Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26152-cd

Model for Interdependent Critical Flows: Addressing Cross-Sectoral Vulnerability

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Societal well-being depends on the continuous operation of vital functions that critically depend on access to flows of essential commodities and services across sectors, i.e., Critical Flows. Understanding these cross-sectoral flow interdependencies requires modelling approaches capable of integrating both service and transfer interdependencies across different scales of analysis. Many existing modelling approaches typically either address the micro scale, capturing asset-specific vulnerabilities of critical infrastructures or supply chains, or the macroscale, dealing with a geopolitical view on security of supply and policy dynamics. Here, we propose a complementary meso-level modelling framework that enables the systematic representation of interdependency among critical functions through a flow perspective. Modelling these flows and their interdependencies is essential to capture cascading effects across vital societal functions. The model represents critical flows based on a modular system where critical infrastructure commodities, forms, and functions enable pathways from sources (productions, imports) to sinks (end-use, exports). Service and transfer interdependencies are explicitly represented in the formulation, allowing cross-sectoral effects to be captured within a unified modelling structure. The model integrates structural elements (nodes, links, spatial) with functional ones (capacities, dependencies, flows) and can be extended with temporal dynamics to account for disruption, buffer, restoration, and policy interventions. It employs a modular and incremental modelling approach, enabling continuous refinement from static flow representations to dynamic case-specific scenario simulations. This modelling development provides a foundation to study and understand cross-sectoral functionality and interdependency, quantify potential system-wide vulnerabilities, and support the strengthening of systemic resilience against diverse disruptions and hazards across sectors. Further, the underlying framework is also useful for researchers, practitioners, and policymakers to integrate resilience management, prioritize resources, and support resilience planning in complex interdependent socio-technical systems and critical entities.

Keywords: Critical flows, Vital societal functions, Critical entities, Interdependency, Cross-sectoral vulnerability, Meso-level modelling, Systemic resilience.

1. Introduction

Modern societies depend on continuous flows of essential goods and services (e.g. energy, transportation, information, food) that are delivered through complex interconnected networks of infrastructures and supply chains. Ensuring the security of these flows is increasingly challenging as emerging risks, from climate change and geopolitical shifts to hybrid and cyber threats, introduce new vulnerabilities (Lindström and Johansson 2022). The growing interconnectedness of infrastructure sectors, combined with the globalization and leanness of supply chains, has increased complexity and heightened systemic fragility. Such progress exposes vulnerabilities in socio-economic activities and increases the probability of localized failures propagating into broader societal crises (Liu and Renn 2025).

Consequently, there is a growing recognition of the urgent need not only focus on isolated, asset-specific protection strategies. It is increasingly essential to develop and reinforce strategic flows that span across sectors, ensuring that critical resources and services remain operational under a wide range of hazards

(Pursiainen 2018). By fostering cross-sectoral resilience, societies can better anticipate, absorb, and adapt to diverse challenges, thereby safeguarding critical entities in the face of both anticipated and unforeseen disruptions (Council of the European Union 2022).

Critical infrastructure operates as a tightly coupled system-of-systems, where interdependencies can improve performance under normal conditions but also enable cascading failures during disruptions. Existing approaches to represent these interdependencies span empirical, agent-based, system dynamics, economic, and network/flow-based methods (Ouyang 2014, Sun et al. 2022). These approaches often lie at two level, each with notable limitations. Micro-level models typically focus on individual assets or localized networks (e.g., Goldbeck et al. 2019, Dubaniowski et al. 2020, Nocera et al. 2024), yielding detailed technical insights but lacking the breadth to incorporate cross-sector interdependencies over larger regions (Ouyang 2014, Sun et al. 2022). Conversely, macro-level assessment, such as multi-national supply security assessments or input-output models based on national economic accounts, often provide a big-picture overview yet often treat each sector either in isolation or with static aggregate interdependency assumptions. As a result, traditional asset-by-asset risk assessments and high-level sector analyses fall short of fully capturing how disruptions evolve and compound across interconnected vital service and goods.

Therefore, a holistic understanding of how diverse systems connect and depend on each other (e.g., Thacker et al. 2017) remains limited. Their heterogeneous nature spanning different resources, scales, and types makes collecting data and analyses on them challenging (Johansson et al. 2016). Addressing this gap is crucial, as it is necessary to capture these interdependencies at broader scales to understand systemic vulnerabilities at regional and national levels (Månefjord and Johansson 2024). Furthermore, the urgency of addressing this gap is reinforced by European Union (EU) to replace earlier protection-oriented framing with explicit requirements focused on resilience assessment, and measures to ensure continuity of essential services by critical entities (Council of the European Union 2022). This new directive demand approaches that address cross-sector dependencies and cascading effects, necessitating a model that can support prioritization across sectors under diverse hazards, including deliberate acts such as sabotage and hybrid activities (Pursiainen and Kytömaa 2023).

In Sweden, these needs are sharpened by the renewed emphasis on total defence, which frames security as a whole-of-society endeavour integrating military defence with civil defence and continuity of critical services (Government Offices of Sweden 2023). The fundamental structure guiding the total defence effort is the outlining of 12 preparedness sectors (c.f. critical infrastructure sectors) and 61 vital societal functions (Swedish Civil Defence and Resilience Agency 2026). Swedish security assessments emphasize persistent hostile activities against these vital societal functions and critical infrastructures, reinforcing the need for cross-sectoral analysis that can capture how disruptions propagate through dependencies among entities and supply chains (Swedish Security Service 2024). Collectively, recent developments motivate modelling approaches that regardless of hazards can support resilience planning under uncertain, compound, and adversarial conditions (Trump et al. 2025).

Here, we propose a meso-level model to represent critical flows in a system-of-systems context. At this scale, interdependent infrastructure networks and flows are modelled in a way that preserves essential cross-sectoral interactions without the burden of full asset-level complexity. This approach affords a level of abstraction that is still sufficient to obtain a valid representation of infrastructures and functions connectivity and event dynamics. It provides a dynamic and flexible simulation architecture for tracing how services and resources flow between sectors and how disruptions propagate through these interconnections. By representing these linkages at an intermediate scale, the framework enables simulation of cascading effects and offers a tractable yet comprehensive basis for assessing multi-sector resilience under disruptive scenarios. This approach captures the essential structural and functional interdependencies of the system, providing a foundation for evaluating strategies to enhance systemic resilience.

2. Concept of Critical Flows

Johansson et al. (2016) and Lindström and Johansson (2022) introduced the concept of *Critical Flows*, as the heterogeneous and interlinked streams of people, goods, energy, or information that are essential for societal, safety and security. They can take vastly different forms and span multiple scales, often cut across sector boundaries, emphasizing interconnectedness within a resilience context. For example, how energy, food, and transportation systems depend on one another, thus safeguarding these flows simultaneously requires both protection (against external disruptions) and resilience (the capacity to anticipate, tolerate, recover, and adapt). Figure 1 exemplifies how critical flows from meso-level are positioned in the intersection and integration of critical infrastructures resilience, supply chain management and security of supply.

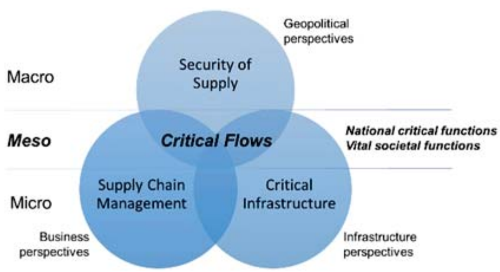

Fig. 1. Notion and basis of critical flows connected to the domains of critical infrastructures, supply chain management, and security of supply.

In conceptualization, modelling critical flows can be segregated into three tiers. The first tier consists of an aggregate, network-based model of individual flow networks and their interdependencies (nodes representing sources/destinations of a flow and links representing pathways), abstracting each flow into a coarse network with its geographical location to allow cross-comparison. In the second tier, the structural and functional details are embedded into each flow, such as capacities and supply and demand variations. Lastly, temporal dimensions and operational specifics such as buffers and stockpiles are available in the third tier. This tiered approach balances detail with tractability, aiming to oversee cross-sector interactions while still providing useful insights on vulnerabilities.

Here, we focus on second tier, outlining the interdependency modelling across flows and sectors.

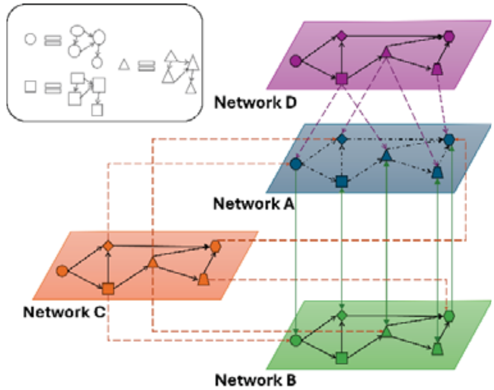

Fig. 2. Collection of interdependent networks. Colour denotes the network sector, while dashed lines represent interdependency between networks and solid lines highlight a flow. Dashed and dotted lines in network A indicating how its flow traversing its sector, although it passes through network B utilising its network to reach the destination. Inset, upper left illustrates how specific critical flows hence comprises of interaction across networks.

We extend structured tiers into mathematical model to broaden the view beyond individual critical infrastructures and supply chains to consider security of supply that these collectively enable. The objective of the model is to enable mapping the entire landscape of critical flows in society. Figure 2 presents an abstract representation of how multiple networks interlink to each other across sectors. In essence, given interdependencies across these networks, particular flow networks can be identified.

3. Modelling Framework

Modelling interdependent system-of-systems from critical flow perspectives requires a framework that allows capturing both the structural configuration and the functional dynamics across a vast variety of systems. Following this, network-based modelling, both topological representation and flow behaviours, is advantageous (Johansson et al, 2010, Ouyang 2014, Sun et al. 2022). This approach allows scalable insights across varying levels of abstraction, which is essential to understand the potentials of multi-scale disruption to nationwide infrastructure networks (Thacker et al. 2017, Sun et al. 2022). Recent developments of modelling focus on having modularity where object-oriented representation applied to accommodate various system's characteristics and network types (e.g., Sharma and Gardoni 2022, Mühlhofer et al. 2023, Nocera et al. 2024). Though previous studies mostly focused on micro-level, asset-specific representations (e.g., Goldbeck et al. 2019, Dubaniowski et al. 2020), these modular thinking helps demonstrate the utility of treating societal systems as interconnected flow networks.

Here we adopt a meso-level approach, enabling the modular representation of interdependencies and flows across sectors and vital societal functions, without relying on detailed, often classified, asset-level data. Our model draws on previous object-oriented templates of interdependent infrastructures introduced by Sharma and Gardoni (2022) and inter-nodal demand-supply shift concept explored by Galbusera et al. (2020) and Lu et al. (2022).

Consider a flow $\mathscr{s}$ in a system-of-systems $\mathcal{S}$ traversing through an acyclic network $\mathcal{G}^{[\mathscr{s}]} = \left(\mathcal{V}^{[\mathscr{s}]}, \mathcal{E}^{[\mathscr{s}]}\right)$. This network consists of $\mathcal{V}^{[\mathscr{s}]} = \{1, \cdots, v\}$ set of nodes and $\mathcal{E}^{[\mathscr{s}]} \subseteq \{(i,j) \in \mathcal{V}^{[\mathscr{s}]} \times \mathcal{V}^{[\mathscr{s}]} : \mathrm{i} \neq j\}$ set of edges, both of which are associated with geographical references.

3.1. *Nodal Attributes*

Nodes here refer to smaller sub-systems operating on micro-level, e.g., food productions factories or electricity generation plants delivering supplies to the network(s). Each node v can have multiple tensor variables such as demand $\boldsymbol{\delta}$, supply $\boldsymbol{\sigma}$, or both, the quantity of which depends on its state $\boldsymbol{\chi}$ and inherent vector parameter(s) $\boldsymbol{\Theta}$ at any time t.

$$\boldsymbol{\delta}_v^{[\mathscr{s}]}(t) = \boldsymbol{\delta}_v^{[\mathscr{s}]}\left[\boldsymbol{\chi}_\delta^{[\mathscr{s}]}(t), \boldsymbol{\Theta}_\delta^{[\mathscr{s}]}\right], \tag{1}$$

$$\boldsymbol{\sigma}_v^{[\mathscr{s}]}(t) = \boldsymbol{\sigma}_v^{[\mathscr{s}]}\left[\boldsymbol{\chi}_\sigma^{[\mathscr{s}]}(t), \boldsymbol{\Theta}_\sigma^{[\mathscr{s}]}\right], \tag{2}$$

$$\boldsymbol{\chi}_\delta^{[\mathscr{s}]}(t) = \boldsymbol{\chi}_\delta^{[\mathscr{s}]}\left[\boldsymbol{x}^{[\mathscr{s}]}, \boldsymbol{D}(t)\right] \tag{3}$$

The state of these components is constructed of the interaction between its initial condition $\boldsymbol{x}$ with disruption function $\boldsymbol{D}$, accounting for a disruption scenario.

3.2. *Flows*

In this study, flows refer to the ongoing movements and exchanges of goods and services that underlie vital societal functions. A flow can be tangible, e.g. the transport of food, the supply of electricity, or intangible, like digital communications or human expertise (Johansson et al. 2017). As an abstract representation in a network, an edge connecting two nodes allows flow $\boldsymbol{f}$ traversing by consuming capacity $\boldsymbol{\gamma}$ therein to deliver supplies from a source node to a demand node, such that:

$$\boldsymbol{f}_{ij}^{[\mathscr{s}]}(t) \leq \boldsymbol{\gamma}_{ij}^{[\mathscr{s}]}(t), \tag{4}$$

where this edge capacity is based on its state and inherent vector parameter(s), similar to supply and demand variables.

$$\boldsymbol{\gamma}_{ij}^{[\mathscr{s}]}(t) = \boldsymbol{\gamma}_{ij}^{[\mathscr{s}]}\left[\boldsymbol{\chi}_\gamma^{[\mathscr{s}]}(t), \boldsymbol{\Theta}_\gamma^{[\mathscr{s}]}\right], \tag{5}$$

The relation between demand, supply, and constraints determines the corresponding flow within and across networks. Subsequently, we can consider the case in which a node's fulfilled demand becomes a new supply for further downstream flow in another network. Let $k \in \mathcal{V}^{[\mathscr{s}]}$, then the flow can be extended from Eq. (4), as follows:

$$\boldsymbol{f}_{jk}^{[\mathscr{s}]}(t) \leq \boldsymbol{\gamma}_{jk}^{[\mathscr{s}]}(t), \tag{6}$$

The demand–supply interlink can be represented as either an intermediate or conversion node, depending on the type of critical flow it accommodates. The main goal of solving these flows is to minimize the unmet demand $\boldsymbol{v}$, using network flow algorithms, such that:

$$\min \boldsymbol{v}^{[\mathscr{s}]}(t) \tag{7}$$

3.3. *Interdependency*

Interdependency between different networks can be either one-way or bi-directional, which consist of:

- *Service interdependency*, where a network depends on another network to enable its flow availability.

- *Transfer interdependency*, where a network utilizes another network to transfer either some or all its flows.

3.3.1. *Service Interdependency*

To account for service interdependency, where a component requires service(s) or function(s) from other system(s) to convert demands it receives to supplies, we introduce a conversion factor ψ. This factor is defined as the weighted geometric mean of the ratios of all necessary services $\boldsymbol{\phi}$. Let $\mathcal{S} = \{\mathcal{A}, \mathcal{B}, \mathcal{C}, \ldots\}$, then conversion factor ψ of a component in network $\mathcal{A}$ will be:

$$\psi_v^{[s]}(t) = \prod_{s \in \mathcal{S} \setminus \{\mathcal{A}\}} \left(\frac{\boldsymbol{\phi}_v^{[s]}(t)}{\boldsymbol{\phi}_v^{[\mathcal{A}]}(t)} \right)^{\omega_s}, \qquad (8)$$

where

$$\sum_{s \in \mathcal{S} \setminus \{\mathcal{A}\}} \omega_s = 1, \qquad (9)$$

$$\psi_v^{[s]}(t) \in [0,1], \qquad (10)$$

and

$$\boldsymbol{\phi}_v^{[s]}(t) = \boldsymbol{\phi}_v^{[s]}\left[\boldsymbol{\chi}_\phi^{[s]}(t), \boldsymbol{\Theta}_\phi^{[s]}\right] \qquad (11)$$

The non-negative weight ω can be set depending on the importance of the service needed for continued operation. If such information does not exist, it can be set to have an equal weight, such as:

$$\omega_s = \frac{1}{|\mathcal{S}| - 1} \qquad (12)$$

The conversion factor then changes the values of the inherent vector parameter given it reliance on services acquired. For example, converting the supply or demand values will proceed following its reliance on the service(s) it must have, in line with traditional system-of-systems and critical infrastructure literatures (Ouyang 2014, Sun et al. 2022).

$$\boldsymbol{\sigma}_v^{[s]}(t) = \boldsymbol{\sigma}_v^{[s]}\left[\boldsymbol{\chi}_\sigma^{[s]}(t), \boldsymbol{\Theta}_\sigma^{[s]}, \boldsymbol{\delta}_v^{[s]}(t), \psi_v^{[s]}(t)\right] \qquad (13)$$

3.3.2 *Transfer Interdependency*

Transfer interdependency captures the fact that many flows are enabled across networks, and where these networks support each other. This type of interdependency is seldomly addressed within system-of-systems and critical infrastructure literature, but crucial to understand critical flows' behaviour. To account for this, we introduce a conversion node τ to convert one flow (e.g., from $\mathcal{A}$'s network) to another network (e.g., $\mathcal{B}$'s network) using conversion factor μ, following:

$$\boldsymbol{f}_{\alpha\beta}^{[\mathcal{A}]\to[\mathcal{B}]}(t) = \boldsymbol{\sigma}_v^{[\mathcal{A}]}(t) \odot \mu_\tau^{[\mathcal{A}]\to[\mathcal{B}]} \qquad (14)$$

where

$$\boldsymbol{f}_{\alpha\beta}^{[\mathcal{A}]\to[\mathcal{B}]}(t) \leq \boldsymbol{\gamma}_{\alpha\beta}^{[\mathcal{A}]\to[\mathcal{B}]}(t) \qquad (15)$$

After receiving the supply and demand from the first network, the second network becomes a network that enables the delivery other networks' flow, and transfer back the commodity to the first flow. This kind of transfer can occur across multitude of networks, not only two.

$$\boldsymbol{\delta}_v^{[\mathcal{A}]}(t) \leq \boldsymbol{\sigma}_v^{[\mathcal{B}]}(t) \odot \mu_\tau^{[\mathcal{B}]\to[\mathcal{A}]} \qquad (16)$$

4. Illustrative Examples

To demonstrate the proposed formulation, we consider two separate cases. In the first case, critical flows operate within their own specific network, where Network $\mathcal{A}$ (food processing) is service dependent on Network $\mathcal{B}$ (electricity system). While the second case is network A (railway transport) has transfer dependency on Network $\mathcal{B}$ (road transport). This set-up allows for the exemplifying service dependency and transfer interdependency that are crucial for ensuring upkeeping of flows to fulfil demands across networks.

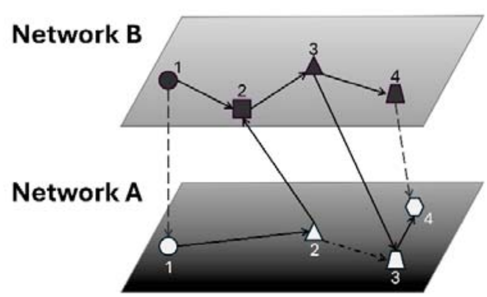

Fig. 3. Example of critical flows passing through their own network. Each flow is enabled by its own network where Network A is having either a service or

transfer dependency to Network B. Dashed lines represent service dependency and solid lines represent transfer dependency from Network A to Network B.

4.1. *Flows with service interdependency*

Let Network $\mathcal{A}$ (food processing) be determined by node 1 (farms) to node 4 (food manufacturing plant), that require service from nodes 1 and 4 from Network $\mathcal{B}$ (electricity). Both flows traverse their own topology and are assumed to be initially fully operational. At first, the supply in $\mathcal{A}$ would be:

$$\boldsymbol{\sigma}_1^{[\mathcal{A}]}(t) = \boldsymbol{\sigma}_1^{[\mathcal{A}]}\left[\boldsymbol{\chi}_\sigma^{[\mathcal{A}]}(t), \boldsymbol{\Theta}_\sigma^{[\mathcal{A}]}\right], \quad (17)$$

and the demand in node 4:

$$\boldsymbol{\delta}_4^{[\mathcal{A}]}(t) = \boldsymbol{\delta}_4^{[\mathcal{A}]}\left[\boldsymbol{\chi}_\delta^{[\mathcal{A}]}(t), \boldsymbol{\Theta}_\delta^{[\mathcal{A}]}\right], \quad (18)$$

where

$$\psi_1^{[\mathcal{A}]}(t) = \left(\frac{\boldsymbol{\phi}_1^{[\mathcal{B}]}(t)}{\boldsymbol{\phi}_1^{[\mathcal{A}]}(t)}\right) \quad (19)$$

Then the flow is passing through Network $\mathcal{A}$ given the capacity.

$$\boldsymbol{f}_{14}^{[\mathcal{A}]}(t) \leq \boldsymbol{\gamma}_{14}^{[\mathcal{A}]}(t) \quad (20)$$

Similar computation occurs in node 4 as well, where it receives service from node 4 of Network $\mathcal{B}$. In this example the flow in Network $\mathcal{A}$ only requires one service from Network $\mathcal{B}$, hence we only use simple calculation of service continuity without geometric mean and weight. Hence, a disruption in Network $\mathcal{B}$ will affect the supply in Network $\mathcal{A}$. In concrete, when there is reduction of electricity, then the food processing will be disrupted as well. Finally, the unmet demand of Network $\mathcal{A}$, which is impacted by disruption, follows:

$$\boldsymbol{v}^{[\mathcal{A}]}(t) = \sum_{v \in \mathcal{V}} \left(\boldsymbol{\delta}_v^{[\mathcal{A}]}(t) - \boldsymbol{f}_{v-1v}^{[\mathcal{A}]}(t)\right) \quad (21)$$

4.2. *Flows with transfer interdependency*

In the second case, we lay out the same designation (see Fig. 3). Due to a disruption of the link between node 2 and 3 (both railway stations) in Network $\mathcal{A}$ (e.g., falling bridge, landslide, or antagonistic attacks), the flow of trains in Network $\mathcal{A}$ no longer have enough capacity between these intermediate nodes to enable the flow. Thus, it relies on the road system (Network $\mathcal{B}$) to fulfil the objective delivering people from node 1 to node 4. Node 2 and 3 in $\mathcal{A}$ and $\mathcal{B}$ have the capability (i.e., resources are in place to enable this) to act as transfer nodes where people from Network $\mathcal{A}$ to Network $\mathcal{B}$ can be transferred by using converted means (from a train to several buses) through. Thus,

$$\boldsymbol{f}_{22}^{[\mathcal{A}]\to[\mathcal{B}]}(t) = \boldsymbol{\sigma}_2^{[\mathcal{A}]}(t) \odot \mu_2^{[\mathcal{A}]\to[\mathcal{B}]}, \quad (22)$$

where

$$\boldsymbol{f}_{22}^{[\mathcal{A}]\to[\mathcal{B}]}(t) \leq \boldsymbol{\gamma}_{22}^{[\mathcal{A}]\to[\mathcal{B}]}(t) \quad (23)$$

Once it traverses through the road network, the flow will follow all available pathways in the road network and return to the train network, if possible. This mechanism allows "push and pull" exchange between two networks. When the flow return to railway system (from node 3 of Network $\mathcal{B}$ to node 3 of Network $\mathcal{A}$), it needs to convert back, such that:

$$\boldsymbol{f}_{33}^{[\mathcal{B}]\to[\mathcal{A}]}(t) = \boldsymbol{\sigma}_3^{[\mathcal{B}]}(t) \odot \mu_3^{[\mathcal{B}]\to[\mathcal{A}]} \quad (24)$$

Finally, the unmet demand Network $\mathcal{A}$ now also considers Network $\mathcal{B}$, such that:

$$\boldsymbol{v}^{[\mathcal{A}]}(t) = \sum_{v \in \mathcal{V}} \left(\boldsymbol{\delta}_v^{[\mathcal{A}]}(t) - \boldsymbol{f}_{v-1v}^{[\mathcal{A}]}(t)\right) + \boldsymbol{v}_{[\mathcal{A}]}^{[\mathcal{B}]}(t), \quad (25)$$

where

$$\boldsymbol{v}_{[\mathcal{A}]}^{[\mathcal{B}]}(t) = \sum_{v \in \mathcal{V}} \left(\boldsymbol{\delta}_v^{[\mathcal{A}]\to[\mathcal{B}]}(t) - \boldsymbol{f}_{v-1v}^{[\mathcal{A}]\to[\mathcal{B}]}(t)\right) \quad (26)$$

Network $\mathcal{A}$ is hence using Network $\mathcal{B}$ to deliver its flows by transferring its supply and demand. Many critical flows in real life behave similarly where, due to capacity constrain in their own network, they use another network to fulfil their objective. We are exemplifying this with flow of people transferring between different modes of transportation (different vital societal functions, railways and roads), and the flow emerged combining both using train (node 1 to node 2) then change to road (node 2 to node 3) and return to train (node 3 to node 4). Due to this interconnection, disruption on the rail system could hamper the flow in the road system, exposing higher vulnerability.

5. Discussions

The two cases laid out in this study exemplify how critical flows can have various ways to operate and rely on different networks across sectors and vital societal functions. The first case, where flows have their own network topology, is prominent in backbone critical infrastructures such as electricity, water supplies, and fibre optic networks. These infrastructures tend to have extensive structures across regions and nations and to mainly have service dependency.

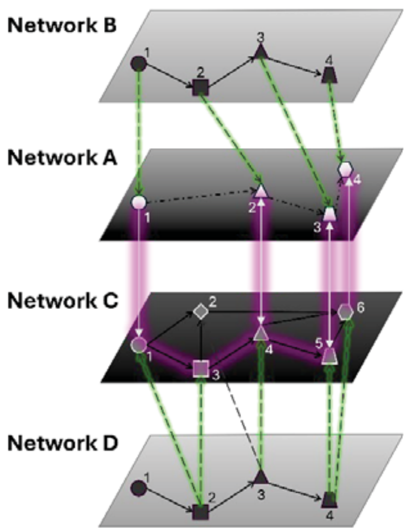

Fig. 4. Example of critical flows using both service interdependency and transfer interdependency. Each flow is enabled by its own network where Network A is having a service dependency to Network B and transfer dependency to Network C, and Network C depends on service from Network D. Dashed lines represent service dependency, solid lines represent transfer dependency, purple glow highlights the flow, and green glow highlights services affecting the flow.

Meanwhile, the second case showcased a type of critical flows that are enabled within and across different networks. Hence, these kinds of flows tend to be more exposed to cross-sectoral vulnerabilities due to their multi-network reliance. Real life examples of this type of flows are food supply, medicine and healthcare, financial and payment system, etc., which rely on transport infrastructure (transfer dependency) and/or telecommunication infrastructure to operate. However, they can have multiple options to ensure the flow. For example, if there is disruption to a road network to deliver foods, it may be able to switch to railway or air transport (e.g., helicopters), if one or more of those networks are available and resources to do so are in place.

In reality, critical flows are often reliant on both service and transfer interdependencies simultaneously. Figure 4 exemplifies of critical flows with both types of interdependencies. The flow in Network $\mathcal{A}$ (solid line with purple glow) is reliant on service from Network $\mathcal{B}$ (dashed line with green glow) and using Network $\mathcal{C}$ to deliver its commodity.

Network $\mathcal{C}$ is also reliant on service provided by Network $\mathcal{D}$, which in turn can also affect the flow of Network $\mathcal{A}$. Disruptions occur in one of these networks can hamper the operation of Network $\mathcal{A}$. It is hence essential to be able to model and analyse the interdependent behaviour of network across sectors and vital societal functions to understand systemic vulnerabilities.

Lastly, although it is not currently explicitly described in the model, all networks and hence flows are directly associated with geographical aspects. This designation in turn exposes another type of geographical interdependency that can expose networks and flows. The aim of this approach is to enable the analysis of a higher order indirect interdependencies across sectors and vital societal functions, as illustrated in Fig. 5. The identification and mitigation of these types of systemic vulnerabilities are critical towards improved societal resilience under adverse hazards and threats.

6. Conclusions and future works

This study introduces a novel meso-level model to address vulnerabilities of interdependent critical flows. This approach offers the ability for comprehensive, holistic and cross-sectoral views that bridges micro-level and macro-level analyses. The proposed model utilises modular design and captures both service and transfer interdependency, rarely addressed simultaneously. Ongoing development aims at inclusion of spatial, temporal, and operational dynamics in the model, with applied disruption and recovery analysis of the Swedish national critical flows.

Acknowledgement

This study is supported by the Joint Exchange of Data and Information on Critical Infrastructure (JEDI-CI) project funded by the Swedish Civil Defence and Resilience Agency (MCF), formerly known as the Swedish Civil Contingencies Agency (MSB).

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