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Assessment of cascading impacts across Europe: an innovative approach for a resilient infrastructure and society

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Introduction

This paper is part of a broader work under development within a European project named "**Multi-risk and risk-informed system for better local and regional disaster risk management (MEDiate)**" which aims to develop a decision support system (DSS) for disaster risk management. The MEDiate project will consider multiple interacting natural hazards and cascading impacts using a novel resilience-informed, service-oriented and people-centred approach that accounts for forecasted modifications in the hazard (e.g., climate change), vulnerability/resilience (e.g., aging structures and populations) and exposure (e.g., population decrease/increase), building on the consortium's existing strengths in this domain.

The impact of **climate change** is anticipated to heighten the vulnerability to multiple risks, influencing the scale, frequency, and geographic distribution of hazardous and disastrous events [2]. In this context, the necessity of embracing a multi-risk approach for evaluating the impacts of climate change is stressed by international organizations across different spatial levels, including the European scale.

One of the most concerning consequences of climate change involves the amplification of cascading impacts, where alterations in a specific aspect of climate or the environment trigger a series of reactions that propagate in multiple directions, intensifying overall impacts.

The intensification of **cascading impacts** in the context of climate change is due to intricate interdependencies, heightened vulnerability and exposure, disruption of ecosystems, social and economic inequalities, and interwoven infra-structure dependencies [2].

This report delivers identification and assessment of the primary types of cascading impacts in European areas as part of the MEDiate project.

Key concepts and Definitions

This section provides an overview of **key concepts and definitions** related to cascading impacts and critical infrastructure to ensure a clear understanding of the paper's content.

CI consists of **complex, geographically dispersed, nonlinear networks** interacting with human owners, operators, and users. They exhibit a high degree of interconnectedness and mutual interdependence. For instance, water and telecommunication systems rely on a continuous supply of electricity to maintain their routine operations, while electric power systems necessitate access to water and diverse telecommunication services for effective power generation and distribution [1].

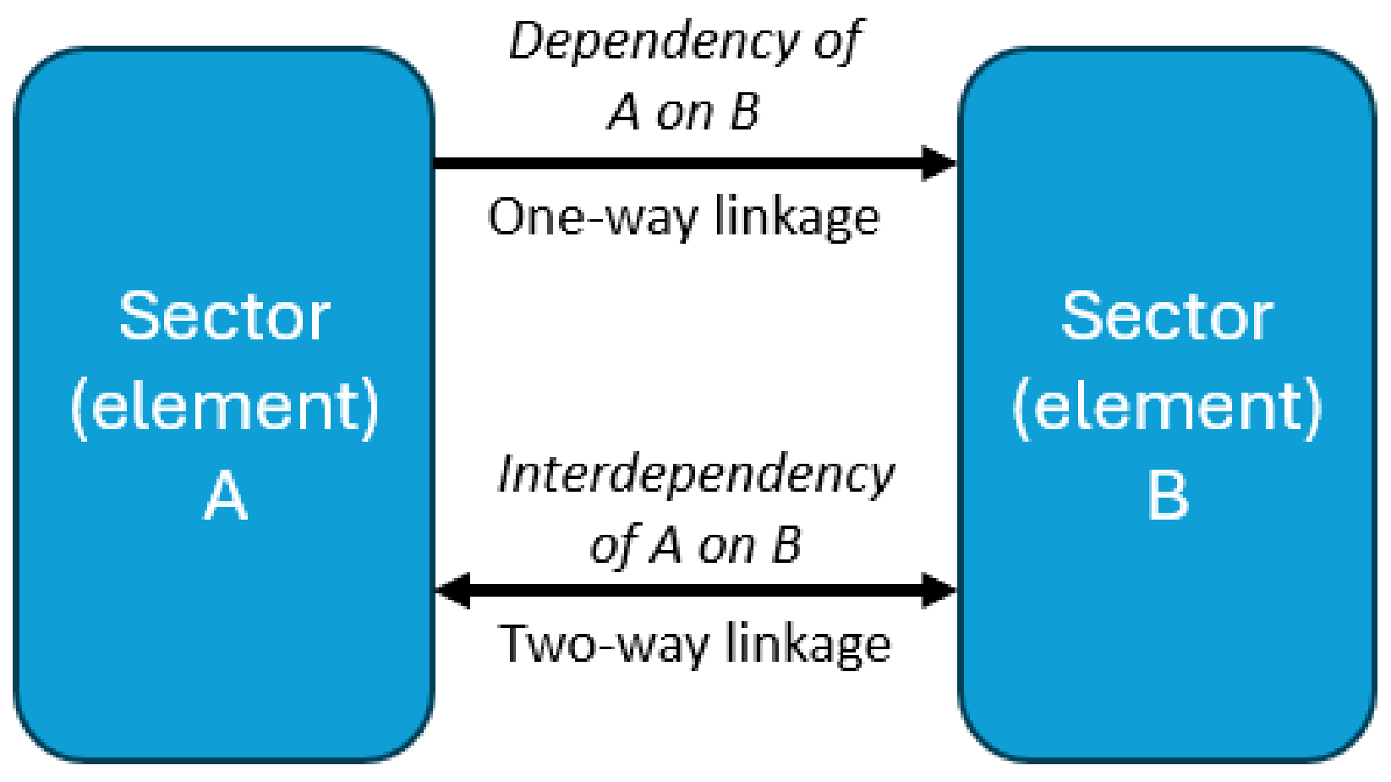
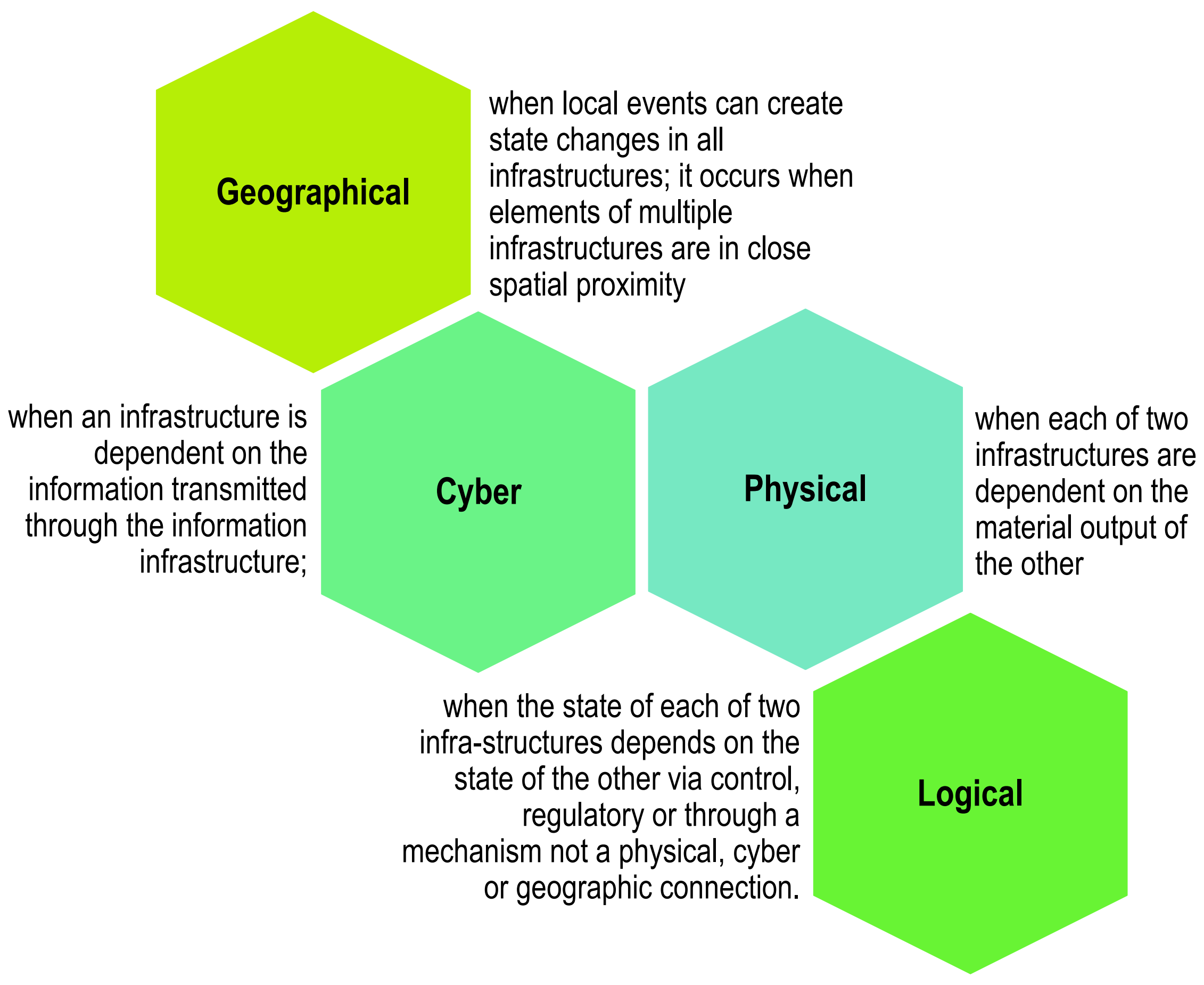


Figure 1: Types of linkages in a critical infrastructure system (adapted from Rehak, 2016)

In the literature several definitions of "dependency" and "interdependency" are present; however, the work of authors Rinaldi et al. [5] is pivotal in evaluating the links between elements. Rinaldi defines (see Fig. 1):

- **Dependency**: A linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other;
- **Interdependency**: A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other.

Rinaldi [5] demonstrated the interdependency of critical infrastructure elements and defined four types of links (see Fig. 2).



Geographical: when local events can create state changes in all infrastructures; it occurs when elements of multiple infrastructures are in close spatial proximity

Cyber: when an infrastructure is dependent on the information transmitted through the information infrastructure;

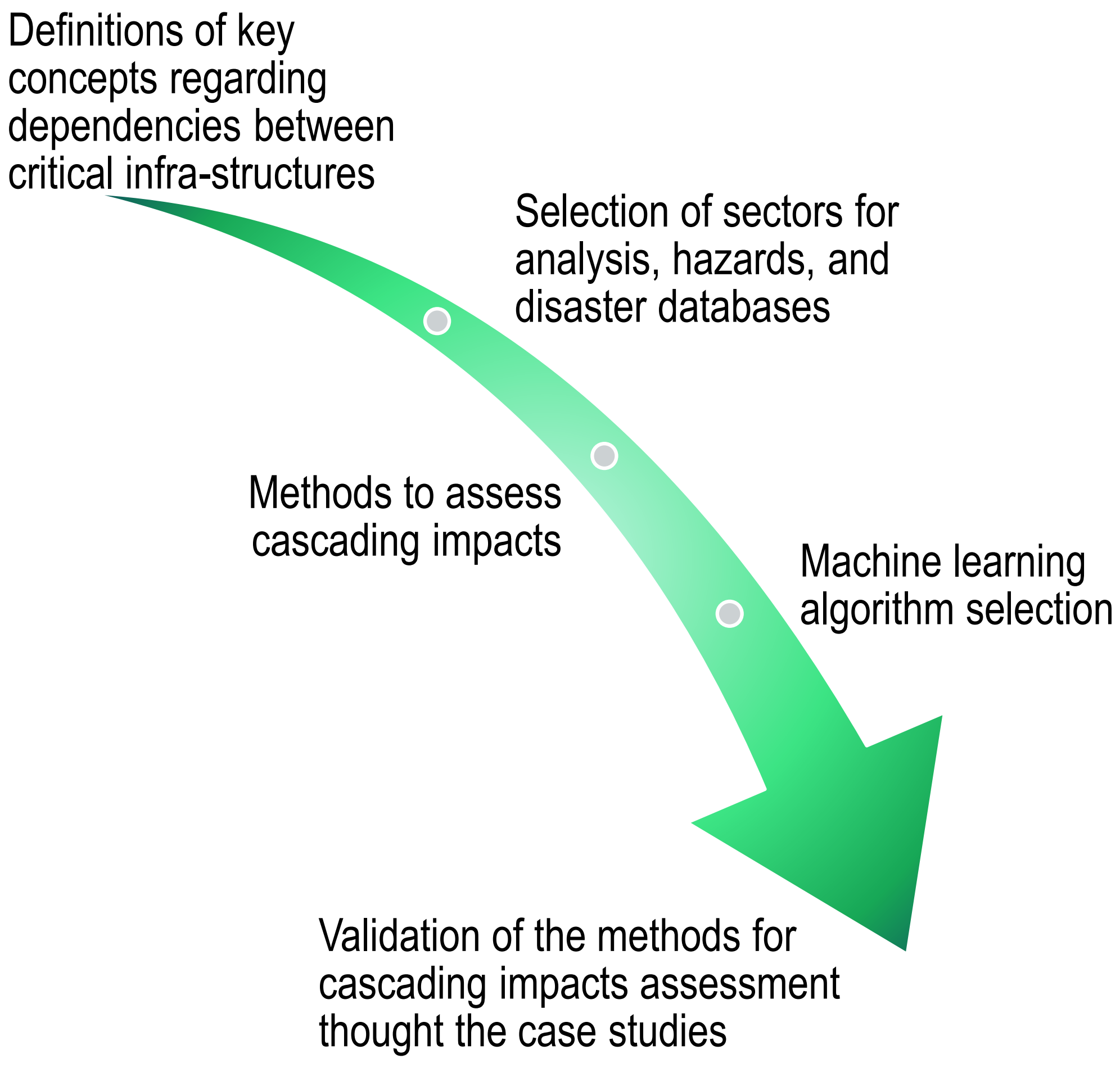
Physical: when each of two infrastructures are dependent on the material output of the other

Logical: when the state of each of two infra-structures depends on the state of the other via control, regulatory or through a mechanism not a physical, cyber or geographic connection.

Figure 2: Types of interdependency of critical infrastructure elements (adapted from Rinaldi, 2001)

Materials and Methods

The methodology developed for assessing cascading impacts is grounded in **machine learning** (ML) algorithms capable of discerning patterns in data and leveraging them to predict outcomes for new data. The initial phase involves defining the inputs required for the analysis, which are informed by the findings of previous literature reviews.



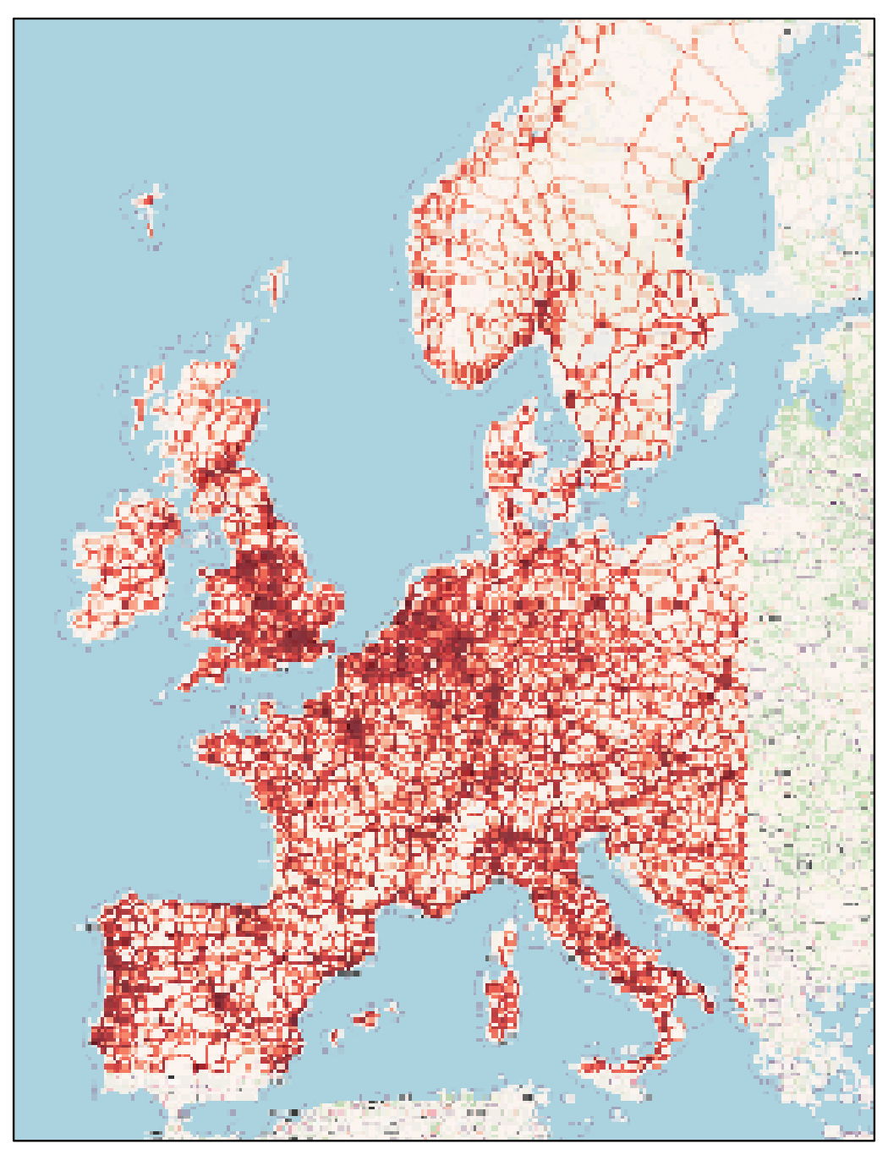
Definitions of key concepts regarding dependencies between critical infra-structures

Selection of sectors for analysis, hazards, and disaster databases

Methods to assess cascading impacts

Machine learning algorithm selection

Validation of the methods for cascading impacts assessment thought the case studies



The publicly available **harmonized global spatial dataset of CI** [3] was used as input to assess cascading impacts. This global dataset is considered a valuable starting point to gain exposure information for cascading impact assessments. The study led by Nirandjan also proposed a Critical Infrastructure Spatial Index (CISI) at the global scale, at a resolution of 0.10 × 0.10 and 0.25 × 0.25 degrees (Fig. 3)

Figure 3: Primary roads in Europe (adapted from Nirandjan, 2022)

ML requires a constantly evolving database of past events for model training and testing. Starting from the comparison between **the existing loss databases**, DesInventar has been selected for the development of the machine learning for the following reasons:

- The events are geolocated: this is a crucial aspect to enable the analysis to be carried out;
- provides the damage of a large set of sectors;
- The collection of historical disaster losses data is provided in a systematic way.

Figure 4 shows the schematic overview of the main components of the proposed methodology.

Machine Learning ALGORITHM based on Past Events

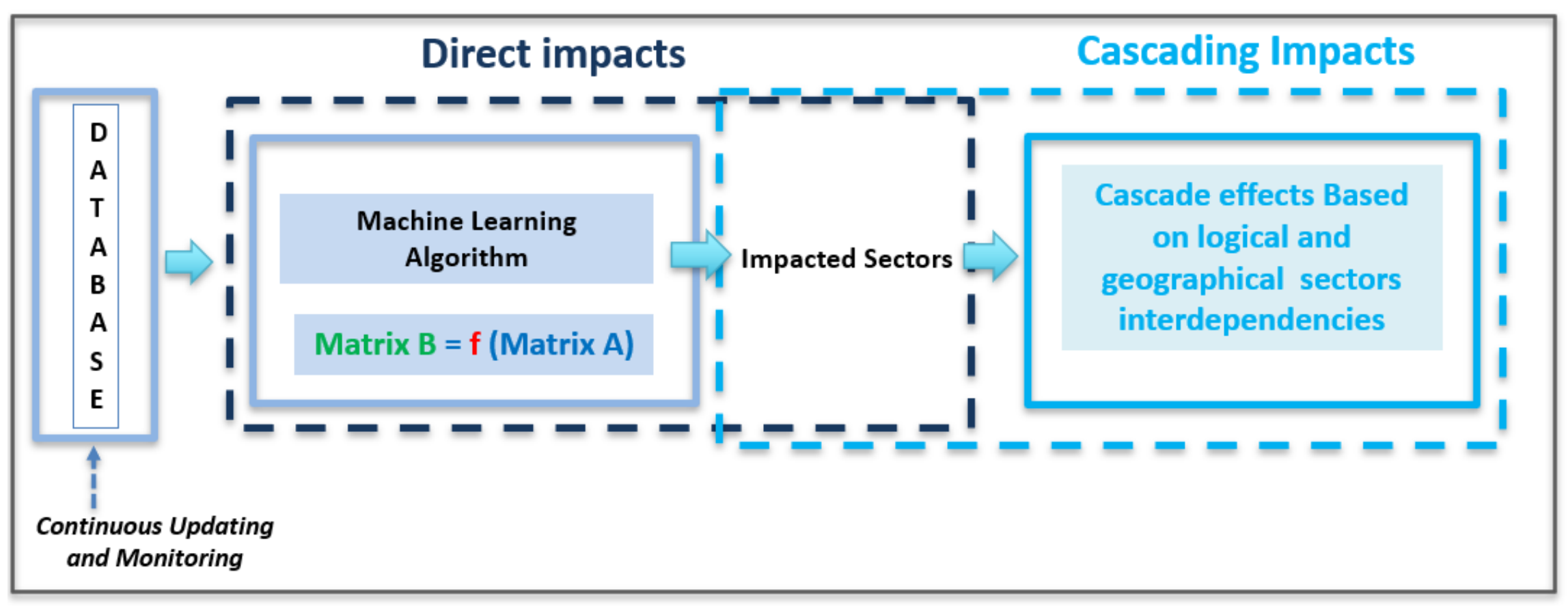


Figure 4: Main workflow of the methodology

The **direct impact** phase of the methodology consists in the identification of the direct impacted sectors starting from the knowledge of the scenario and its context with the ML approach. From this first phase the direct impacted sectors are obtained considering a geographical dependency [5]. Then, starting from the directly impacted sectors, is possible to foresee the **subsequent cascading impacts** over the other remained sectors considering a geographical and logical dependencies.

References

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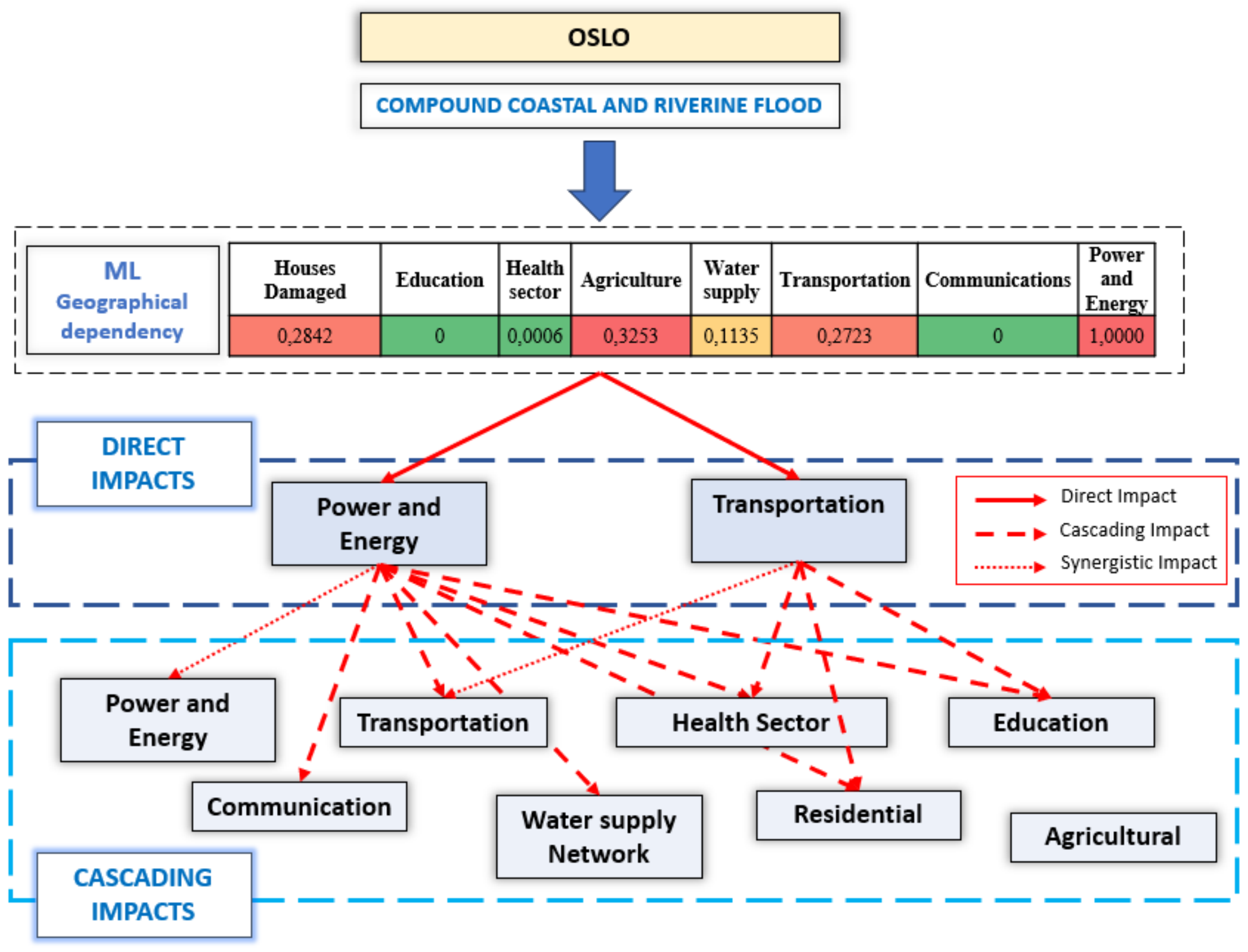
Results

In order to ensure the robustness of their developed method, the researchers applied the methodology to several case studies. These case studies encompassed a diverse range of scenarios, allowing them to test the method's effectiveness in real-world situations beyond the controlled environment of the initial development phase. By analyzing the results from each case study, the researchers aimed to validate the method's ability to consistently produce reliable and accurate outcomes (see Fig. 5)



OSLO

COMPOUND COASTAL AND RIVERINE FLOOD

ML Geographical dependency	Houses Damaged	Education	Health sector	Agriculture	Water supply	Transportation	Communications	Power and Energy
	0,2842	0	0,0006	0,3253	0,1135	0,2723	0	1,0000

Figure 5: Assessment of cascading impacts – worked example

Discussion

The methodology grounded in machine learning techniques, has the potential to enhance decision-making processes aimed at addressing the challenges associated with cascading impacts. The main point of this discussion concerns the methodology itself, as the model can delineate impacted sectors based on hazards, only considering their spatial proximity and surrounding context. One key aspect highlighted by the task is the non-availability of a sufficient number of historical event data in the case studies, which is essential for a machine learning-based methodology.

This shortage necessitated the development of a method that extracts data from global databases, albeit validated only within the case studies.

Given the multitude of variables involved but the limited scenarios available, the reliability of predictions faces some challenges, especially regarding differentiating impacts based on magnitude.

Nevertheless, despite these challenges, the developed methodology has demonstrated functionality and yielded satisfactory results during validation.

The involvement of stakeholders in the MEDiate project as partners and actors of the same project indeed represents an opportunity to improve this aspect, asking that those dealing with natural hazards at the local level collect detailed information on events, in terms of event impact location and event magnitude.

Conclusion

The method should be applicable for describing cascading impacts among a broad variety of societal sectors and critical infrastructures. The approach presented within this framework, seeks to develop a flexible and innovative instrument that offers an overview of infrastructures condition in terms of risks, possible losses and resilience assessment for different kind of hazards. The steps out-lined in this framework represent the core of the approach, but each individual phase can be refined or substituted with more detailed analysis or methods. This possibility assumes realistic appearance if input (about hazard, infrastructure system and asset) and specific resources are available. Some of the simplified approaches described here are deemed to be appropriate to a large portfolio of infrastructure's assets.

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