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Multi-Layer Conceptual Framework for Multi-Dimensional Interdependencies in Critical Infrastructure Systems

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Critical infrastructure systems, such as water and energy systems, are fundamental to support our daily lives, yet their complexity and dynamic nature present significant challenges for analysis and modeling. Traditional approaches often fail to capture the multi-dimensional interdependencies that evolve over time across various infrastructure types. To address this gap, this paper introduces the Multi-Layer Conceptual Framework, which provides a new perspective for analyzing and modeling interdependent infrastructure systems. The model distinguishes interdependencies based on the infrastructure types (water, energy, transport), contextual layer (technical, institutional, and societal), and analysis time frame (short, mid, and long term). The framework enables the identification of cross-layer interactions, co-evolution patterns, and emergent behaviors within and across infrastructure systems. The model's applicability is demonstrated through a case study on energy transition, which demonstrates how the framework is used in the problem of new energy source deployment, considering the social attitude toward different alternative sources of energy, impact on the new policies, and technological development.

Keywords: infrastructure, systems, interdependency, interconnectedness, modeling.

1. Introduction

Infrastructure systems, like roads, energy, and water distribution networks, are essential to society, serving as the backbone of our daily activities. These infrastructure systems are highly complex, large-scale socio-technical systems spanning many temporal, spatial, and organizational scales (Rinaldi et al., 2001). They are embedded in, intertwined with, and co-dependent on other systems. Such defined System of Systems is extremely vulnerable to the continuously changing environment. Complex challenges we face as a society, like climate change or energy transition, add even more pressure on the infrastructure systems. Thus, there is an increased focus on understanding the dynamics of coupled infrastructure systems, and the importance of modeling relationships across and within different types of infrastructure systems is becoming more and more pronounced.

Rinaldi et al. (2001) suggest different dimensions of infrastructure interdependencies, like physical or logical, and factors, like political and social concerns or technical issues, that define interdependencies between different infrastructure systems. However, the application of all the identified dimensions in specific cases is hardly found. Most applications focus on one dimension of relations among different types of infrastructure systems or multiple dimensions of relations affecting one type of infrastructure.

Some approaches allow for investigating across-infra relationships, focusing on how the specific disruption of one system affects the functionality of other systems. Studies in this group typically use a deductive approach, which implies a short-term impact of rapid system dis-

ruption. However, the causal relationship between the system's level across different time-frame and contexts is either not explained or is only briefly mentioned (Johansen and Tien, 2018; Lee II et al., 2007; Jayasinghe et al., 2023; Akbarzadeh and Katsikas, 2021; Laugé et al., 2015).

To address the need for more comprehensive methods to solve real-life challenges embedded in multi-infrastructure topology, this paper presents a new multi-layer conceptual framework for Multi-Dimensional Interdependencies within and across different type of critical infrastructure systems, constituting the base for further research in the field.

1.1. *Literature Gap and Research Objective*

Current literature studies suggest several methods to identify and study interconnected, co-dependent infrastructure systems that could be grouped based on the types of infrastructure systems modeled, the time frame of the given scope of the research, and the type of relations investigated.

Within the first group of studies, the main focus is put on only one infrastructure type (Markolf et al., 2019; Albasrawi et al., 2014; Mansouri et al., 2009; de Corte and Sörensen, 2014; Sitzenfrei et al., 2013; Song et al., 2022). Within the second group, the impact of failure spreading mechanisms on the critical infrastructure systems performance shortly after the failure occurrence is studied (Wang et al., 2022; Lee II et al., 2007; Burgers, 2024; Song et al., 2022; Markolf et al., 2019; Poljanšek et al., 2012). In both cases, the problem is that only one dimension is investigated; in the first group, it is one infrastructure type, and in the second group, it is only one-time frame: the short-term effect of the failure.

There is also another group of literature that propose more holistic approach. Mansouri et al. (2009) suggested the implementation of system thinking to increase the accuracy of the interconnectedness study in the example of Maritime Transportation System. There are a few examples of thinking about interconnections between critical infrastructure systems of different types, investigating the role of policymaking and its impact on the different infrastructure types (White et al., 2017; Markolf et al., 2019). There are also studies that imply the importance of different time-frames while conducting research on relations across different types of infrastructure systems (Rinaldi et al., 2001; Laugé et al., 2015). However, none of the above propose a systematic way how to investigate relations between different infrastructure types.

To conclude, existing approaches do not explicitly identify causal relationships among different infrastructure system types and thus are questioned to fulfill this need (Jayasinghe et al., 2023). This paper makes the first step towards achieving this objective by presenting an innovative way of looking at infrastructure systems and relations within and across them with the conceptual framework aiming to gain a new perspective while investigating interdependent infrastructure systems.

2. Multi-Layer Conceptual Framework

This section presents the proposed Multi-Layer conceptual framework inspired by the Brand (1994) shearing layers of building structure that evolve at their own pace, implying the importance of adaptability of structures. By improving buildings' sustainability and longevity, using the shearing layers concept, their functionality despite disruption over time is ensured (Brand, 1994). The core characteristic of the proposed framework is the way of defining infrastructure systems, from the perspective of the scope context, that continuously reacts with each other and adapts to each other, following the concept of Complex Adaptive Systems presented by Waldrop and Stein (1992). That is a pure practical example of the common phrase *Easier said than done*... Therefore, to avoid misinterpretations, let us define what we meant by each phrase depicted in Figure 1.

2.1. *Preliminaries for Multi-layer conceptual framework*

As depicted in Figure 1 the framework consists of multiple components.

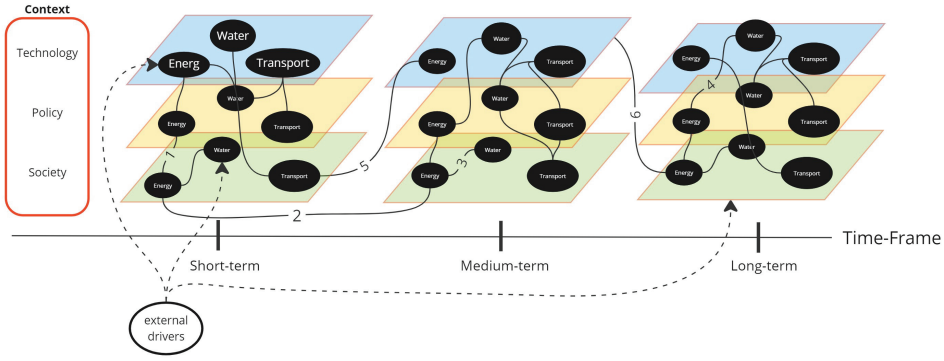

Fig. 1. Visualization of Multi-Layer Conceptual Framework

Infrastructure System

Based on the definition by Rinaldi et al. (2001), we use the term *infrastructure system* to refer to the socio-technical network composed of physical, digital, and organizational components that provide different types of services to society. Its dual nature of technical constructs and socially embedded systems make it an adaptive and evolving structure in response to changing conditions of different sources, e.g., societal or environmental ones. In Figure 1, we represent the energy, water and transportation infrastructure systems visualized by black ovals.

Relation Context

Based on the interdependencies dimension proposed by Rinaldi et al. (2001), for presentation clarity, we focus on three contexts, technical, institutional, and societal, out of many dimensions and factors mentioned in the paper. Depending on the individual case study, other contexts might be added, some removed or replaced. However, the usage of the conceptual framework remains unchanged. Each context represents the perspective from which chosen infrastructure systems are modeled. What does it mean exactly? Inspired by Goerge Box's famous quote *All models are wrong, but some are useful* (Box, 1979), we claim that depending on the perspective taken, one system can be modeled differently depending on the model's purpose. Let's take the example of the Water Infrastructure System. From the technological context, our model could be a network of nodes and edges representing, consequently, pipelines and pumps of a water distribution network. From the institutional context, the model could be representation of the waste and drinking water network. Meanwhile, the societal context could be the agent-based model of societal acceptance of circular water economy in farming.

External drivers

By external drivers, we are referring to all types of external events, policies, and factors that impact infrastructure systems models, systems performance and dynamics, or the scope of the study. It compounds both stochastic events (e.g., natural disasters, economic shocks) and deterministic influence (e.g., planned interventions, regulations, investment decisions).

Time-frame

To clarify the time dimension in the proposed conceptual framework, we do not mention the particular moment of time when the system stops or the continuous scale. The focus is on the short-, medium-, and long-term effects on the systems. Depending on the study to be conducted, the time frame needs to be defined considering the context

and type of relations under investigation. An example of how the time frame can be defined is shown in section 3. Using the framework, it is possible to also implement different time dynamics, meaning it is possible to move between the layers and observe emergent patterns and flows on different dimensions. Different types of relations and their meaning are explained further below.

Types of relations

In Figure 1, each relation is represented by one black line. We can observe that the lines represent six types of relations:

- one system type across different layers (1) in time (2)
- systems of different types embedded on the same (3) or different layers (4) in time (5)
- layer connected to specific infrastructure system (6)

That means that using the framework, co-evolution within and between layers is observable, revealing emergent behavior of different infrastructure types. Moreover, even one infrastructure system impacts itself in different contexts, e.g., a social energy system through the institutional layer can influence the technical layer of the energy system over time.

With such defined core concepts and terms, the Multi-Layer conceptual framework is described in the next sections with its potential use and further research steps.

2.2. *Framework description*

The proposed framework changes the perception of infrastructure systems. Depending on the context, one system can be approached differently, which also implies different modeling techniques, scope, assumptions, and even the system's component definitions. This means that one type of infrastructure system can be represented by three different models, as mentioned in the previous subsection in the example of the water infrastructure system.

In Figure 1, we can see that each time frame with each context creates a contextual layer in which three types of infrastructures are placed, based on the concept of multiplex graph (Santoro and Nicosia, 2020), where each layer consists of the same set of nodes (infrastructure systems), but the connections between them represent different types of relations depending on the layer. In the presented conceptual framework, we go one step further, adding possible connections between the nodes across different layers and connections between the layers themselves. Each of the layers could be perceived as a System of Infrastructure Networked Models, which, in the broader picture, creates a large-scale System of Systems. This implies, theoretically,that every component might impact other components, is influenced by other components, and, as a result, evolves in time. That is the moment when the complexity of relations makes them deeply entangled.

The proposed framework constitutes a base for a systematic way of decomposing any case study, revealing the specific relations that need to be investigated to address the stated problem or challenge. The significant advantage of the Multi-Layer framework is that even though one type of infrastructure system is investigated, the framework distinguishes three different models that influence each other in time, driving the evolution of each infrastructure system. By that, the entangled interdependency is scoped down to multi-modeling problems, which is one of the methods proposed by literature and possible to implement (Huang and Nikolic, 2024).

To grasp the idea behind the framework, in the following subsection, we use it to analyze the infrastructural change accompanying the energy transition process in a simplified, though realistic, thought experiment.

3. Energy transition model case

An energy transition case in climate-neutral policies is taken to demonstrate how the Multi-Layer framework could be used as seen in Figure 2. For demonstration purposes, the given case is scoped down to:

- Three types of infrastructure: energy (1),

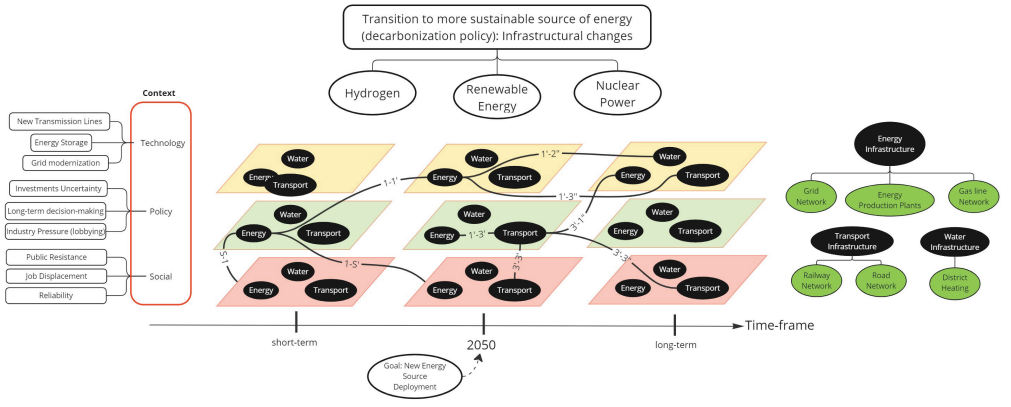

Fig. 2. Multi-Layer Framework application: Energy Transition case

water (2), and transportation (3).

- Due to the climate-neutral policies of the European Union, the time reference point is set to 2050, the year of achieving the goal of deployment of the new energy source.
- Three contexts are considered: society (S), policy (P), and technology (T); each aligned with three key challenges, see Fig.2
- The main problem is limited to the implementation of the new, more sustainable source of energy: hydrogen, renewable energy, or nuclear power

With the scope defined, let's take hydrogen as a prior strategy towards energy transition. The implementation of the Multi-Layer framework starts with the society layer. In the case of hydrogen, negative social attitudes towards hydrogen-based energy and transportation might drive new policies that subsidize developments of alternative bio-fuels, which in Figure 2 is depicted as a layer-to-system (S-1) relation. Change of policy determines building new assets like production plants, visualized as the relation between the same infrastructure system but perceived from different contexts and time-frame (1-1'). In the development phase, it might appear that the change in the energy distribution network flow impacts the transportation (1'-3") and water (1'-2") systems by requiring new road facilities and adaptation of the water district heating network. Therefore, the significance of possible long-term investments might drive policy-makers to search for an alternative option.

Then, as an external driver, we could consider a positive campaign towards hydrogen-based energy (1-S') and then investigate previously identified relations one more time, supporting investment decision-making. Such campaigns might decrease public resistance towards hydrogen, resulting in increased support for alternative transportation modes and forcing policy-makers to establish new regulations, e.g. hydrogen public transport requires new safety procedures while refueling (3'-3') that would affect energy distribution (3'-1") including logistics like production and storage that also requires new regulations (1'-3') ensuring safety and reliability (3'-3").

The similar logic flow can be also conducted for the nuclear power case and different contextual challenges investigating each system at each layer at a chosen timeframe.

As we can see in Fig2, some elements of the framework are not used, and some infrastructure systems are more connected than others, which could be the core focus of the next step for the multi-modeling step, addressing the complex

problem of deployment of the new source of energy complying with the climate-neutrality policies.

Limitation

The above logic and presentation are simplified for demonstration purposes; however, in empirical research projects, relations could be investigated by using already existing methods, including interviewing experts or simulation models. Although the hypothetical example shows the framework's possible contribution, a few points are worth further clarification. The presented conceptual framework is highly dependent on the given case of study. Visualization presented in Figure 1 is an example of a holistic approach to capture only relevant relations. The chosen contexts and infrastructure systems might and will differ when applied to different cases problem formulation. First, a clear scope is needed to identify relevant infrastructure system type and contexts of relations to further on define the time-frame, as with continuously evolving infrastructure systems and their complex nature creating an all-mighty multi–model simulation of the whole possible dimension captured its simply not possible.

Moreover, the framework focuses on the relations, not the infrastructure system *per se*. As presented in the previous section, various modeling techniques are applied in different domains to model particular infrastructure systems and methodologies to capture specific relations, like failure spreading mechanisms, risk mitigation, or decision-making models. Therefore, the model is a base for a new methodology that joins existing approaches, compares models, and steers further case studies, which could be an essential core for inventing a new technique to model codependent infrastructure systems.

4. Conclusion and future steps

In closing, we have shown that the existing literature already proposes different approaches and modeling techniques to study interconnected, codependent infrastructure systems. Some of them investigate different infrastructure types but from the limited time perspective of failure propagation mechanisms. Some of them investigate the impact of long-term policies by using qualitative methods and social science to explore possible scenarios. However, none of them capture the complexity of multi-dimensional relations within and across different infrastructure types. Therefore, there is a need to create a new methodology that would support researchers, investors, or decisive parties to better understand the interdependency among different types of infrastructure systems in the given context and problem formulation. The presented framework distinguishes different context of relation that determines different approaches on how we look at and model infrastructure systems that influence each other in time, driving their evolution. This paper constitutes a base for the next step toward such methodology. The presented conceptual framework contributes with its innovative approach, which could be operationalized further in the form of system decomposition to formulate the scope and identify relevant relations between adequate infrastructure system models. Future research could build on these findings by further formalizing each layer and implementing the framework to realistic cases.

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