passengers in Europe in 2020, with freight estimates projected till 2030.
Railway networks and flows	TEN-T Corridor (CEDR, 2020), OpenRailwayMap (Bubeck et al., 2019), OpenStreetMap (Koks et al., 2019c), Eurostat (Lahti et al., 2017), UNECE E-Rail Census (UNECE, 2010)	Location and connectivity of railways stations, junctions, bridges, electrification (dependence on electricity). Statistics and estimates on freight train numbers, and passenger numbers in Europe in 2020.
Inland and maritime port networks and flows	Global Ports data (Verschuur et al., 2022a), Eurostat (Lahti et al., 2017)	Location and connectivity between inland ports in Europe and between maritime ports

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		globally. Statistics of port tonnages, and passenger numbers with commodity/industry level breakdowns.
Airport networks and flows	Air Cargo Transport Network (Bombelli et al., 2020), OurAirports, Eurostat (Lahti et al., 2017)	Location and connectivity between airports in Europe and globally. Statistics of air freight cargo and passenger numbers.
Multi-modal transport flows	Eurostat (Lahti et al., 2017)	Statistics and estimates on freight and passenger numbers in Europe by modal-split in 2020.
Telecom assets	OpenCellID (Ulm et al., 2015), OpenStreetMap Telecoms features	Locations of telecoms masts, cell towers, data centres, exchanges and cables. Topology can be built from it to infer connectivity.
Education assets	ESPON school locations (Kompil et al., 2022)	Point locations of primary and secondary schools for 2016 and 2021. Useful for linking to electricity, telecom and road networks.
Health assets	Global HealthSites (Saameli et al., 2018), Eurostat Healthcare services.	Point locations of health sites at the global scale and for Europe. Useful for linking to electricity, telecom and road networks.
Building datasets	EUBUCCO (Milojevic-Dupont et al., 2023), GHSL-BUILT-H (Pesaresi & Politis, 2022)	Europe-wide polygon vector and raster areas (100m) of residential and non-residential buildings with estimates for 2020, 2025 and 2030. Useful for inferring the type of demand (household or

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		businesses) for infrastructure services.
Population datasets	GHS-POP (Schiavina et al., 2023)	Europe-wide raster areas (100m) of population estimates for 2020, 2025 and 2030. Useful for mapping populations to all CI assets.
Land-use datasets	CREODIAS (Malinowski et al, 2020)	Europe-wide real-time and historic raster areas (10m) of 13 land use classes. Useful for mapping types of economic activity to CI assets.
Economic activity datasets	Eurostat supply-use and trade datasets, EU MRIO data (Huang & Koutroumpis, 2023) EU MRIO data	Datasets of macroeconomic industry/sector level activity and trade at the NUTS2 level regional classification in Europe. Useful for mapping the economic value of industry specific activity that would be dependent on CI networks.

The review of the above datasets demonstrates that there is good quality spatial data at CI asset scale along with disaggregated buildings, population, land use, and economic activity. Such data provide a good starting point towards creating CI network models with service flows. However, there are a number of data limitations that would require gap filling.

Firstly, to the best of our knowledge, there is no database in existence that maps CI interdependencies in Europe, across two or more of energy, transport and telecom, health, and education assets. The above review has noted that information on the electrification of railway lines is available, from which the dependence of railways on electricity can be inferred. In Great Britain, detailed data on interdependency mapping for the railway network has been created by collecting CI asset data at more granular levels such as signalling, heating, SCADA systems (Pant et al, 2016; Ilalokhoin et al., 2023), but such detailed information would be difficult to obtain at the pan-European scale. Again, for Great Britain, a coarser level of CI interdependency data has been created for electricity, telecoms, water, roads and railway networks by inferring the nearest

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connectivity between CI assets that are in close proximity (Pant et al., 2022). Similar principles could be applied to MIRACA.

Secondly, there are no open pan-European datasets on electricity distribution networks available, which is a major data gap. Generally, electricity distribution networks are most vulnerable to cascading failures due to the sparse and radial nature of the networks (e.g., where one substation might be the only one supplying electricity to a whole community) (Thacker et al., 2018). Also, in most cases, other CI networks and assets will connect with the electricity network at the distribution level, rather than transmission (except for natural gas network). Potential solutions for MIRACA to gap fill this data requirement would be to explore methods for creating synthetic electricity networks (Thacker et al., 2018) from some samples of non-synthetic distribution network data created at the European urban scale (Koirala et al., 2020).

Thirdly, similar to electricity networks, the data on distribution networks for telecom systems are also lacking in addition to the limited information on connectivity between assets in the existing data that has been identified through this review. Analysis from Great Britain has shown that telecom networks are designed in a multi-layered core structure where, at the innermost layer, all assets are connected to each other, and at the outermost layer, the network structure is radial (Pant et al., 2022). Similar principles could be applied to MIRACA.

Fourthly, while the review has identified existing electricity and transport datasets and models with network flows, there is a need to develop standardised output metrics for these or the telecom networks. For example, there are no datasets that inform us about the spatial connectivity of health centres, education buildings, population and businesses to the electricity, telecom and transport networks. The development of these datasets is needed in MIRACA, which this review has identified as a necessary next step.

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5. Conclusions and future opportunities

This review, for the MIRACA project WP2 Task 2.1, has focussed on CI interdependencies in the context of energy, transport, telecom networks and health and education sites. It has demonstrated that the case for considering CI interdependencies in vulnerability and risk modelling is a very strong one, supported by real-world instances of large-scale cascading failure events. Due to interdependencies, instances of localised CI failures can propagate beyond an individual CI system and create socio-economic impacts at multi-country scales. There is a strong policy focus at the pan-European level on incorporating interdependencies in CI climate risk assessments and moving away from the siloed nature of CI resilience planning. The latest Critical Entities Resilience Directive (CER) of the European Union reinforces this notion. Hence, a key takeaway from this review is that it is very relevant for the MIRACA project to focus on CI interdependency modelling for wider socio-economic impact analysis.

Taking a system-of-systems approach that considers interconnectivity between different CIs modelling approaches was found to be the most pragmatic approach to follow, a view supported by a large body of current research covered in this review. Towards creating the CI system-of-systems models the most relevant typologies and definitions of the CI interdependencies proposed in the literature were next identified. It was concluded that a coherent system-of-systems approach would involve capturing and modelling geographic, functional (combination of physical and cyber), social, market and economic, budgetary and policy, as well as culture and norm interdependencies. The different classes of interdependency modelling approaches adopted over the years were reviewed, which included networks science-based models, expert scenario-based methods, empirical evidence-based and historical data-driven methods, macroeconomic IO and its inoperability-IO models, macroeconomic CGE-based methods, aggregated systems dynamics-based models of stocks and flows, agent-based models, Bayesian network-based approaches, and population mobility models. Based on the data requirements, computational complexity, and scalability of each of these modelling approaches, it was concluded that no single approach was sufficient by itself in capturing CI interdependencies across multiple spatial and temporal scales. However, the most relevant system-of-systems approach for modelling CI cascading failure propagation in MIRACA to follow was identified to be the one that combined network science-based models with the other types of models including population mobility models and macroeconomic IO models.

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The development of any system-of-systems model would be heavily dependent upon the quality of spatial datasets. From a review and compilation of the current state-of-the-art datasets it was concluded that there is good quality spatial open-source data suitable for pan-European CI networks mapping and flow modelling. However, several gaps with existing data were identified including: (1) lack of any datasets on (inter)dependency linkages between two or more CIs; (2) no open-source data on pan-European electricity distribution networks that could potentially lead to an underrepresentation of network interdependency and cascading failure estimations; (3) limited information on telecom asset connectivity and no data for mapping telecoms distribution networks as well; and (4) no data or models on consistent measures of network usage across CIs, which would help in the intercomparison of vulnerability and risk outcomes across different CIs.

All the above data and model gaps provide opportunities for the MIRACA project's next steps towards developing a system-of-systems framework for interdependent CI vulnerability and risk assessments. The review has identified some of the ways data gaps in creating networks and (inter)dependencies could be filled based on existing research. Also, the opportunity for combining spatial datasets on CI assets, networks, population, buildings, and macroeconomic activity for creating consistent socio-economic service usage measures across all CIs is quite clear.

It is also quite important to integrate the detailed spatial data analysis techniques with user groups who are interested in risk governance (Van Asselt et al., 2015). A review comparing CI research using data-driven geospatial analysis methods with CI research using risk governance perspectives, highlighted the opportunity to build synergies between two approaches by combining rich data analysis and visualisations to inform risk communication for decision-making (Arvidsson et al., 2021). This is an opportunity for MIRACA which will be explored through stakeholder engagements involving the five Use Cases (UC) proposed in the project. These UCs span a wide range of geographies exploring climate hazard risk impacts on: (1) the Trans-European Transport Network (TEN-T) Corridor; (2) services dependent upon electricity and transport networks in Spain's Catalonia region; (3) services dependent upon electricity and telecom networks in The Netherlands; (4) health and education services in Greece; and (5) power and gas networks in Slovenia. Understanding how infrastructure planners, operators, and users evaluate CI interdependencies in these UCs will provide MIRACA with opportunities to obtain data and generate policy-relevant outcomes.

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A final key opportunity for MIRACA is to explore and make the case for exploring new CI interdependencies as being viable options for strengthening systemic resilience. The general policy and research community have only focussed on CI interdependencies with the lens of risks (Ouyang et al., 2014; Sun et al., 2022) and following that up with making the case for prioritising existing interdependencies to improve CI resilience (Lee II et al., 2007; Almoghathawi et al., 2021; Der Sarkissian et al., 2022; Ilalokhoin et al., 2023). However, these perspectives ignore the possibility of exploring options for strengthening CI coupling in a proactive way towards improving the redundancies and robustness across CI networks, which could reduce failure cascades by providing backups and alternative routes (Carhart & Rosenberg, 2016; Grafius et al., 2020). Studies that have experimented with scenarios of increasing CI coupling between electricity and telecom networks in Great Britain (Pant et al., 2022) and Poland (Korkali et al., 2017) have demonstrated that the network failure cascades get reduced significantly due to improved coupling done strategically. It is a worthwhile exercise to discuss such possibilities with MIRACA stakeholders and incorporate them in the adaptation planning within the UCs.

In conclusion, from this review, there are a significant number of existing methodological and data advances that have been identified for CI interdependency modelling. Several new methodological and data opportunities have also been identified for further developments of system-of-systems models in MIRACA. The review has provided useful insights to further explore in MIRACA towards making the risk and resilience outcomes more relevant to decision-makers and providing new opportunities for CI planning in Europe.

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