Chapter 15

A HOLISTIC-REDUCTIONISTIC APPROACH FOR MODELING INTERDEPENDENCIES

Stefano De Porcellinis, Gabriele Oliva, Stefano Panzieri and Roberto Setola

Abstract Modeling and analyzing critical infrastructures and their interdependencies are essential to discovering hidden vulnerabilities and threats. Several current approaches engage a holistic perspective and rely on abstract models; others incorporate a reductionistic perspective and focus on inter-domain and intra-domain interactions among elementary components. This paper proposes a mixed approach in which holism and reductionism coexist. A critical infrastructure is expressed at different, albeit interrelated, levels of abstraction, and intermediate entities that provide specific aggregate resources or services are introduced.

Keywords: Interdependencies, complex systems, holistic-reductionistic modeling

1. Introduction

Infrastructures such as energy grids, transportation networks and telecommunications systems are vital to every facet of society [2]. A malfunction or disruption in any of these complex systems of systems can have serious impacts on the health, safety, security and economic well-being of citizens and on government functions [4].

In order to be effective, a critical infrastructure protection strategy requires detailed knowledge about the global behavior and intrinsic weaknesses of infrastructures and their components, especially in the presence of adverse events. Most infrastructure protection strategies leverage analysis and simulation. However, the complexity of the infrastructures [15] renders common systems analysis and simulation methodologies ineffective, especially due to the many interdependencies existing within and between infrastructures [1]. These interdependencies are often implicit, hidden and not well understood even by infrastructure owners and operators.

Rinaldi, *et al.* [17] categorize interdependencies into four, not necessarily mutually exclusive, classes:

- **Physical Interdependency:** Two infrastructures are physically interdependent when the operations of one infrastructure depend on the physical output(s) of the other.
- **Cyber Interdependency:** An infrastructure has a cyber dependency if its state depends on information transmitted by means of the information infrastructure.
- **Geographical Interdependency:** A geographical interdependency exists when elements of multiple infrastructures are in close spatial proximity. Adverse events affecting one element may generate cascading failures in one or more proximal infrastructures.
- **Logical Interdependency:** Two infrastructures are logically interdependent when the state of one infrastructure depends on the state of the other because of control, regulatory or other mechanisms that are not physical, geographical or cyber in nature.

De Porcellinis, *et al.* [6] introduce an additional type of interdependency:

- **Social Interdependency:** An infrastructure has a sociological interdependency when its operativeness is affected by the spreading of disorder related to human activities, i.e., the emergence and diffusion of collective behaviors that have a negative impact on the ability of the infrastructure to operate.

Nieuwenhuijs, *et al.* [14] treat only physical and functional dependencies as real dependencies; the others are viewed as common vulnerabilities that are shared by two or more infrastructures or components (and are, therefore, not considered to be dependencies). However, we believe that there is the need to represent failures and their spread in order to highlight criticalities and to identify adequate countermeasures and policies to prevent or mitigate their effects. This need derives from the fact that shared threats and propagating failures occur as a result of different mechanisms. Shared threats (e.g., an earthquake) derive from vulnerabilities that are shared due to particular conditions or properties of the elements (e.g., spatial proximity). In contrast, failures and the propagation of failures derive from direct or indirect interactions among the elements (e.g., fire is propagated from one element to other proximal elements that have "geographical" interactions with each other).

Several approaches have been introduced to address the problems posed by the complexity of infrastructures and their interdependencies. Holistic approaches treat infrastructures as unique entities; reductionistic approaches model systems as sets of interconnected elementary elements; other approaches use multiple formalisms and the agent-based paradigm to model infrastructures and components. The various modeling paradigms have their advantages, but

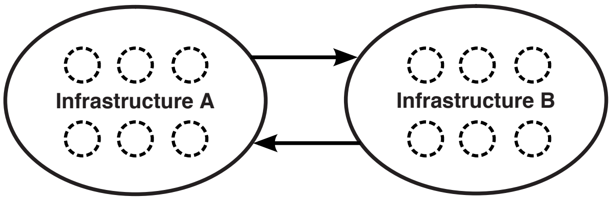

Figure 1. Holistic modeling.

all of them are limited in their ability to cope with the complex, multidimensional nature of critical infrastructures [6, 17].

De Porcellinis, *et al.* [5] have proposed a mixed holistic-reductionistic (MHR) approach to address this key limitation. The MHR approach merges the holistic and reductionistic paradigms into a single framework, thereby providing the benefits of both types of modeling approaches. This paper describes an enhancement of the MHR approach, which incorporates mediation mechanisms to enrich the original modeling paradigm. These mediation mechanisms constitute the basis of the mixed approach in which holism and reductionism coexist.

2. Modeling Interdependencies

The safety, security and dependability of critical infrastructures are strongly dependent on mutual interaction phenomena. Direct dependency mechanisms are easily identified and modeled in small portions of a critical infrastructure. However, in a large, complex infrastructure, direct and indirect dependencies among the various elements form multiple loops, which give rise to mutual dependency or "interdependency" mechanisms. Such interdependencies are difficult to understand, and manifest themselves only after the entire infrastructure has been modeled. At the same time, they pose serious threats to the stability of a critical infrastructure.

Several approaches have been proposed to model critical infrastructure interdependencies and their potential effects. They may be classified based on their use of three (possibly overlapping) perspectives: (i) holistic perspective; (ii) reductionistic perspective; and (iii) agent-based hybrid perspective.

2.1 Holistic Perspective

In the holistic perspective, each infrastructure is viewed as a single, monolithic entity (Figure 1) with well-defined boundaries and a (possibly reduced) set of functional properties. Infrastructures are assumed to interact with each other according to an identifiable (and limited) set of relationships.

The holistic perspective simplifies the identification of dependencies and interdependencies, which is a natural outcome of the modeling procedure. An example is the Input-Output Inoperability Model [9] based on the economic

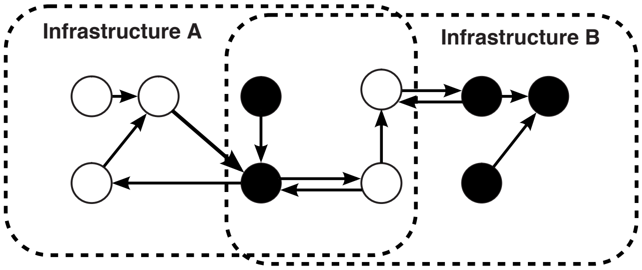

Figure 2. Reductionistic modeling.

theory of Leontief [11], which expresses the cascading effects that a failure in one critical infrastructure induces in other critical infrastructures.

A holistic approach typically models interactions between elements at a high level of abstraction, usually based on statistical data, market rules, sociological trends and strategic policies. The high-level representation masks low-level interdependencies that are based on the exchange of physical quantities. In addition, the abstraction and simplification mechanisms often do not capture the structure and geographical scale of infrastructures and the dynamics of the various infrastructure components.

2.2 Reductionistic Perspective

A reductionistic approach identifies "elementary" components within an infrastructure and then describes the evolution of the entire system based on the "aggregated" behavior of these components. The elementary components, which are characterized by their own dynamics, receive/provide resources from/to other components. A failure in one component propagates to other components.

In the reductionistic perspective, the boundaries of each infrastructure tend to fade (Figure 2), but the interactions between components can be detected.

Reductionistic approaches are very powerful and well-suited to representing the complexities of cross-infrastructure interactions. However, the modeling effort can be overwhelming and massive computational resources are required, especially for large, complex infrastructures. Reductionistic approaches also require deep knowledge about the modeled systems and their interdependencies. This is problematic because, in addition to the large amount of data required, there often is a lack of detailed information about elements and their interdependencies. Thus, reductionistic approaches often simplify and/or reduce the scope of the analyses, which limits the applicability of the resulting infrastructure models.

2.3 Agent-Based Modeling

Agent-based modeling and simulation (ABMS) approaches model infrastructures and their elements as software agents. Each software agent implements a specific infrastructure component that interacts with other agents and the environment. The agent-based approach does not impose any limits on the granularity used to describe the decomposing/aggregating elements of an infrastructure, thereby providing an extremely flexible framework for modeling and analyzing complex systems.

Several agent-based simulation tools have been developed for analyzing critical infrastructures [16]. Notable examples include EPOCHS [10] and various ABMS tools created as a result of the CRESCO Project [18].

One of the key results of the CRESCO Project is a federated framework that can be leveraged by ABMS tools. The federated framework incorporates a two-layer architecture that enables the representation (within a single simulation environment) of different infrastructures and different functional aspects of their elements. The bottom layer of the framework contains simulators that simulate intra-domain relationships at a high level of detail (e.g., power flows and transients in an electrical power grid). The top layer contains agent-based simulators that simulate inter-domain interactions [3, 6] at high levels of abstraction. The "horizontal" simulators in the top layer implement components belonging to the same infrastructures modeled in the bottom layer. "Super agents" within these horizontal simulators are used as connectors between the two layers [18], permitting the access of detailed information from simulators in the bottom layer and data transfer to the "component" agents in the horizontal simulators.

The federated ABMS approach demonstrates how multi-scale modeling techniques can overcome the limitations of pure holistic and reductionistic approaches. However, in order to accomplish this, it is necessary to encapsulate the representation of the entire infrastructure and the services involved within unique black-box agents. At the same time, the federated ABMS approach requires all intra-domain dependencies to be modeled by dedicated simulators and super agents, which expose the resources and the behaviors resulting from functional inter-domain interactions to the multi-domain simulators.

3. Mixed Holistic-Reductionistic Approach

De Porcellinis, *et al.* [5] developed a mixed holistic-reductionistic (MHR) formulation to address the limitations of other approaches. MHR is designed to capture the dynamics that characterize an infrastructure while maintaining model complexity at a manageable level.

The MHR approach uses reductionistic techniques to model interdependencies between components, and a holistic paradigm to express the logical and functional dependencies involving infrastructures as a whole. Thus, an infrastructure is simultaneously represented within a common modeling paradigm as monolithic entity and as interconnected components. For example, a control room, which represents the "brain" of an infrastructure, can be viewed as a high-level entity. The same control room, with its buttons, lights and communication lines, can be modeled as a collection of interconnected components according the reductionistic (and physical) perspective.

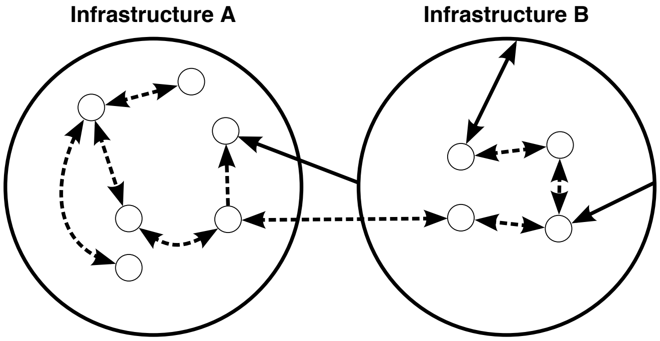

Figure 3. Mixed holistic-reductionistic modeling.

Figure 3 illustrates the mixed holistic-reductionistic perspective. The framework expresses the dependencies and interdependencies existing between reductionistic components belonging to the same or different infrastructures. At the same time, the framework also represents the high-level relations among the holistic views of different infrastructures.

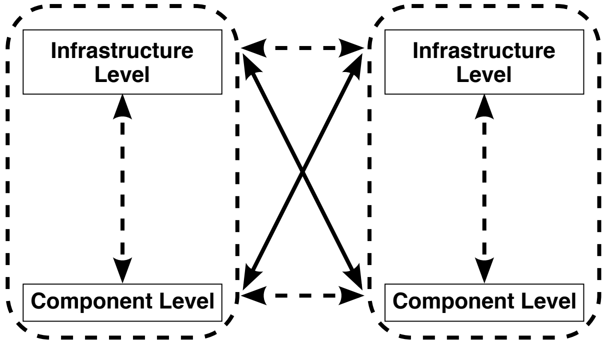

Figure 4. Interdependencies in the MHR approach.

The stack-like schema in Figure 4 shows how the holistic and reductionistic perspectives capture the "horizontal" relations among elements and the "vertical" dimension corresponding to a hierarchical decomposition (or aggregation), which is used to express the inner relationships existing within an infrastructure and its components. The MHR paradigm also uses "diagonal" links to explicitly model functional relationships between heterogeneous components and infrastructures, i.e., elements with different levels of granularity and belonging to different domains (solid lines in Figure 4). Indeed, diagonal relations can be expressed using horizontal and vertical dependencies, enabling the specification of all the links between the reductionistic components of one infrastructure and all the other involved elements. Note, however, that an explosion in complexity can occur due to the large number of interconnections that must be considered.

Also, many required links are generally hidden and may not be well understood from the point of view of a single component.

Representing dependencies and interdependencies using links between reductionistic components and the holistic view of an infrastructure leads to a simplified model. Moreover, only general information about the overall state of infrastructures is required, and there is no need to know the state of every component in the infrastructure.

As described above, each layer of an MHR model comprises several elements (or blocks) belonging to the holistic or reductionistic layers. All the elements with the layers conform to a common general model [6]:

- Elements exist in order to supply and/or consume tangible or intangible resources (e.g., goods, services and operativeness).
- Elements may suffer from faults or failures.
- Faults may propagate (or propagate their negative effects) based on various types of proximity.
- The ability of an element to provide the required resources depends on its operative condition, which is based on the availability of the resources it requires and on the severity of the failures that affect it.

The internal representation of a single block can be heterogeneous (e.g., rule-based system, dynamic system, finite state machine, etc.). The coupling of elements with different internal models is enabled by a common exposed interface.

4. Mediating the Perspectives

Although the framework described in the previous section simplifies the resulting model, it is not rich enough to capture the complexity of the problem at hand. In fact, reductionistic elements often rely on specific functionalities instead of depending on the overall state of the infrastructure. For example, the operativeness of a node in a telecommunications network may depend on the efficiency of the UMTS service in its zone rather than on the global state of the infrastructure. The model described above is unable to handle relations involving such specific, yet high-level, system views.

The same problem has emerged in other fields. Recent research in genetics [8] has shown that the exact knowledge and sequencing of the genome is not enough to understand the complex behavior of the human body. Therefore, it has become necessary to study functional gene aggregates (proteins, RNA, etc.) [7, 12] in order to "mediate" interactions between the genes and the human body as a whole.

We employ a similar strategy to improve the modeling capabilities of MHR. In particular, we introduce an additional layer in the framework to better represent how the effect of the holistic representation is propagated into the reductionistic representation of the overall system. An element in the intermediate layer of the model represents a tangible or intangible (logical, organizational, etc.) entity that provides an "aggregate resource" or "service." These intermediate entities are called "service providers" because they are characterized by the functionality they provide.

Consider, for example, a simple computer network composed of interconnected servers and user terminals. Clearly, the ability to provide end-to-end VoIP communications depends not only on the physical path, but also on the VoIP status and quality of service. Creating an exact reductionistic model of the dependencies and interdependencies in this scenario is not a trivial endeavor. Moreover, if many different functionalities exist in the overall system, model creation may require several iterations. Traditional end-user services such as GSM, SMS and electrical power are only some of the possible aggregate resources provided by service providers. In fact, other support and management functionalities (e.g., supervisory control, emergency backup generation, fire protection, etc.) should be considered.

Based on the biological perspective, a service provider is not just the sum of its components, but an emerging entity whose bounds are not easily modeled. In fact, a reductionistic component of an infrastructure may have multiple service contributions (e.g., a router in a computer network that forwards network packets for many different services). Moreover, a service can be "transversal," i.e., not necessarily limited to a single infrastructure. For example, a service provider belonging to one infrastructure can provide outputs to external entities (e.g., power distribution), or, less frequently, a service provider can emerge from the cooperation of entities belonging to different infrastructures. Finally, some aggregate resources may be required only in critical situations (e.g., a "network reconfiguration" service that handles overloads in a power grid or an emergency power supply for a router in a telecommunications network). As described above, service providers are mediation entities created to represent how specific high-level functions of a critical infrastructure are provided to reductionistic elements. The aggregate resources provided by the different service providers can be interrelated. For example the operativeness of a telecontrol service can depend on the state of the power distribution system and the emergency power supply, or the efficiency of traffic redirection and monitoring services in the transportation infrastructure can be mutually dependent.

An important issue is how to reverse the (monodirectional) dependencies between service providers and reductionistic elements. In fact, specifying the exact contribution exerted by every reductionistic element on the different service providers may render the overall complexity unmanageable. Indeed, such inverse dependencies are complex and are mostly hidden from the point of view of a single service provider. Also, it is often the case that the control actions performed to grant an acceptable quality of such "services" are demanded by entities with a wider perspective (e.g., a control room). Therefore, it is more appropriate that a service provider relays data provided by a management entity (with an overall vision and able to filter the huge amount of reductionistic data) instead of considering the contribution of every single component.

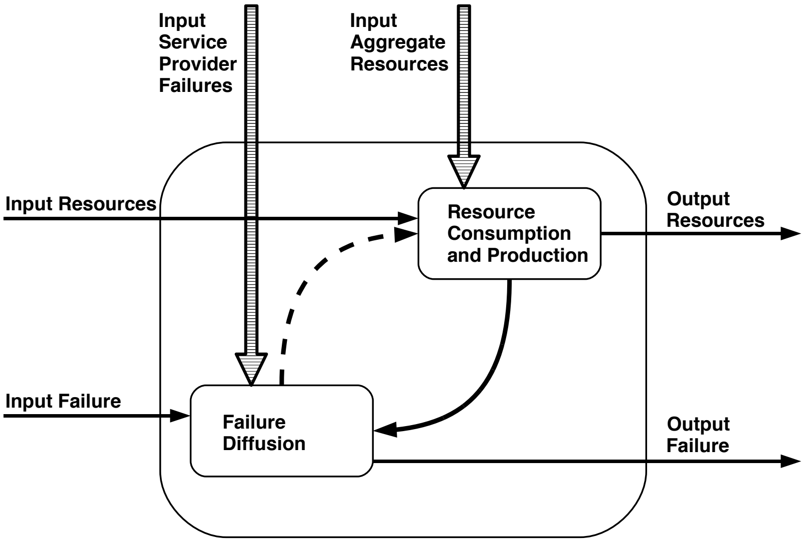

Figure 5. Reductionistic entity structure.

Such an approach takes into account the experience of human actors. It is more useful to engage this experiential knowledge within the holistic layer (e.g., via a rule-based system) rather than incorporating it within every service provider. Indeed, the operativeness of a service provider is largely influenced by the operative condition of the infrastructure and by the specific policies and management strategies adopted by the infrastructure owners and operators.

5. Mixed Holistic-Reductionistic Framework

The MHR framework has three possibly overlapping layers: (i) reductionistic layer; (ii) service layer; and (iii) holistic layer.

According to the reductionistic perspective, each infrastructure is decomposed into a web of interconnected elementary entities (or blocks). These entities receive and generate resources and propagate failures based on "proximities" of various types. Therefore, their behavior depends on the (mutual or not) interactions with other reductionistic elements. Moreover, their ability to operate properly depends on the availability and quality of aggregate resources (or services) offered by service providers (Figure 5).

Service providers are introduced as functional blocks to provide specific, yet high-level, functions to reductionistic elements belonging to the same or different infrastructures (Figure 6). Like reductionistic elements, service providers require and provide (aggregate) resources and may suffer from and propagate failures; this permits the modeling of complex, high-level failures (e.g., cyber attacks) that are difficult to model using a pure reductionistic perspective. The capability of each service provider is influenced by the operative condition of

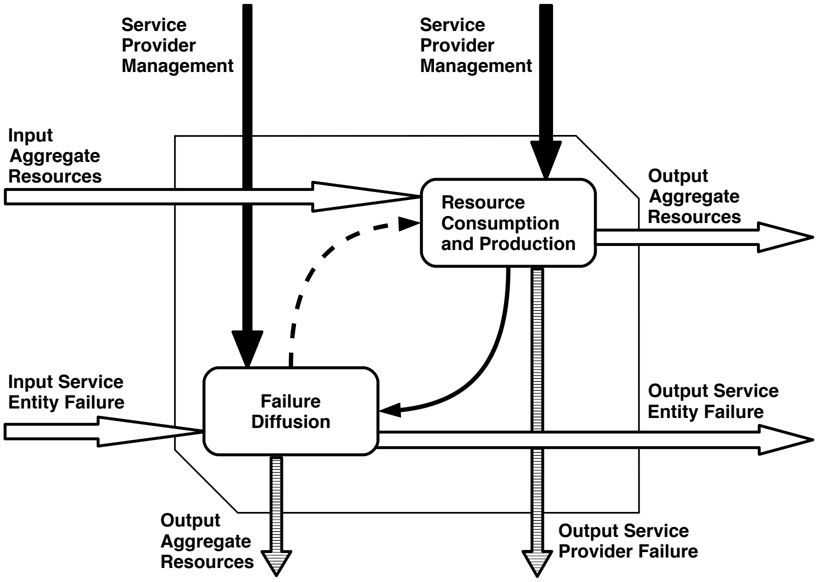

Figure 6. Service provider structure.

the infrastructures and by the policies and management strategies adopted in the specific context by infrastructure owners and operators.

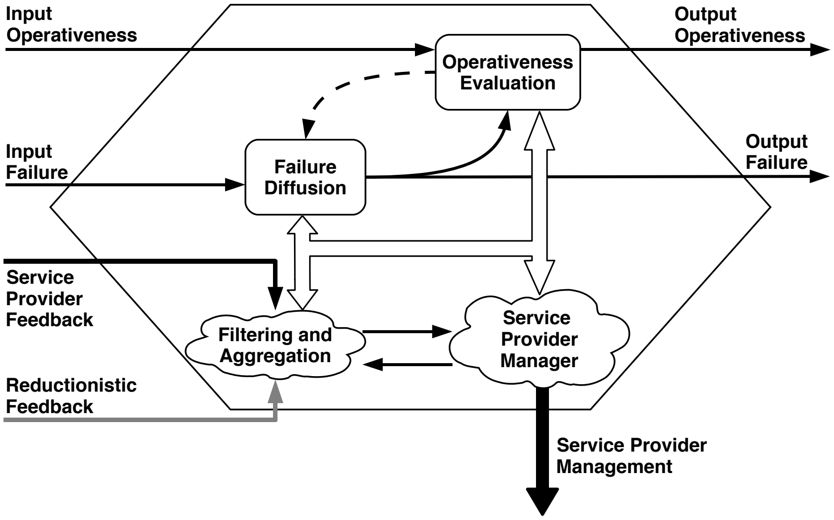

Figure 7. Holistic entity structure.

Holistic blocks (Figure 7) represent the holistic view of infrastructures. They interact with other holistic entities to exchange their operativeness. In this

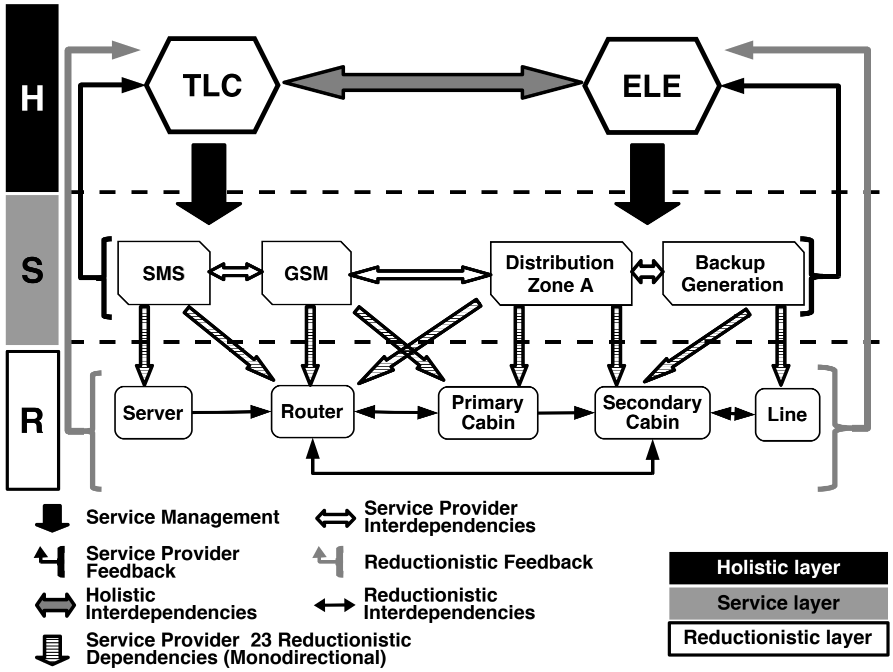

Figure 8. Example MHR architecture.

case, the failure block permits the modeling of sociologically-related events (e.g., strike, panic and malicious behavior) that are very difficult to model at a different level of abstraction. Holistic blocks influence the operative conditions of service providers based on the feedback received from reductionistic elements and on the overall state of the infrastructure. Moreover, every top node must provide adequate management service to the service providers by defining and executing appropriate control actions (e.g., flow redirection, parameter configuration, event-driven suspension/reactivation/recovery) in order to react to adverse events that may degrade or deny the aggregate resources provided by service providers and result in the cascading propagation of faults. Finally, a holistic node must be aware of the operativeness of its own service providers in order to obtain complete knowledge of the state of the infrastructure and update the overall operativeness accordingly.

Figure 8 shows an example MHR architecture. Note how the telecommunications (TLC) and electrical (ELE) infrastructures are naturally decomposed into holistic blocks, service providers and reductionistic entities.

6. Conclusions

The proposed MHR approach facilitates the modeling of complex, heterogeneous infrastructures and their interdependencies by simultaneously expressing the holistic interactions between infrastructures and the mutual influence of their components expressed using a reductionistic perspective. Aggregated and intermediate entities are used to model complex relationships existing between elementary components and complex, high-level structures. Also, service providers are engaged to mediate interactions between the holistic and reductionistic representations of the infrastructures. The MHR approach is well suited to the analysis of complex scenarios and to the design of innovative infrastructure cooperation mechanisms that can enhance the ability of an infrastructure to operate properly in the presence of adverse events. Our future work will focus on using the MHR paradigm to model and analyze real-world scenarios in the context of the EU IST Project MICIE [13].

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