Logical interdependencies in infrastructure: What are they, how to identify them, and what do they mean for infrastructure risk analysis?

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Abstract

A useful theoretical lens that has emerged for understanding urban resilience is the four basic types of interdependencies in critical infrastructures: the physical, geographic, cyber, and logical types. This paper is motivated by a conceptual and methodological limitation—although *logical* interdependencies (where two infrastructures affect the state of each other via human decisions) are regarded as one of the basic types of interdependencies, the question of how to apply the notion and how to quantify logical relations remains under-explored. To overcome this limitation, this study focuses on institutions (rules), for example, rules and planned tasks guiding human interactions with one another and infrastructure. Such rule-mediated interactions, when linguistically expressed, have a syntactic form that can be translated into a network form. We provide a foundation to delineate these two forms to detect logical interdependence. Specifically, we propose an approach to quantify logical interdependence based on the idea that (1) there are certain *network motifs* indicating logical relations, (2) such network motifs can be discerned from the network form of rules, and that (3) the higher the frequency of these motifs between two infrastructures, the greater the extent of logical interdependency. We develop a set of such motifs and illustrate their usage using an example. We conclude by suggesting a revision to the original definition of logical interdependence. This rule-focused approach is relevant to understanding human error in risk analysis of socio-technical systems, as human error can be seen as deviations from constraints that lead to accidents.

1 INTRODUCTION

A notable feature of modern cities is the presence of an array of civil infrastructures that are becoming increasingly connected in material flow, physical layout, or both. This connectedness in material flow (for instance, situations where water supply systems require electricity from power plants and vice versa) and physical layout (such as the co-location of gas and water pipelines beneath roadways) gives rise to either one-directional (dependent) or reciprocal (interdependent) relationships among the infrastructures, whereby the condition of one infrastructure impacts the state of another. When these relationships lead to the localized breakdown of one infrastructure escalating into a system-wide failure involving multiple infrastructures, the results can be detrimental to human society, leading to compounding or cascading disasters (Cutter, 2018; Pescaroli et al., 2018). Consequently, an essential aspect of understanding the fragility of urban systems requires evaluating how such connectedness shapes the interdependence and dependency among multiple and diverse forms of infrastructure components (Markolf et al., 2018; McDaniels et al., 2008; Yu et al., 2020).

A useful theoretical lens that emerged to aid the development of this critical understanding is the four basic types of interdependencies in critical infrastructures put forth by Rinaldi et al. (2001). In this highly cited work, the authors discuss reciprocal relationships in infrastructures and show that various instances of such relationships can be categorized into four basic types: (1) physical interdependencies, where the condition of one infrastructure depends on the output or state of another due to connected material flows; (2) geographic interdependencies, where multiple infrastructures are situated in close proximity and, as a result, affect one another; (3) cyber interdependencies, where the state of an infrastructure relies on information generated by an information infrastructure; and (4) logical interdependencies, where two infrastructures affect the state of each other through mechanisms other than the three types above and in ways that involve human decisions. This classification scheme is a valuable work that guides our thinking on the various connections that exist among infrastructures with an eye toward system-level resilience. This conceptual lens has been a source of ideas for urban resilience research in the last couple of decades and spurred numerous studies, especially in the analysis of the physical and geographic linkages (Ouyang, 2014).

However, as useful as it is in understanding aspects of urban resilience, we think that the current approach to one type of Rinaldi et al.'s classification—namely, the *logical form* of interdependency—is hindering effective knowledge development. It is not that the current notion of logical interdependency is wrong or misleading, but that it is incomplete and directs our thinking in ways that are less relevant for operationalizing the concept. The current thinking on logical interdependencies is that of a mixed bag, stemming from its all-encompassing definition: "two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection" and "human decisions may play the predominant role in logical interdependencies" (Rinaldi et al., 2001, p. 16). As can be seen, it is a residual, catch-all concept that, as a result, can mean different things to different people depending on the context. A variety of things, ranging from market-driven social dynamics in the demand for an infrastructure to non-market regulatory rules on infrastructure operation, are interchangeably used to explain what constitutes logical interdependence (Heracleous et al., 2017; Ouyang, 2014; Petrenj & Trucco, 2014).

But these things are quite different in nature! While individual behavior and its aggregation are often dynamic and self-organizing in nature, regulatory rules are, in essence, human-devised (designed) and purposeful constraints that are created to affect the former, that is, they are crafted with an intent to shape what must or must not be done among animate human actors and inanimate physical entities to achieve certain outcomes. We think that this distinction between designed and self-organized aspects of human systems holds a key towards building a more robust understanding of logical interdependencies in infrastructures. The current approach, as proposed by Rinaldi et al. (2001), tends to be ambiguous about this difference. Consequently, it presents two hurdles for those aiming to better analyze risks in complex socio-technical systems.

To begin with, the current approach may cause underestimation of the hybridity in interdependence that is prevalent in the real world. This is an unfortunate connotation of the residual, catch-all definition of logical interdependencies. This emphasis on the residual nature, in combination with an overlook of designed aspects of human systems, may lead one to think that a logical interdependency is mutually exclusive to and does not co-occur with the other three types (physical, geographic, and cyber) of interdependencies. While this mutual exclusivity may hold true in the instances of tele-connected vulnerability (Adger et al., 2009; Ouyang, 2014; like a demand shift between two geographically distant infrastructures causing undesirable propagative effects), it is likely an inaccurate assumption in numerous real-world urban situations. Take, for instance, the case of co-located gas and water pipelines within a large urban setting. These pipelines are not just interdependent based on their geographic proximity; they are also interconnected through an intricate web of planned regulations and resultant human actions. Rules and tasks codified in plans by different stakeholders to guide and constrain the repair and maintenance of these two pipe networks and the spacing requirement between them, as well as the behavior of field crews and inspectors shaped by those rules, create logical linkages on top of the existing geographic linkage. This hybridity in interdependence, where different types of interdependencies coexist— such as the combination of the physical *AND* logical connections and the combination of the geographic *AND* logical connections —likely prevails in numerous cases (e.g., Li et al., 2020). Holistically assessing urban resilience therefore requires methods to systematically identify these hybrid interdependencies.

Next, the "mixed bag" nature of the current thinking on logical interdependencies invites a "babbling equilibrium" in communication (Lewis, 2008; Ostrom, 2005), that is, different people referring to different things as they exchange information about a concept, which can lead to suboptimal outcomes. Suppose a team of city planners wanting to discuss with various stakeholders to identify vulnerabilities in the city's public subway system from the standpoint of logical interdependencies. Without clearer guidance, the planners may get quite different answers depending on who they ask. Those from the subway system's business sector might emphasize the consumer dynamics influenced by market forces, for example, how people's demand for the subway system may fluctuate due to external market forces and cause a sudden demand shift between the subway and public buses. Infrastructure operators might focus on the operational protocols and procedures of other mobility services that may affect the subway system. They could delve into how the scheduling rules for subway trains may impact and be impacted by the operations of public buses. Station personnel could center on rule enforcement, concentrating on how surveillance of fare evasion and public safety within subway stations could influence subway usage and create cascading effects on other linked mobility systems. With such varied viewpoints and the intangible nature inherent in logical relationships, the city planners could struggle to determine where their analysis should concentrate. This state of babbling equilibrium perhaps explains why there have been so few serious works on the subject.

The outlined hurdles suggest that an updated approach is needed on logical interdependencies to achieve greater clarity and applicability. The aim of this paper is to contribute to filling this gap, a niche that has not been adequately addressed in the literature to date. To achieve this, we concentrate on the deliberate design of logical relationships within infrastructures: institutions (rules) that serve as constraints shaping human behavior and their interactions with each other and with inanimate objects (Anderies et al., 2004; Yu et al., 2023). It is critical to see that when such *rule-mediated interactions* underlie the operation of two or more infrastructures that require some degree of coordination, a logical interdependency is potentially present, especially when a good "fit" is needed among the rule designs, required coordination, and changing external environments (Yu et al., 2020, p. 1,528). Whether they are grounded in formal rules outlined in official documents or unwritten informal rules understood and shared among group members, these interactions mediated by rules can give rise to logical interdependencies.

Another key reason for focusing on the rules and rule-mediated interactions is the presence of a *form* inherent in them arising from their designed nature. By "form," we mean that rules have a syntactic form with placeholders that specify which actor may or may not do what to which entities, and under what contexts (Crawford & Ostrom, 1995; Siddiki et al., 2019). For example, an infrastructure rule might have the following syntactic form: US Army Corps of Engineers (an actor) must release water at certain rate (do something to an entity directedly acted upon by that action) to a hydropower unit and a downstream camping site (entities indirectly affected by that action) in Mendocino County, California (a spatial context) during certain months (a temporal context). Crucially, such syntactic form can be translated into a meaningful network, i.e., human actors and inanimate physical entities as nodes and rule-prescribed actions involving them as links (Olivier, 2019; Olivier et al., 2020). This translation into a network form and an analysis of the resulting network connectivity enables a way to identify logical interdependencies and their characteristics in a system of infrastructures (see Sections 2 and 3). Both formal and informal rules, when extracted and conveyed through language, exhibit a syntactic structure that can be converted into a network representation.

Our focus on rules and networks resonates with the research on environmental governance and infrastructure resilience that both increasingly call for more attention to understanding interdependencies as network patterns. Studies of how governance institutions shape sustainability and resilience highlight the importance not only of how different actors interact (Bergsten et al., 2019), but how these institutional network structures fit with the underlying networked (e.g., ecological or social-ecological) system they are supposed to be managing (Ekstrom & Crona, 2017; Sayles & Baggio, 2017) or connected set of tasks they are supposed to be completing in various situations (Bodin & Nohrstedt, 2016). In an urban infrastructure context, such tasks are often outlined in local plans, such as transportation, flood control, or disaster response plans (Li et al., 2020; Mesdaghi et al., 2022). Similarly, an emerging body of urban planning scholarship applies different methods to examine the integration of "networks of plans" relevant to a particular area or planning issue (e.g., flooding), demonstrating that plans are often disconnected, and the policies and tasks they contain contradictory, arguably undermining resilience (Berke et al., 2015; Woodruff et al., 2022). Yet very few studies explicitly link governance actor networks and plan, or rule-networks (Olivier & Schlager, 2022), or take the additional step of mapping these networks to the related networks of tasks and infrastructure systems (Bodin et al., 2022; Li et al., 2020; Manny et al., 2022; Mesdaghi et al., 2022). Our approach builds on this foundation by focusing on both syntactic and network forms of rule-mediated interactions, with an eye toward clarifying logical interdependence in infrastructures.

The risk analysis literature is well-acquainted with the emphasis on rule-based constraints and the interactions among system components dictated by such rules. For example, in the systems-theoretic accident model and processes (STAMP), a qualitative method for analyzing accidents in complex socio-technical systems, the fundamental concept revolves around constraints (rules) implemented to regulate system components and interactions (Leveson, 2004). According to the STAMP model, the cause of an accident is attributed to inadequate constraints on both system design and operations, rather than external events. This inadequacy stems from the safety constraints that are violated and the controls that are ineffective in enforcement.

Recently, there have been efforts to quantitatively assess the effects of human factors (e.g., violation of safety constraints) on the propagation of risks within complex socio-technical networks (Sun et al., 2022; Yao et al., 2023). These studies suggest the documentation of system safety control structure as the first step in risk analysis, that is, eliciting the baseline of how system component nodes (human actors and inanimate object) and their linkages are structured. Hence, our approach of translating syntactic forms of regulatory rules into a human-infrastructure network can be useful for capturing such baseline and human errors with respect to the baseline, that is, "any deviation from the performance of a specified or prescribed sequence of actions" (Leveson, 2004). Despite the relevance, studies that cite Rinaldi et al. (2001) in *Risk Analysis* have not adequately addressed the role of logical interdependencies and the syntactic and network forms of rule-mediated interactions (e.g., Curt & Tacnet, 2018; Gomez et al., 2019; Kong & Simonovic, 2019; Nozhati et al., 2019; Thacker et al., 2017).

This paper proceeds by proposing an updated approach to logical interdependencies. Relevant theories and supporting methods are introduced to substantiate the approach. Then, we show how this revised approach can be put into practice by highlighting an applied example. Finally, in light of the approach, we suggest a revision to Rinaldi et al.'s current definition of logical interdependencies.

2 SYNTACTIC AND NETWORK FORMS OF RULE-MEDIATED INTERACTIONS

Human decisions around infrastructure operation are not made in vacuum. Those decisions are prescribed and become predictable through various rules and procedures that have been codified by agencies and operating units. Such rules, referred to as *institutions*, are essentially humanly devised constraints that are often created through collective choice to achieve an agreed-upon goal (Ostrom, 2008). Institutions are the basic "rules of the game" that reduce uncertainties in human interactions and thus outcomes of such exchange (North, 1990). The stability and predictability of various human-dominated situations, ranging from market exchange to the use and management of shared resources, are enhanced by the influence of institutions (Anderies & Janssen, 2013). Civil infrastructure systems are no different in this aspect. Institutions influence outcomes, such as the performance of infrastructure services, by mediating human interactions with each other and with the built environment.

Here, we introduce an approach to bringing out syntactic and network forms of rule-mediated interactions. These two forms of representation, as we shall show, provide a way to probe logical interdependencies in a system of infrastructures. In demonstrating our approach, we focus on formal institutional (rule) statements extracted from rule-containing documents. Note that, despite our focus on formal rules, the methodological approach proposed here can be extended to implicit informal rules that exist beyond rule-containing documents. Our development of syntactic and network representations of rule-mediated interactions is based on the linguistic expressions of rules and is independent of whether these expressions are written or verbal. Whether a rule statement is present in written language form (such as in an official document) or verbal language form (like an unwritten norm shared among group members), its linguistic expression remains consistent when articulated.

2.1 Syntactic form

To understand how to describe rule-mediated interactions, suppose a system of infrastructures comprised of the following parts next to a river1: four built components (a dam reservoir, a hydropower plant, an emergency spillway, and a recreational facility) and three human actors responsible for operating these components (Agency X, City Y, and Park Manager Z). Figure 1 shows the basic setup of this system. The reservoir dam, the hydropower plant, and the emergency spillway are co-located (although the latter two can be viewed as part of the dam reservoir, we treat them as separate entities here because of their distinct functions). While the dam reservoir and the emergency spillway are managed by Agency X, the hydropower plant is controlled by a different actor, the City Y. A recreational facility exists downstream to the reservoir, and is managed by the Park Manager Z. This facility can be affected by the level of streamflow, which is directly tied to the releases from the reservoir upstream. More importantly, suppose that the functioning of this system of infrastructures is prescribed by a host of institutions, a small subset of which is the rule statements R1-R8 shown in Figure 1.

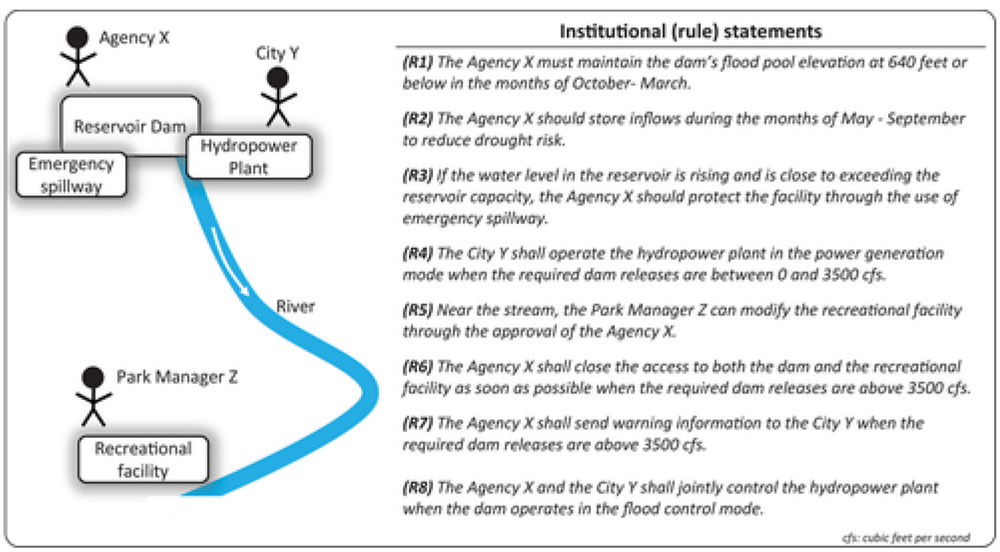

FIGURE 1: An illustrative case of a coupled human–water system centered on a dam reservoir.

Our approach begins with collecting a volume of rule statements that define infrastructure ownership and operation. It is critical to see that such rules are generally "relational" in nature, meaning that one–to–one, one–to–many, many–to–one, and many–to–many relations are created by formal rules that mandate interactions among human actors and inanimate entities (Olivier et al., 2020). Individual rule statements of this kind are the basic unit of analysis in the approach proposed here. For example, in Figure 1, the rule statements R1 and R4 describe one–to–one relations between a human actor and another entity. R1 and R4 describe that a human actor should do something to an inanimate built entity (the dam in R1 and the hydropower plant in R4). The statement R6 describes a one–to–many relation in which one actor (dam operator) should do something to two inanimate built entities (the dam and the recreational facility). A many–to–one relation is described by R8. This statement basically says that two actors (Agency X and City Y) should jointly control a piece of infrastructure (a hydropower plant) under certain conditions.

Although such relations can be deduced from the rule text itself, a more structured method is preferred to formalize both the relational and syntactic forms of rule statements. For this, we apply the Institutional Grammar (IG), a methodological tool that allows the identification and disentangling of the specific syntactic elements that comprise a rule statement (Crawford & Ostrom, 1995; Siddiki et al., 2019). This tool provides a way to consistently identify the actor who must, may (or may not) do a certain action, who (or what) is the recipient of that action, and under what conditions the rule applies. Specifically, using the IG tool, we partition a rule statement into six elements known as ABDICO2: **A**ttribute, o**B**ject (direct and indirect), **D**eontic, a**I**m (aim), **C**ontext, and **O**r-else (Frantz & Siddiki, 2021).

The actor taking an action is termed Attribute by the IG; the main action or goal of a rule statement assigned to the actor is termed aIm; and an animate part (e.g., another actor) or inanimate part (e.g., infrastructure, a piece of information, etc.) of the statement that receives the action captured in the aIm is termed oBject. In R4 above, the City Y is the Attribute that should take an action “operate” (aIm) on the hydropower plant (oBject). Thus, the relational structure in a rule statement is made more explicit by identifying its Attribute, aIm, and oBject. An oBject is further classified as either direct or indirect. An oBject is direct if it is directly targeted by the action captured by the aIm of a statement. For example, in R7, the direct oBject that the aIm (“send”) targets is “warning information.” An oBject is indirect if it is the receiver of the action specified in the aIm-direct oBject combination. In R7, “City Y” is the indirect oBject because it is the receiver of the aIm-direct oBject combination “send warning information.”

The remaining syntactic elements elaborate the rule-mediated interactions between the Attributes and oBjects defined by an aIm. Deontic is a placeholder for the “may” (permitted), “must” (obliged), and “must not” (forbidden) aspect of the aIm of a rule statement. In R4, “shall” is the Deontic (which is equivalent to “must”) and “operate” is the aIm to which this Deontic is assigned. Context specifies diverse conditions (when, where, how, and why) that qualify an action or outcome associated with the aIm of a statement. The following are a few examples: the clause “in the months of October–March” specifies the temporal Context of the action in R1, the clause “near the stream” specifies the spatial Context of the action in R5, the clause “when the required dam releases are between 0 and 3500 cfs” indicates the event/state that instantiates the action in R4, the clause “to reduce drought risk” is the purpose behind the action in R1, the clause “through the use of emergency spillway” defines the means by which the action in R3 is performed (method—instrument), and the clause “in the power generation mode” specifies the manner by which the action in R4 is carried out (method—manner). Finally, Or-else specifies consequence for not following a rule. While Or-else is absent in all the statements (R1–R8) for ease of explanation, in the real world, it is common to find a set of general statements that prescribe varying degrees of punishment for serious or minor violations of operational rules.

Table 1 provides the ABDICO elements extracted from the rule statements R1–R8. A caveat here is that some ABDICO elements are inferred through interpretation. For example, in R2, it appears that an indirect oBject is absent because the statement is phrased as "Agency X should store inflows during the months…" However, one can infer that the dam reservoir is the indirect oBject because it is the receiver of the aIm-direct oBject combination "store inflows." Another caveat is how we infer an ABDICO element even if it is described using a different expression. In R3, the word "facility" is used to describe an oBject that the actor must protect. We can infer that the "facility" is the dam reservoir. In addition, when a rule statement mentions a feature or part of an artefact as its oBject, we assume that the entire artefact itself is the oBject to make our analysis more tractable. This is demonstrated in R1, where we assumed that the oBject "the dam's flood pool elevation" is the dam reservoir because the former is a feature of the latter. Finally, note that not all the ABDICO elements need to be present in every institutional statement (although Attribute and aIm should be present at minimum). Depending on the presence or absence of the remaining elements, an institutional statement can represent either a shared strategy, norm, or a formal rule (for more details, see Crawford & Ostrom, 1995).

TABLE 1. Decomposition of the rules R1–R8 into the ABDICO elements of the Institutional Grammar (IG). Terms shown in square brackets indicate the ABDICO elements that are inferred from the text through interpretation. Diverse types of Contexts (temporal, spatial, event/state, method-instrument, purpose, etc.) are tagged using round brackets. The tag '#' is used to indicate the oBjects and Context that are included as nodes in the network representation.

Rule statement	**Attribute**	**Deontic**	**Aim**	**Object (direct)**	**Object (indirect)**	**Context**
R1	Agency X	must	maintain	the dam's flood pool elevation [#dam reservoir]		(temporal) in the months of October–March (method-manner) at 640 feet or above
R2	Agency X	should [must]	store	Inflows	[#dam reservoir]	(temporal) during the months of May–September (purpose) to reduce drought risk
R3	Agency X	[must]	protect	facility [#dam reservoir]		(event/state) If the water level in the reservoir is rising and is close to exceeding the reservoir capacity (method-instrument) #through the use of emergency spillway

Rule statement	Attribute	Deontic	Aim	Object (direct)	Object (indirect)	Context
R4	City Y	shall [must]	operate	#hydropower plant		(event/state) when the required dam releases are between 0 and 3,500 cfs (method-manner) in the power generation mode
R5	Park Manager Z	can [may]	modify	#recreational facility		(method-manner) #through the approval of the Agency X (spatial) near the stream
R6	Agency X	shall [must]	close the access	#dam reservoir, #recreational facility		(method-manner) as soon as possible (event/state) when the required dam releases are above 3,500 cfs
R7	Agency X	shall [must]	send	warning information	#City Y	(event/state) when the required dam releases are above 3,500 cfs
R8	Agency X, City Y	shall [must]	control	#hydropower plant		(event/state) when the dam operates in the flood control mode. (method-manner) jointly

2.2 Network form

With the ABDICO data, we can translate a rule statement into a network. We apply the lens of the networks of prescribed interactions (NPI; Olivier, 2019; Olivier et al., 2020) for the translation, a type of network representation in which the nodes (Attributes and oBjects) and the links connecting them are defined by formal rules. Note that rule-mediated relationships are supra-dyadic in nature, meaning that they can specify one–to–one, one–to–many, many–to–one, or many–to–many interactions between Attributes and oBjects (Bonacich et al., 2004). For the purpose of identifying logical interdependencies in infrastructures, the NPI approach shows two potential avenues: 1) hypergraph, a graph containing multiple hyperedges (Butts, 2009), with each hyperedge representing a multi-lateral relation, and 2) bipartite network with rule statements on one level and entities (Attributes and oBjects) on another. As will be elaborated below, Figures 2 and 3 show the hypergraph and the bipartite network representations, respectively, of the ABDICO elements extracted from R1–R8.

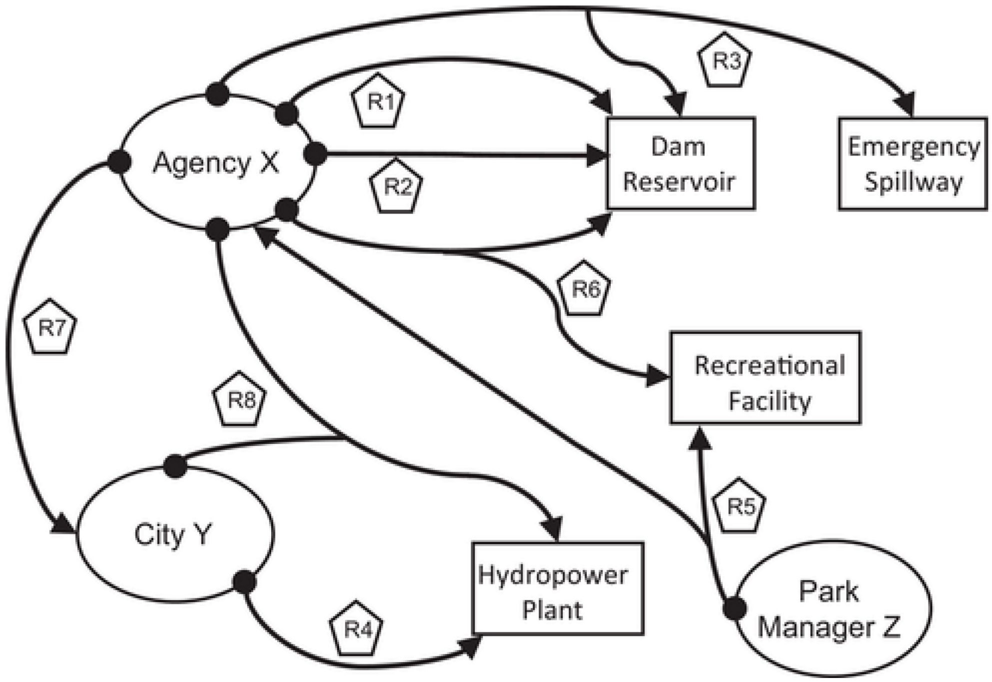

FIGURE 2

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A hypergraph representation of the supra-dyadic relations captured in the syntactic form shown Table 1. Oval shapes indicate the Attributes and animate oBjects of the system. Rectangle shapes indicate inanimate oBjects. Directed links indicate something that one or more Attributes must do to one or more oBjects according to rule statements (pentagon shapes).

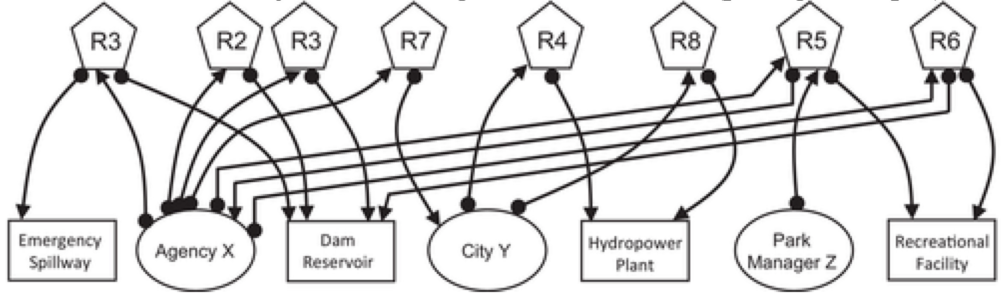


FIGURE 3: A bipartite network representation of the syntactic form shown Table 1, with rule statements on one level and entities on another. In this "rule-entity" bipartite network, the links are directed because each rule statement (pentagon shape) specifies that one or more Attributes (oval shape) must do something to one or more other entities that are either physical stocks (rectangle shape) or animate objects (oval shape).

Before proceeding further, we make a point about the particulars of the NPI approach used in this study. While we do build on the NPI approach, we make a distinction by tailoring the original NPI to better reflect infrastructure interdependencies and apply this variant to the ABDICO data. The key difference between the original NPI and the variant used here is the focus on animate actors and physical stocks. That is, when representing direct and indirect oBjects of a rule statement as nodes in a network, we include those that are animate actors and physical stocks while omitting all other things that belong to other types, such as material flows (e.g., inflows and outflows of water), abstract notions (e.g., beliefs, concepts), intangible entities (e.g., information, data), and procedural aspects (e.g., activity, process, etc.). This tailoring leads to a more concise network representation with a clearer view on logical interdependencies in infrastructures.

Furthermore, we include as nodes certain Context elements that touch on the statement's Attribute acting on a physical stock or an animate actor as an input or intermediate step to the main action. For example, in R3, the Context "through the use of emergency spillway" is the secondary action on a physical stock by the main actor as an input step to the main action "protect the facility." Another example is in R5, where the Context "through the approval of the Agency X" is the secondary action defining what the main actor needs to do with another actor as an input step to the main action "modify the recreational facility". Note that, in Table 1, we use the tag '#' to indicate the oBjects and Context that are included as nodes in Figures 2 and 3. Those without the tag '#' are not included as nodes in the networks.

In a hypergraph, links, known as hyperedges, can link any number of nodes, rather than just two nodes (Butts, 2009). This means hyperedges are not restricted to depicting relationships between pairs of nodes; they can be used to illustrate relationships among multiple nodes simultaneously. In line with this notion, the NPI approach uses hyperedges and their aggregation (hypergraph) to represent several rule-mediated relationships. Figure 2 shows a hypergraph created based on the rule statements R1-R8. The hyperedges for R1, R2, R4 and R7 are dyadic, that is, connecting one Attribute node to one oBject node that is either physical stock or an animate actor. In the remaining rule statements, we see either one party having an obligation to two other entities (R3, R5, and R6) or two parties having a shared obligation to a third entity (R8). Note that links between the Attributes and oBjects are directed. This is so because each rule statement specifies something that one or more actors (Attributes) must do to another entity (oBjects). Moreover, by default, only actors may send linkages to other entities. This results in network representations where an actor may send or receive linkages, whereas an inanimate oBject (i.e., a form of infrastructure) may only receive linkages. Preservation of this information requires the use of directed links.

Bipartite network is another way of describing rule-mediated relationships (Olivier et al., 2020). A bipartite network is a type of graph where the set of nodes can be divided into two distinct groups such that all the edges in the network connect nodes from one group to the nodes in the other group, but not within the same group (Newman, 2018). In other words, there are no edges connecting nodes within the same group. Bipartite networks are often used to model relationships between two different types of entities, such as users and products, actors and movies, or students and courses. In our bipartite network, a set of rules and the entities mentioned in them appear as the two distinct groups of nodes (Figure 3). Links between rules and entities are also directed here because each rule indicates that one or more Attributes must do something to one or more oBjects and Contexts that are either physical stocks or animate actors in nature (with the caveat that those Context elements are about an input step to the main action). Figure 3 shows a bipartite representation of the hyperedges shown in Figure 2, with the rule statements R1–R8 appearing as nodes on one level and the associated entities appearing as nodes on another level. In this study, such "rule-entity" bipartite network is the preferred way of representing rule-mediated relationships because it can be transposed to discern an infrastructure–to–infrastructure association (how two infrastructures are connected via different rule nodes) or a rule–to–rule association involving two infrastructures (how two rules are connected via commonly occurring infrastructure and actor nodes). We suggest that these associations can be used to infer a degree of logical interdependencies between a pair of infrastructures (see Section 3 for more details).

Lastly, rule-mediated interactions, either in the form of hypergraph or bipartite network, can be thought of as a network layer that exists on top of other layers of networks defined by physical, geographic, or cyber relationships. Such multilayered network representation helps to capture the hybridity of interdependence, where different types of interdependencies co-occur—such as physical *AND* logical and geographic *AND* logical. The hypothetical case illustrated in this section (Figure 1) has this hybrid form of interdependence. In addition to being part of rule-mediated interactions (R1–R8), the reservoir dam, the hydropower plant, and the emergency spillway are also geographically interdependent (dam ←→ hydropower plant, dam ←→ emergency spillway, hydropower plant ←→ emergency spillway) and, thus, connected by a bidirectional link. Moreover, these forms of infrastructure are also connected through physical interdependences. Dam releases, for example, immediately pass through the turbines of the hydropower plant. Similarly, in addition to being affected by the rules R5–R6, the recreational facility shows one-way physical dependence with the dam, that is, the link involving the recreational facility is directed (dam → recreational facility). This is because dam releases flow downstream and can affect the recreational facility in times of high or low stream height. Figure 4 shows a multi-layered network representation based on the bipartite network of rule-mediated interactions.

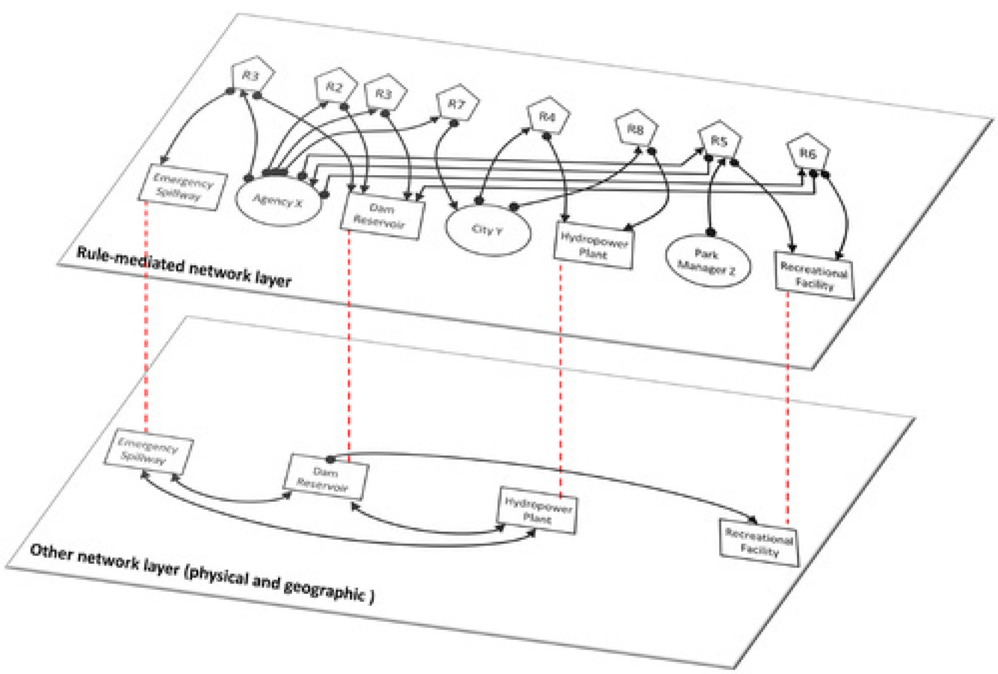


FIGURE 4: A multilayered network representation of the hybrid interdependencies in the case system. In the top layer, the links represent rule-mediated relationships. In the bottom layer, the links represent either the physical or geographical connections among the nodes.

3 IDENTIFYING LOGICAL INTERDEPENDENCIES

With the syntactic and network forms data in hand, we now consider a central question of this paper: how can we identify logical interdependencies in infrastructures? In other words, what is possible with this rule-focused approach that was not possible or was difficult to do before? In addressing this question, our approach centers around the idea that 1) there are certain *network motifs* indicating logical interdependencies, 2) such network motifs can be discerned in the network forms of rules data converted from their syntactic forms, and that 3) the more often these motifs occur between a pair of infrastructures, the greater the degree of logical interdependency between them. In network science, a *network motif* refers to a recurring network building block characterized by a relatively small number of nodes and connections, consistently appearing in the same arrangement at frequencies significantly greater than those anticipated in a comparable random network (Takes et al., 2018). As a network can be made up of such motifs to a considerable extent, it may be more efficient to identify patterns by directing attention to its motifs (Vantaggiato & Lubell, 2023). This approach streamlines the identification process, avoiding the need to wrestle with the intricacies of the entire complex network.

In Figure 5, we develop an initial set of such network motifs (motifs-A to C) using the "rule-entity" bipartite network representation. This representation is used because a rule-entity network can be transposed to elicit a degree of infrastructure–to–infrastructure associations, that is, how a pair of infrastructures is jointly tied to one or more rules with an overlapping set of actors. Although the motifs-A to C shown in Figure 5 do not constitute an exhaustive list of all such network motifs, they exemplify how a pair of infrastructures is logically interconnected through actions dictated by rules.

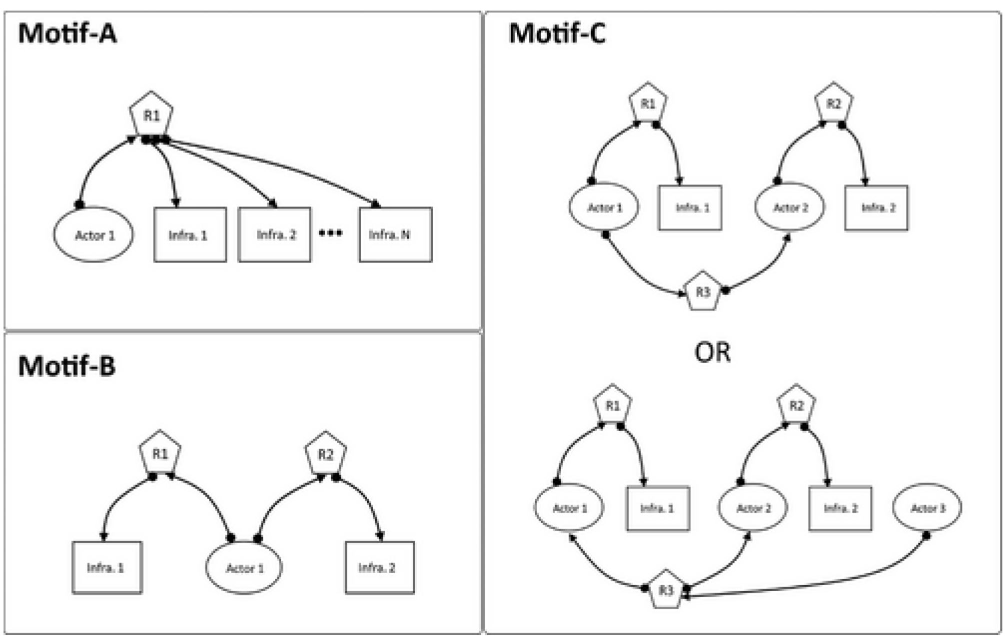


FIGURE 5: Network motifs of logical interdependencies that signal a degree of logical relationship between a pair of infrastructures. The motif-A represents a situation in which two or more infrastructures are tied to one actor via a prescribed action. The motif-B represents two possibilities: co-occurring and alternatively occurring actions specified over two rule statements. Co-occurring actions mean that an actor takes one action to an infrastructure and concurrently takes a different action to another infrastructure depending on a contextual condition.

Alternatively occurring actions mean that an actor takes mutually exclusive, alternative actions to a pair of infrastructures depending on a contextual condition. The motif-C means that, although a pair of infrastructures are seemingly unrelated when looking at the rules that concern them individually, their corresponding actors are connected via a third rule (R3).

The motif-A shown in Figure 5 illustrates two or more infrastructures linked to a single actor through a prescribed action. It is plausible to think that if one actor is prescribed to do something to a pair of infrastructures, then there is a chance that these two infrastructures affect each other through that human action. This aligns with the original concept of logical interdependencies, which emphasizes that two infrastructures affect each other through human decisions. For example, if a rule says that a pair of infrastructures should be shut down whenever one of them needs to be repaired, then the two infrastructures clearly affect each other via a rule-prescribed action. However, if all that a rule mandates are that an actor should monitor a pair of infrastructures, then it is far-fetched to think that a logical interdependency is present based on that fact only.

The motif-B signifies either co-occurring or alternatively occurring actions specified over two rule statements. Co-occurring actions mean that an actor takes one action to an infrastructure (R1) and concurrently takes a different action to another infrastructure (R2) depending on a contextual condition. For example, the operator of an underground effluent storage tank system can be prescribed to store inflows from one drainage area in the storage tank (R1) and direct inflows from remaining drainage areas straight to a nearby treatment facility (R2) depending on where harmful chemical spills occurred. Alternatively occurring actions mean that an actor takes mutually exclusive, alternative actions to a pair of infrastructures depending on a contextual condition. For instance, the operator of the underground effluent storage tank system can be asked to either store all inflows in the storage tank (R1) or direct inflows to a regular treatment facility (R2) depending on where the inflowing water stands in terms of a water quality standard. As can be seen, such co-occurring and alternatively occurring actions specified over two rule statements indicate a degree of logical interdependency between a pair of infrastructures.

The motif-C means that, although a pair of infrastructures (infrastructures 1 and 2) are seemingly unrelated when looking at the rules that concern them (R1 and R2) individually, their corresponding actors (actors 1 and 2) are connected via a third rule (R3). In such situations, there can be a degree of logical interdependency between the pair. Consider, for example, the following set of rules: "actor 1 must operate infrastructure 1 in an emergency mode under certain weather conditions" (R1); "actor 2 must shut down infrastructure 2 whenever risks are perceived" (R2); and "actor 1 should inform and communicate with actor 2 whenever the emergency mode is in effect for infrastructure 1" (R3). In such a case, the two infrastructures are likely to be logically interdependent. Note that the top version of the motif-C in Figure 5 is not the subset of the bottom version. The difference lies in what the third rule (R3) means in the two versions. In R3 of the top version, one of the two actors (either Actors 1 or 2) is the Attribute of the rule statement, and the remaining actor is its Object. It means that the operator of one infrastructure must, may, or is forbidden to do something to the operator of another infrastructure. In R3 of the bottom version, the third actor (Actor 3) is possibly an actor of authority situated at a higher level in the organizational hierarchy. This third actor is the

Attribute that must, may, or is forbidden to do something to the operators of both infrastructures (Objects).

We interpret the frequency of these network motifs within a pair of infrastructures as an indication of its magnitude of logical interdependence. Therefore, a method to identify logical interdependencies can be implemented as follows. Given a pair of infrastructures and after deriving a rule-entity bipartite graph, an analyst can scan for the motifs-A to C involving the pair and count their frequency to grasp its level of logical interdependency. The analyst can repeat the same for all possible pairs of infrastructure entities in a focal system and then cross-tabulate their frequencies of the motifs (for an example, see Figure 10). If the frequency value is high for a subset of the pairs, the analyst can then narrow down to those pairs and probe the actual content of the rules to further understand the nature of logical relationships in them.

However, this interpretation should be accompanied by a caveat that measuring logical interdependency based on rule statements can be multifaceted. At first, for each pair of infrastructures, the frequency of all network motifs can be determined as the most fundamental and primary measure of its extent of logical interdependence. In addition, variant measures can be derived to develop a more nuanced interpretation. For this, the rule classification scheme developed and popularized by E. Ostrom (2005) may be useful. Ostrom proposed that all rules can be classified into seven types based on the function they serve in an action situation: *Position Rules, Boundary Rules, Choice Rules, Information Rules, Aggregation Rules, Payoff Rules*, and *Scope Rules* (please refer to E. Ostrom (2005) for more details, as the detailed explanations of these rule types and how to classify rules based on them are beyond the scope of this paper).

In the context of rules concerning infrastructure operation, these rule types are not the same in terms of the degree of actual control actions performed on affected infrastructures. For example, while the position rules and boundary rules establish a set of positions for actors to occupy (e.g., chief engineer, maintenance worker, emergency manager, etc.) and who is eligible for such positions, the choice rules and scope rules specify what particular actions are allowed to different positions and what outcomes are to be achieved by actors occupying such positions, respectively. The latter rule types clearly indicate a greater degree of control actions applied to infrastructures. Furthermore, while the information rules are about information exchange (e.g., how frequently monitoring should be done on infrastructures and results should be reported), the aggregation rules concern how to make decisions when multiple stakeholders are involved (e.g., a rule that specifies that the US Army Corps of Engineer has a greater say over county-level water agencies in a dam's water release decisions and hydropower generation in certain months). The latter rule type also represents a greater degree of control actions applied to infrastructures.

As such, the network motifs A–C can be further classified according to these seven rule types based on their rule content. The frequencies of these different types of the network motifs, in turn, signal a different degree of logical interdependency, that is, the network motifs based on the choice, scope, or aggregation rules may indicate a greater degree of logical interdependency compared to those based on the position, boundary, information, or payoff rules. Therefore, an analyst can derive the frequency of the motifs per rule type to develop a more nuanced interpretation. For example, suppose that infrastructures P and Q exhibit five network motifs between them that all belong to the choice rule type and infrastructures R and S have the same number of motifs all belonging to the information rule type. Even though the primary measure of logical interdependence (the combined frequency of all network motifs) is identical for both pairs of infrastructures, the former pair can be interpreted as having a higher level of logical interdependency.

3.1 An applied example

To illustrate further how to detect logical interdependencies using the rule-focused approach explained so far, we now present an applied example based on an actual operations guide document of an infrastructure system. This operations guide document (Ministry of Environment, 2022), created by the central government of South Korea, contains generic institutional (rule) statements about how to operate a buffer storage system for chemical effluents and flood waters in South Korea. The central government drafted and published the document (written in Korean) with the aim that local municipalities will use it as a template to operate their buffer storage systems3.

Based on the operations guide, the setup of a buffer storage system can be described as the following without loss of generality (Figure 6). Four component facilities comprise the focal system: 1) an intercepting facility (with sensors) that directs inflows from a set of drainage areas for either storage in the system or by-pass to a nearby water stream; 2) a debris collection facility that filters out and removes all particulate matters in the inflows; 3) two or more storage facilities that can store effluents and stormwaters; and 4) a discharge facility that directs all outflows from the storage facilities to either a wastewater treatment facility or a nearby stream. External to the focal system are four physical entities that interface with it: a set of drainage areas that can feed either stormwater or chemical effluents to the focal buffer storage system; a wastewater treatment facility to which the focal system discharges its stored water; a nearby water stream; and a neighboring buffer storage system that operates independently. In terms of animate actors that take actions, there are three social units: an organization responsible for the operation, maintenance, and safety management of the focal system, which is hereafter referred to as the operator; an organization that operates the neighboring buffer storage system; and a local municipal government that oversees all physical entities and actors just described.

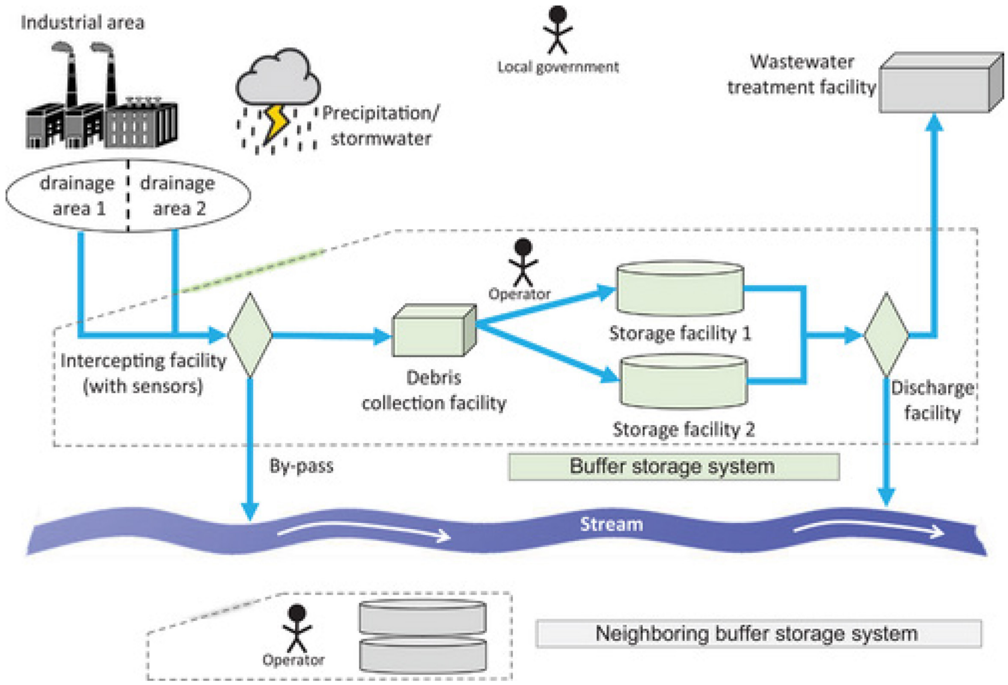


FIGURE 6: The setup of a buffer storage system conceptualized in the document the *Guideline for Implementing, Operating, and Maintaining Buffer Storage Systems* (Ministry of Environment, 2022). Each operator shown in the figure can be interpreted as an operating unit composed of multiple staff members commanded by a higher-level operator.

Finally, we take a broader perspective to what constitutes infrastructures and consider the water stream as a type of "natural infrastructure" (Anderies et al., 2016). Natural infrastructure is defined as part or whole of the network of natural and semi-natural elements providing ecological, economic, or social benefits for humans and other species (Chung et al., 2021). The water stream in our case is consistent with this definition—it can be viewed as part of a network of channelized and natural water bodies that assimilate and neutralize the outflows from the focal storage system.

The lead author translated much of the chapter 4 of the operations guide (titled *Operations and Maintenance*) into English and extracted 82 rule statements from the chapter. The IG was then applied to code the ABDICO elements of those rule statements, closely reflecting the content of the IG 2.0 codebook (available in https://institutionalgrammar.org). We focused on the rule statements that are of the regulative type, those that describe actions linked to specific actors within certain contextual parameters (Frantz & Siddiki, 2021). These rule statements generally concern how to direct inflows from the drainage areas using the built infrastructures and the natural infrastructure under three scenarios: when weather is clear, when chemical spills occur, and when stormwater occurs. Depending on the rules that apply, there are three destinations for the incoming water: one of the storage facilities in the system, the water stream, and the wastewater treatment facility. Through these rules, rule-mediated interactions may occur among the nodes (actors, built and natural infrastructure components, and interfacing units), some of which can generate logical interdependencies.

In this section, we highlight three subsets of such rules to illustrate the network motifs of logical interdependencies and how to detect a degree of logical interdependencies based on them (for simplicity, we focus on deriving the frequencies of all network motifs per pair of infrastructures, not the frequency of motifs per rule type per pair of infrastructures). The first subset of the rule statements illustrates the motif-A. In this type, a single rule specifies that an actor must do something to two or more infrastructures. The rule statements R1–R3 below belong to this category.

- ***(R1)*** *In preparation for stormwater overflows that often occur in the times of monsoon or typhoon, the entire facilities in the system are to undergo safety inspection and improvement*.
- ***(R2)*** *In times of clear weather, prevent the inflows from stormwater drainage into a storage facility through the control of valves and gates in the intercepting facility*.
- ***(R3)*** *When chemical spills occur while there already exist stored volumes or recent precipitation in the storage facilities, each storage facility is emptied swiftly in sequential order to prepare for additional inflows of chemical spills*.

In R1, although not explicitly stated, it can be inferred that the actor taking an action is the operator of the focal storage system (Attribute). The action is to conduct a safety inspection and improvement (aIm). The direct oBject is "*the entire facilities in the system*," which includes the facilities for interception, debris collection, storage, and discharge. The Context of R1 is about the purpose of the action: "*In preparation for stormwater overflows that often occur in the times of monsoon or typhoon*." The IG coding results and the corresponding bipartite network are shown in Figure 7A.

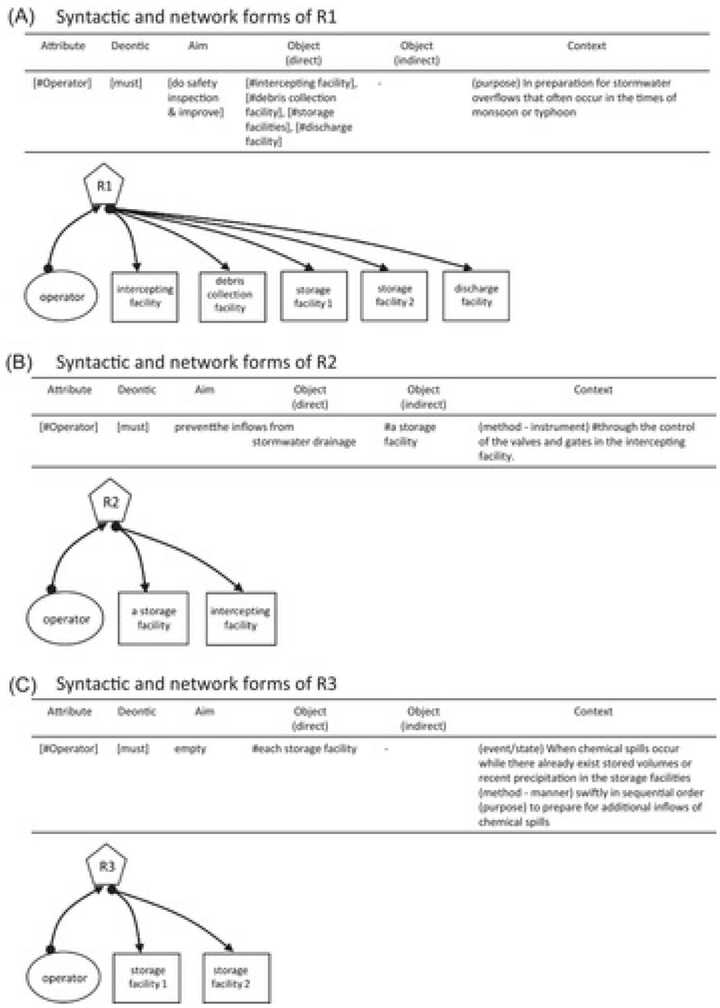


FIGURE 7: The IG coding and network representation of the rule statements R1-R3 (the motifs-A). The tag '#' is used to indicate the Attributes, oBjects, and Context elements that are included as nodes in the network representation.

Similarly, in R2, the actor taking an action is the operator (Attribute). The action for R2 is "*prevent*" (aIm). The direct and indirect oBjects are "*the inflows from the stormwater drainage*" and "*a storage facility*," respectively. The Context is about the instrumental method used to achieve the aIm-direct oBject combination, that is, "*controlling the valves and gates in the intercepting facility*." The IG coding results and the corresponding bipartite network of R2 are shown in Figure 7B. Note that the direct oBject ("*the inflows from the drainage system*") is omitted in the network representation because it is neither physical stock nor animate actor.

In R3, the Attribute taking an action and the action are "*the operator*" (Attribute) and "*empty*" (aIm), respectively. The direct oBject is "*each storage facility*," that is, storage facilities 1 and 2. The Context of R3 touches on the event/state triggering the action ("*When chemical spills occur while there already exist stored volumes or recent precipitation in the storage facilities*"), the manner by which the action should take place ("*swiftly in sequential order*"), and the purpose of the action ("*to prepare for additional inflows of chemical spills*"). The IG coding results and the corresponding bipartite network are shown in Figure 7C.

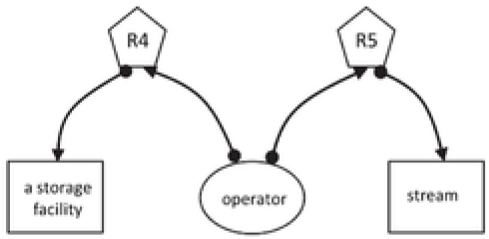
The second subset of the rule statements concerns the motif-B. This type signifies either co-occurring actions (an actor takes one action to an infrastructure and concurrently takes a different action to another infrastructure depending on a context) or alternatively occurring actions (an actor takes mutually exclusive, alternative actions to a pair of infrastructures depending on a context) specified over two linked rule statements. Whether co-occurring or alternatively occurring, a pair of infrastructures indirectly affects each other through human actions that depend on rules. The rule statements R4–R7 below belong to this category.

- ***(R4)*** *If the point of chemical spill is known, only the inflows from the corresponding drainage area are directed to a storage facility, and* ***(R5)*** *the inflows from the remaining drainage areas are by-passed to maximize the room in the storage space*.
- ***(R6)*** *If within the water quality standard, discharge to the stream, and* ***(R7)*** *if not meeting the water quality standard, direct and store into a storage facility*.

In R4–R5, it can be deduced that the actor taking an action (Attribute) is the operator of the focal system. The aIm and direct oBject for both R4 and R5 are about directing the inflowing water in some way. The key difference lies in the indirect oBject, or the receiver of the action performed on the direct oBject (inflowing water). While a storage facility receives the inflowing water being directed by the operator in R4, it is the water stream that receives the inflowing water from drainage areas being bypassed by the operator in R5 (although not explicitly stated, we can infer that the water stream is the indirect oBject of R5). These co-occurring actions depend on the event/state "*If the point of chemical spill is known*." The IG coding results, and the corresponding bipartite network, are shown in Figure 8A. Note again that the direct oBjects of R4 and R5 ("*the inflows from…*") are omitted in the network representation because they are neither physical stock nor animate actors.

(A) Syntactic and network forms of R4 and R5

Attribute	Deontic	Aim	Object (direct)	Object (indirect)	Context
[#Operator]	[must]	direct	the inflows from the corresponding drainage area	#a storage facility	(event/state) If the point of chemical spill is known
[#Operator]	[must]	by-pass	the inflows from the remaining drainage areas	[#the stream]	(event/state) If the point of chemical spill is known



(B) Syntactic and network forms of R6 and R7

Attribute	Deontic	Aim	Object (direct)	Object (indirect)	Context
[#Operator]	[must]	discharge	[the inflows]	[#the stream]	(event/state) If within the water quality standard
[#Operator]	[must]	direct and store	[the inflows]	#a storage facility	(event/state) if not meeting the water quality standard

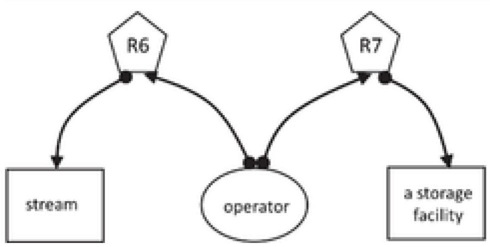


FIGURE 8: The IG coding and network representation of the rule statements R4-R7 (the motifs-B). The tag '#' is used to indicate the Attributes, oBjects, and Context elements that are included as nodes in the network representation.

The rule statements R6 and R7 show that the actor (operator) is to take a set of alternative actions depending on the quality of the inflowing water. The aIm and direct oBject for R6 are about directing the inflows when the water quality is within a standard. For R7, the aIm and direct oBject are about directing and storing the inflows when the water quality is worse than the standard. The IG coding results, and the corresponding bipartite network, are shown are Figure 8B.

The last subset of the rule statements is chosen to demonstrate the motif-C. This type signifies that a pair of infrastructures are seemingly unrelated when looking at two rules that concern them individually but are possibly logically related through a third rule specifying that the actors of the two infrastructures must coordinate their actions in some way.

- ***(R8-A & R8-B)*** *In preparation for chemical spills, always operate one of the storage facilities in empty state.*
- ***(R9)*** *If two or more effluent/stormwater storage systems are present, appoint an operator for each system for its operation.*

- ***(R10)*** *If required, a cooperative system is implemented in which a joint response with a neighboring effluent/stormwater storage system is enabled*.

In this subset, the two mandates that individually concern a pair of infrastructures are defined in R8-A and R8-B. Although it is a single rule statement, it can be treated as two separate rules because it applies to the operators of both infrastructures (focal buffer storage system and its neighboring buffer storage system) and guides each operator to do something to its own infrastructure, i.e., "*operate one of the storage facilities in empty state*" (Figure 9). Here, we show two examples of a third rule suggesting that the actors of the two infrastructures must coordinate their actions in some way. In R9, the local government (Attribute) is instructed to appoint (aIm) an operator (direct oBject) for each buffer storage system. In addition, some degree of coordinated action is likely to be present between the two operators if the two buffer storage systems are not distant from each other. This is shown in R10 where the operator of the focal system (Attribute) is instructed to organize a joint action (aIm) with the operator of the neighboring system (direct oBject). R9 and R10 imply a case of multi-level governance: the operators of the two infrastructures are vertically linked to the local government in addition to being horizontally linked to each other for cooperative joint responses. From these vertical and horizontal linkages, a logical interdependency might emerge. The IG coding results and the corresponding bipartite network are shown Figure 9.

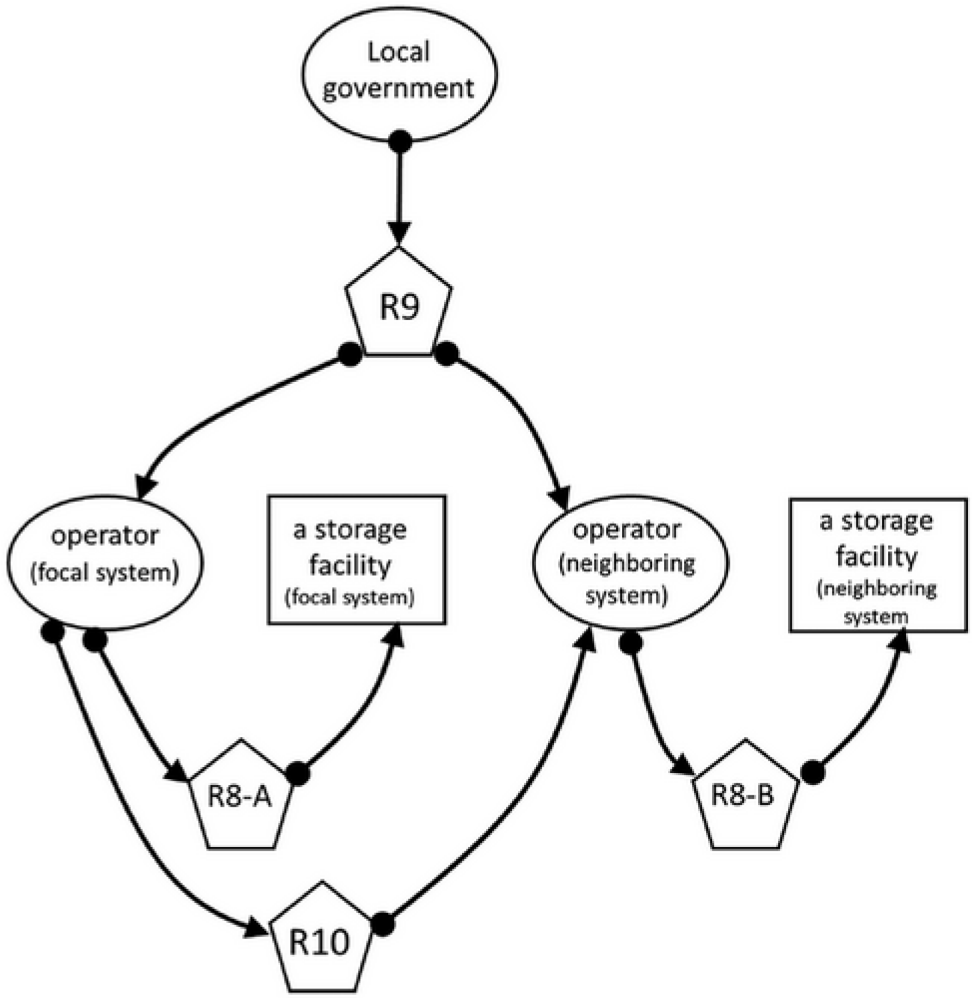


FIGURE 9: The IG coding and network representation of the rule statements R8-R10 (the motifs-C). The tag '#' is used to indicate the Attributes, oBjects, and Context elements that are included as nodes in the network representation.

Based on the network motifs identified above, one can assess the degree of logical interdependencies among the identified systems components. For this, it is convenient to cross-tally a matrix showing the frequencies of the network motifs found for all possible pairs of infrastructure entities (Figure 10). The higher the frequency of the motifs found for a pair, the greater the degree of a logical relationship between the pair. In this particular applied example, the following pairs show a relatively higher degree of logical interdependence: storage facility 1 & storage facility 2 (freq. = 7), intercepting facility & storage facility 1 (freq. = 2), intercepting facility & storage facility 2 (freq. = 2), storage facility 1 & water stream (freq. = 2), storage facility 2 & water stream (freq. = 2), storage facility 1 & storage facility of a neighboring system (freq. = 2), and storage facility 2 & storage facility of a neighboring system (freq. = 2). Based on this cross-tally result, one can determine which pairs to focus on for further analyzing the nature of logical relationships. For example, for those pairs, one can derive the frequencies of motifs per rule type (the seven rule types of E. Ostrom (2005)) to further gauge the strength of logical relationships. An analyst can also create a matrix for each motif type (A–C). For instance, one matrix can show the frequency of network motif-A, another can display the frequency of motif-B, and so on, providing a varied perspective.

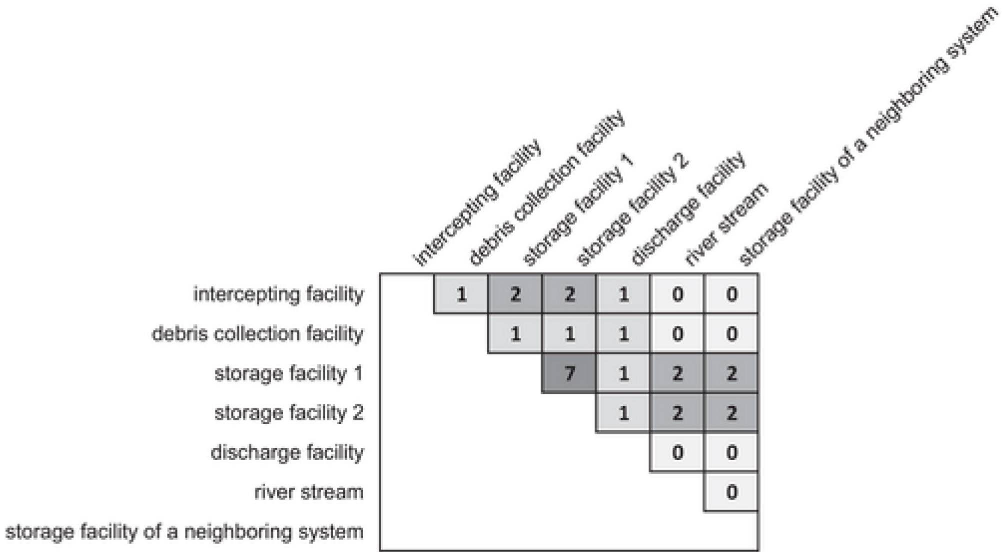


FIGURE 10: A matrix showing the frequencies of the network motifs A-C for all possible pairs of infrastructure entities (based on the rule statements R1-R10 provided in Section 3.1).

4 CLARIFICATION AND A REVISED DEFINITION OF LOGICAL INTERDEPENDENCIES

This paper is motivated by a research gap in infrastructure interdependencies, which are crucial for understanding the fragility of entire systems. Although the logical form (how two infrastructures are connected via human decisions) is regarded as one of the fundamental types of such interdependencies, the question of how to apply the notion in practice and how to quantify a degree of logical interdependencies between a pair of infrastructures remains under-explored. We argued that this gap stems in part from the definition of the notion that is perhaps too broad, that is, two infrastructures are logically interdependent if they affect the state of each other via mechanisms other than materials and information exchange and geographic proximity and in ways that involve human decisions (Rinaldi et al., 2001). This is such a wide-ranging description that it has kept the notion vague and caused the real-world identification of logical relations difficult. There is currently no structured approach to identifying the logical form of interdependencies in a system of infrastructures.

We took a step towards addressing this gap by focusing on rules, or *institutions* (*sensu* Ostrom, 2008). These institutions, whether formal rules delineated in official documents or unwritten informal rules understood and shared among group members, establish the guidelines for human interaction with one another and with physical entities. When such rule-mediated interactions underlie the operation of two or more infrastructures that require some degree of coordination, logical interdependencies may be latent unrecognized. Indeed, previous studies suggest that institutional and plan silos are common in practice and this lack of coordination potentially threatens overall system resilience (Berke et al., 2015; Hannibal et al., 2022; Sellberg et al., 2018). Our focus on rules also stems from the recognition that such rule-mediated interactions, when linguistically expressed, have a syntactic form that can be translated into meaningful networks. These syntactic and network forms data allow a structured approach to identifying logical interdependencies.

Our approach employs the Institutional Grammar (IG) (Crawford & Ostrom, 1995; Frantz & Siddiki, 2021) and a variant of the Network of Prescribed Interactions (NPI) lens (Olivier, 2019; Olivier et al., 2020). We applied these two conceptual tools to a dam reservoir case to illustrate how the syntactic and network forms data can be extracted from a set of rule statements. A lesson from the application is that logical interdependencies rarely occur in isolation to other forms of interdependencies (physical, geographic, and cyber forms). More often than not, these different forms co-occur, such as the combination of physical and logical connections and the combination of geographic and logical connections. Building on the syntactic and network forms data, we developed a way to quantify a degree of logical interdependency. The approach is based on the idea that there are certain network motifs indicating logical interdependencies in a pair of infrastructures, and that such motifs can be readily discerned in the rule-entity network forms data. The higher the frequency of these network motifs around a pair of infrastructures, the greater the extent of logical interdependency. We proposed an initial set of such network motifs (the motifs-A to C shown in Figure 5) and a cross-tabulation matrix for organizing the motif frequencies (Figure 10). We also discussed how these network motifs can be categorized according to the seven generic rule types proposed by E. Ostrom (2005) to develop a more nuanced interpretation of the motif frequencies. We then demonstrated our approach using an applied example based on an actual operational guide for an infrastructure system designed for disaster prevention (a buffer storage system for containing effluents and floodwaters).

Going forward, we suggest an update to Rinaldi et al.'s original definition of logical interdependency. Their definition conceives the notion as interdependencies in a pair of infrastructures caused by human decisions and in ways that do not involve the physical, geographic, and cyber linkages. In light of what has been discussed so far, we argue for the following two-part definition of logical interdependency: ***(1) two infrastructures are logically interdependent if the state of each depends on the state of the other through human decisions and the formal and informal rules guiding those decisions; and (2) logical interdependencies can occur either independently or in conjunction with other types (physical, geographic, and cyber) of interdependencies***. This revised definition offers greater clarity and applicability to the concept while remaining consistent with the approach proposed in this paper. Table 2 below contrasts the original and the two-part definition suggested in this paper.

TABLE 2. Comparison of the original definition of logical interdependencies and the revised definition proposed in the current paper.

Original definition	Revised definition
"Two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber,	(1) two infrastructures are logically interdependent if the state of each depends on the state of the other through human decisions and the formal and informal rules guiding those decisions; and (2) logical interdependencies can occur either independently or in

Original definition	Revised definition
or geographic connection.”. (Rinaldi et al., 2001, p. 16) “Furthermore, human decisions may play the predominant role in logical interdependencies in particular.” (Rinaldi et al., 2001, p. 16)	conjunction with other types (physical, geographic, and cyber) of interdependencies.

From network science and governance perspectives, we also make the following observations. First, certain network metrics can be derived from the rule-entity bipartite networks to assess the degree of linkage between a pair of infrastructures. For example, the strength of a linkage connecting two nodes, measured as the number of individual rules that prescribe the same pattern connecting two nodes, can shed light about the level of logical coupling in a pair of infrastructures. It is not the same to have one single rule mandating an actor to perform an action on an infrastructure than having multiple rules specifying situations and scenarios where an actor performs an action on an infrastructure. Depending on the type of situation, the latter may be preferred since it adds redundancy and strength (in the form of multiple rules) to that specific prescribed relation. In other words, tight logical coupling in a pair of infrastructures based on such multiplicity of overlapping rules does not necessarily lead to bad outcomes. Although cascading failures can result from logical coupling in certain situations (e.g., presence of two operational rules on a pair of infrastructures that contradict each other), there could be also positive effects resulting from stronger logical relations in other contexts (e.g., rules that foster backup actions or cooperative actions in times of emergency). Either negative or positive effects can arise depending on the type of situation, that is, double-edged swords or spillovers (cascading vs. synergy) can result from two infrastructures that show a tight logical coupling. Relatedly, one could argue that the stronger the other form of coupling (e.g., geographical proximity) in a pair of infrastructures, the stronger the need for logical coupling in the pair, that is, a correspondingly tight logical coupling may emerge in the same pair to deal with potential risks. For example, when two infrastructures are geographically interdependent (e.g., dam and hydropower plant), multiple rules that mandate safety measures will likely emerge regarding their repair and maintenance to avoid accidental damages.

Second, a benefit of the network approach is that it allows capturing of patterns beyond what is expressed by individual rules. In that sense, networks enable a configurational analysis of rule mandates (Olivier & Schlager, 2022). For example, if the average of all path lengths between a pair of infrastructure nodes (measured as the average number of links constituting paths between two infrastructure nodes) is low, it can be interpreted as the presence of rules prescribing a tightly coupled system where two things happen: actors with authority over infrastructures have multiple (and potentially redundant) responsibilities over similar infrastructures; and those rules are formally prescribing some form of interaction (such as authority relations, information sharing, consultation) among those actors. In the context of our study, this should lead to a higher likelihood of logical interdependency in a pair of infrastructures. From a governance perspective, such closed structures may facilitate the quick identification of infrastructure flaws or gaps in coordination among actors. Conversely, high average path lengths may correlate with rules distributing responsibilities among a wide variety of actors which, ultimately, would require high levels of coordination among decision makers when managing infrastructure that is physically or geographically interdependent. Such instances of decoupling between rule-mandated interactions and physical or geographic interdependences may lead to a suboptimal management of an infrastructure complex.

Third, the use of network motifs can facilitate comparative empirical work. Through the identification of specific network building blocks or motifs (Bodin & Tengö, 2012; Bodin et al., 2019; Kininmonth et al., 2015), networks can be compared to assess the prevalence or absence of structures associated with specific collaboration or coordination processes (Morrison et al., 2023) or the extent to which logical interdependencies are created via different motifs (as shown in Figure 5). From a governance perspective, the reliance on some network motifs may result in different challenges at the time of managing logically interdependent infrastructures. Figure 11 below showcases two hypothetical scenarios based on two different motif structures. The scenario in Figure 11A presents a situation of potential logical interdependence between two infrastructures, where only one actor is mandated to influence these infrastructures. The scenario in Figure 11B, from a pure logical interdependence approach, is the same, but with the difference that this time *two* actors are mandated by rules to influence these infrastructures. From a governance perspective, scenarios like the latter case could exacerbate the coordination challenges that exist when two infrastructures are logically interdependent. For this type of comparison, it may be informative to develop an "actor-to-actor" frequency matrix that captures how different actors jointly act on two or more infrastructures (e.g., Figure 11C). In this actor-to-actor matrix, the cells represent the frequency of motifs involving the corresponding row and column actors acting on two or more infrastructures. This matrix can be used to distinguish between the logical interdependencies created by the action of a single actor (e.g., Figure 11A) and the logical interdependencies created by the actions of multiple actors (e.g., Figure 11B). With this actor-to-actor matrix, an analyst can dig into further details when certain cells show a high frequency value, i.e., what venues are involved there and what pairs of infrastructures are involved.

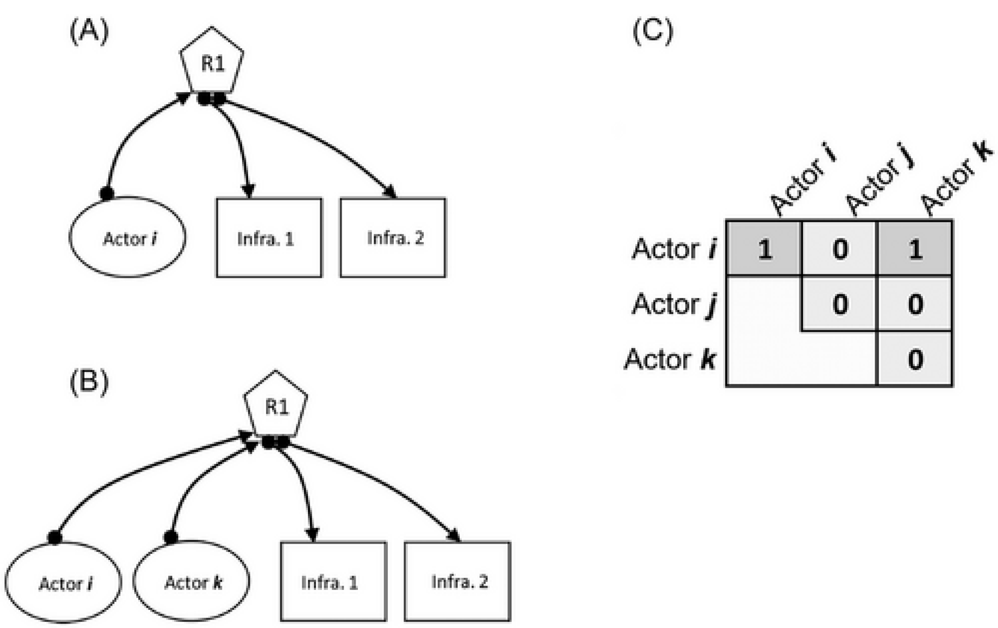


FIGURE 11: Two hypothetical scenarios of motif structures. While one actor is mandated to influence two infrastructures (A), two actors can also be involved in the same pair in a logical relation (B). In the panel C, an "actor-to-actor" frequency matrix that corresponds to the two motifs is shown. In the matrix, the frequency represents the frequency of the network motifs involving the corresponding row and column actors acting on two or more infrastructures. The cell (1,1) shows the frequency value of 1, meaning that there is one network motif in which a logical interdependency is created through the action of a single actor (Actor *i*). The cell (1,3) also shows the frequency value of 1. This time, however, it means that a logical interdependency is created through the joint actions of two actors (Actor *i* and Actor *k*).

Last but not least, we discuss some implications of our approach to the risk analysis of complex socio-technical systems. Given the importance of understanding human error in risk analysis within such systems, we can assert that human error can be seen as deviations from rules or normative constraints, which can lead to accidents. (Leveson, 2004). In particular, the violation of rules can trigger a risk propagation process because various risk factors interact and compound (Ma et al., 2022; Yao et al., 2023). Bayesian networks can be used to quantify the likelihood and impact of human error in such risk propagation processes through the categorization of human factors (e.g., unsafe acts and lack of supervision) and assignment of conditional probabilistic relationships among them (Qiao et al., 2020; Uğurlu et al., 2020). Our approach can contribute to this quantitative method by delineating the control structure (rule-mediated interactions among actors and animate objects) and specifying unsafe acts and lack of oversight as violations of rules by facility operators and their supervisors. For example, in a Bayesian network, conditional probabilities can be conceptualized as follows. The probability of supervisor *S* violating a rule is

; given the , the probability of operator *O* violating a rule is . Next, given the and , the failure probability of Infrastructure *A* operated by *O* is . Given those three probabilities above, the failure probability of Infrastructure *B* in a logical relation to infrastructure A is

.

In addition to rule violations, inadequate coordination is also considered a human-driven risk factor, especially when multiple actors within a network may take conflicting control actions (Leveson, 2004). Utilizing network motifs derived from formal rules can assist in identifying potential coordination problems within a network. For instance, in Figure 11, two hypothetical scenarios based on two different motif structures are shown. As previously discussed, the scenario depicted in Figure 11A illustrates a potential instance of logical interdependence between two infrastructures, where only one actor is tasked with influencing them. In contrast, the scenario in Figure 11B, analyzed from a pure logical interdependence perspective, is analogous, except that this time two actors are governed by rules to influence the infrastructures. In the latter case, a hypothetical example of conditional probabilities is as follows: the probability of Actor *i* choosing a coordination strategy is

; given the , the probability of Actor *k* choosing a coordination strategy is ; given the probability of failure in coordination , the failure probability of Infrastructure *1* is ; and given those three probabilities above, the failure probability of Infrastructure *2* is

.

Finally, there are a few caveats to the current study that should be noted. First, the set of network motifs of logical relations (the motifs-A to C) provided in this study does not constitute an exhaustive set and can be expanded to include additional ones as more rule statements are analyzed by future studies. Second, the frequency of the motifs found for a given pair of infrastructures depends on the scope of rule-containing documents included for analysis and how the text in such documents is written. Many different types of plans, for example, shape infrastructure systems and their governance in cities. If the scope of the documents and texts included for analysis is not comprehensive and balanced enough, the frequencies of the motifs found can be misleading and unrepresentative of reality. Care must be taken to achieve a balance in the scoping of the rule-statements.

Third, there may be informal rules, those that are not written down in rule-containing documents. Interviews and participant observations can be conducted to elicit and include such informal rules for analysis. Though not always, rules-in-use and rules-in-form may not coincide. The presence of informal rules outside rule-containing documents and what to do with them is really the matter of data collection and scoping of the rules to include for analysis. Had we collected the information on informal rules through other methods (interviews, observation, etc.), we could have applied the same motif-based approach to the verbal linguistic expressions of those unwritten rules to identify the network of interactions and logical interdependencies. Fourth, relatedly, not all rules written in formal documents like plans will be implemented, with some plans being written primarily to “signal” preferences and positions to other actors (Hopkins & Knaap, 2018).

Fifth, the approach proposed in this study does not provide a way to diagnose logical interdependencies. That is, there is no explicit provision on whether and how the presence of a logical relation is good or bad for a system-level goal (sustainability or resilience) and what can be done about it. Although Rinaldi et al. (2001) mentions that a crisis can result from a logical relationship, there could also be positive effects resulting from a logical relation. Thus, to be effective, an approach is needed that is both descriptive and *diagnostic* in the analysis of logical interdependencies. Sixth and as the final item, we reiterate the significance of the current research. Although the use of IG and the identification of network motifs and their frequency counts may seem quite time-consuming to apply, we underscore that the proposed approach provides a systematic way to identify and quantify a degree of logical interdependency based on the robust theoretical foundations. Currently, there seems to be no viable alternative methods to do the same.

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