Towards HLA-based Modeling of Interdependent Infrastructure Systems

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Abstract –

The accurate modeling of critical infrastructure systems (CISs) and their interdependencies is essential to assessing and predicting the behavior of interdependent CISs under various operation scenarios. Existing modeling approaches have limited ability to incorporate CIS domain knowledge and capture the systemic heterogeneity among the CISs, and thus cannot simulate the behavior of interdependent CISs with much detail and accuracy. In this study, a high level architecture (HLA)-based framework for modeling interdependent CISs is proposed that provides a methodology for co-simulating heterogeneous fine-grained CIS domain-specific models, reproducing with high fidelity the complex coupled systems. The results from a case study of two interdependent power and water systems revealed that the HLA-based CISs model could capture and simulate various systemic heterogeneity dimensions and their impact on the systems behavior, thus proving the efficacy of the proposed framework.

Keywords –

Critical infrastructure system (CIS); High level architecture (HLA); Distributed simulation; interdependencies; Domain knowledge; Systemic heterogeneity

1 Introduction

With the growth in scale and complexity of urban critical infrastructure systems (CIS) such as water supply systems and power supply systems, CISs are becoming increasingly dependent on each other for proper operation. Various events in history have shown that tight interdependencies among CISs can significantly increase the systems’ vulnerabilities, leading to catastrophic chain of events throughout the complex system of systems. On the other hand, the presence of interdependencies can play a significant role in improving the efficiency of CISs, since the CISs can provide functional and operation support to each other. Therefore, understanding the nature of CISs interdependencies and the role they play in the day-to-day operations of CISs is essential to assessing and predicting the behavior of CISs in various operational scenarios.

Several modeling approaches have been proposed in previous studies for modeling interdependent CISs and analyzing systems behaviors and interactions. Among these approaches, the agent-based modeling (ABM) and network-based (NB) modeling are the most commonly adopted approaches to develop monolithic interdependent CISs models [1]. A significant challenge when adopting monolithic models is to reasonably model, within a single conceptual framework, the heterogeneous nature and behavior of multiple systems [2]. Heterogeneities in physical network features, transported material properties, operational mechanisms, and disaster response patterns, among the CISs are usually not captured by these models because of the limited ability of these models to incorporate low-level features and domain knowledge of the various CISs within the monolithic model. A few studies have attempted to overcome the limitations of monolithic models by co-simulating multiple CIS models [3, 4]. However, due to the challenges in ensuring the interoperability of complex heterogeneous models, these studies either relied on highly abstracted CIS models or modeled the CISs using general-purpose modeling and simulation tools to facilitate model interoperability. Consequently, the developed models did not incorporate the domain knowledge of each CIS and had a limited ability to simulate the interdependent systems' behavior with sufficient details and accuracy.

This study therefore aims at addressing the challenges in developing interdependent CIS models that can extensively utilize domain-specific knowledge to simulate CISs functions and capture various systemic heterogeneity dimensions among the CISs. The study proposes a framework for modeling interdependent CISs, one that will allow for the integration of multiple fine-grained CIS domain-specific models, leveraging well-tested practices, data, and simulation tools accumulated over years of wide usage in the various

CIS domains. The framework takes advantage of the data management and synchronization capabilities of the high level architecture (HLA) standards for distributed simulation to facilitate the interoperability of multiple CIS models. A case study of two interdependent power and water systems was conducted to demonstrate the efficacy of the framework and reveal the importance of incorporating domain knowledge and accounting for systemic heterogeneity when simulating interdependent CISs behavior.

The proposed framework provides a methodology for developing high-granularity interdependent CISs models that can contribute to unveiling in-depth knowledge on CISs interdependencies, feedback loops, system vulnerabilities, cascading failure mechanisms, and so on, and hence improve the accuracy and reliability of future models for CISs behavior prediction, vulnerability assessment, disaster response management and so on.

2 Background

2.1 Overview of HLA

HLA is an open international standard for distributed simulation platforms, initially developed by the U.S. Department of Defense (DoD) and is nowadays known under the IEEE 1516 family of standards [5]. The HLA simulation environment (federation) allows multiple simulators to work together and seamlessly interact. A typical HLA federation architecture, as depicted in Figure 1, consists of simulators known as federates, a middleware known as the run-time infrastructure (RTI), and a federation object model (FOM). The RTI provides data exchange management, synchronization and coordination services during federation execution. The FOM, which serves as the federation language, contains detailed information about the object and interaction classes, attributes, and data types of the federates, and is designed following the HLA OMT specifications [5].

2.2 Related Work

In his review article, Ouyang [1] reviewed several interdependent CISs modeling approaches. The majority of these approaches model the topological and functional characteristics of CISs, as well as the spatial and functional interdependencies between CISs using generic modeling principles instead of algorithms or nonlinear equations specific to each CIS domain. Wang et al. [6] demonstrated how by doing so, systemic heterogeneities among CISs may not be captured, which could impact the reliability assessment of CISs. This study adopts HLA standards to develop interdependent CISs models using CIS domain-specific models.

In its early stage of development, HLA was used as a gaming environment to simulate joint-attack strategies involving multiple military units, vehicles and aircrafts [7]. Over the years, HLA applications have expanded to a wide range of domains including the modeling and simulation of large-scale computing systems [8], cyber-physical systems [9], infrastructure systems [10], and so on.

Meanwhile, HLA is slowly paving its way into the interdependent CISs domain. A few studies have adopted HLA to develop interdependent CISs models. In these studies the simulator outputs are either directly exchanged between the CIS models through the RTI middleware [11], or merged in an abstract model to reproduce the inter-system interactions [12]. The limitation of the former is that only simple interactions can be modeled when using heterogeneous CISs simulators because the simulators have limited ability to manage and assimilate the data published by the other simulators. The limitation of the latter is that by abstracting the functionalities of the system components, the developed compound model may significantly lose its ability to accurately simulate systems behavior since portions of the data representative of component states, functions and operations are lost. The above limitations arise due to the challenging task of achieving the interoperability of heterogeneous models. Most prior studies therefore either relied on general-purpose simulators, which can provide better interoperability but lack simulation functions specific to the modeled CIS domain, or simply adopted homogeneous models to represent their CISs. Consequently, the developed models could not leverage the CIS domain knowledge offered by specialized simulation tools and could not reasonably account for systemic heterogeneities. Therefore, the HLA-based framework proposed in this study aims to address the above limitations.

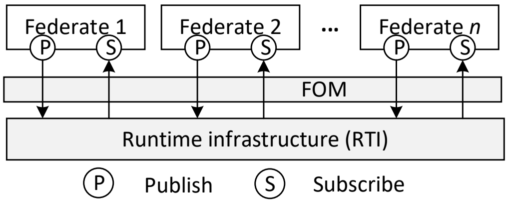

Figure 1. HLA federation architecture

3 Methodology

With the aim of incorporating CISs domain knowledge and capturing systemic heterogeneity when modeling and simulating interdependent CIS, this study proposes to integrate and coordinate fine-grained CIS domain models in a compound interdependent CISs model. The proposed framework presents a federation architecture that describes the structure of the interdependent CISs model as well as its data management and exchange scheme.

3.1 Interdependent CISs Federation Architecture

When studying the behavior of interdependent CISs, the developed interdependent CISs model must accurately represent the topology and functionalities of the CIS, and capture, with high fidelity, the various formalisms governing the CISs interdependencies and their interactions with the external environment. To meet the above requirements, the interdependent CISs model is developed as an HLA federation consisting of a few functionally distinct modules that communicate via a central RTI, as illustrated in Figure 2. A module is a federate or a group of associated federates responsible for simulating a particular system, agent or factor composing the interdependent CISs model. There are three types of modules, namely the CIS modules, User module, and External Environment module.

The CIS module consists of all the models and simulation tools responsible for simulating a particular CIS. These can include a CIS simulator for modeling the system's physical network and component functions, as well as management and control simulators for modeling additional management and control functionalities such as SCADA (supervisory control and data acquisition), backup systems, decision-making, and resource allocation. The External Environment module consists of the simulators necessary to model and simulate various external factors that affect the CISs, such as socio-economic variables, government policies, natural disasters, and so on. The User module consists of the user interfaces necessary to facilitate the interactions between the federation users and federation components such as GUI (graphical user interface), GIS (geographic information system), data output monitor, visualization tools, and so on.

3.2 CIS Module Implementation

Each CIS module comprises three layers, including the application layer, organizational layer, and communication layer.

The application layer consists of the various domain simulators responsible for simulating the CIS and its management and control functionalities. Some CIS models might have the management and control functionalities embedded within their simulators, in which case extra management and control simulators are not needed.

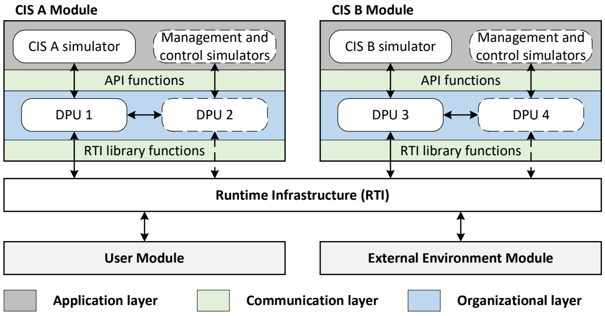

Figure 2. The proposed interdependent CISs federation.

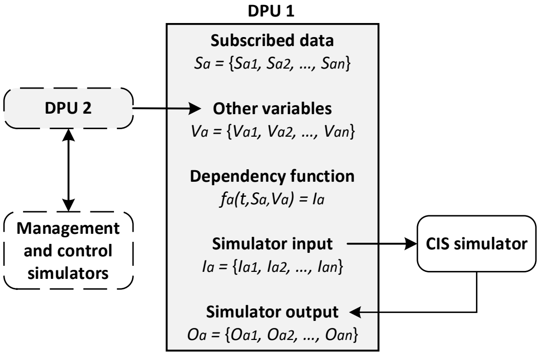

Figure 3. Data management and exchange through the DPUs.

The organizational layer consists of data processing units (DPUs) that process subscribed data to generate input data that can be assimilated by simulators in the application layer. The DPUs can be used to model functions such as failure dynamics of components, data conversions, and so on. The organizational layer can be implemented as a single DLL (dynamic link library) wrapper file that contains all the DPU functions, or as multiple small programs.

The communication layer consists of the application programming interface (API) function libraries and RTI libraries necessary to control the simulators and communicate with the RTI. API functions are specific to a simulator and are used to invoke model functionalities that edit, update or retrieve model attributes. The RTI library consists of the federate ambassador and RTI ambassador that allow the RTI to manage calls and callbacks between the CIS module and the rest of the federation.

The data exchange mechanism of the CIS module, depicted in Figure 3, is controlled by the DPU of the organizational layer. The DPU identifies the subscribed data (S) and other variables (V) provided by the management and control simulators, if any. It then processes the subscribed data by means of dependency functions (f) to generate the simulator input (I). The input and output data of a simulator are values assumed by entity attributes at time (t) of the simulation. An entity is a model component that plays a particular role during simulation. An attribute is a parameter that characterizes an entity. The DPU can also retrieve simulator output (O) to be published to the rest of the federation as well as generate logfiles for the model users.

4 Case Study

4.1 Case Description

The proposed framework was tested in a case study of the Shelby County's interdependent water and power supply systems. The topology of the case systems was adapted from [13, 14] and considered only the major facilities and trunk distribution elements of the systems, as described in Section 4.1.1 below.

4.1.1 Topology of the Interdependent CISs

The Shelby County power network consists of eight gate stations that act as the system's supply facilities. The electric power is then transmitted via 115 kV and 23 kV transmission lines to 23 kV and 12 kV substations which relay the electric power to end-users loads. The dense power grid of the original system was simplified to avoid undue complexities in modeling by considering only 17 substations, nine of which supplied power to the pumping stations of the water network. Figure 4 depicts the simplified power supply network.

The Shelby County water supply system consists of nine pumping stations which draw water from deep wells and deliver it to six elevated storage tanks and numerous distribution nodes via buried pipes. The node elevations range from 63.6 m to 126.6 m and pipe diameters range from 16 cm to 122 cm. The network was simplified to consider 43 distribution nodes and 71 pipelines that can reasonably represent arterial water mains and major secondary feeders. Figure 5 depicts the simplified water supply network.

4.1.2 System Interdependencies

The power and water supply systems depend on each other to perform their intended functions. The power substations supply electric power to the pumping stations of the water supply system, and thus the power consumption of the pumps was modeled as loads on the power substations. Meanwhile, the generators of the power supply system depend on water supplied at the water distribution nodes, and thus the power generators were modeled as demand nodes on the water network. The interdependent system facilities were coupled based on their geographic proximity. Each pump station and power generator were linked to the closest power substation and water node, respectively, as depicted in Figure 6.

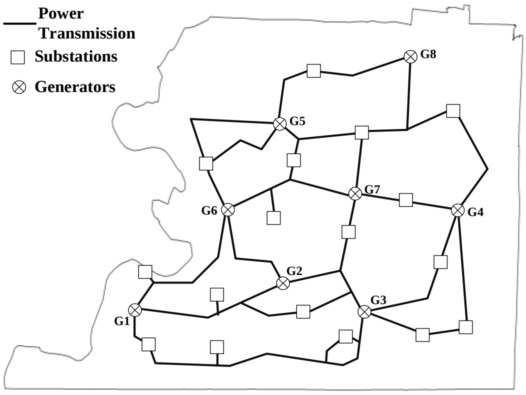

Figure 4. Topology of the power system (not to scale).

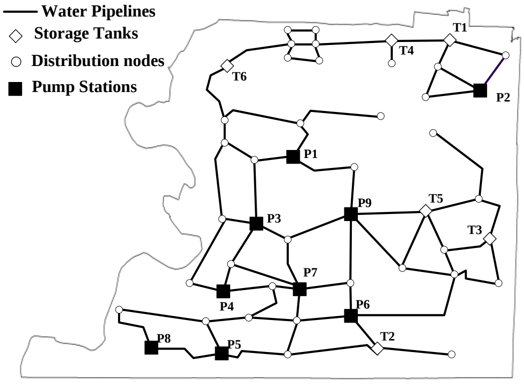

Figure 5. Topology of the water system (not to scale).

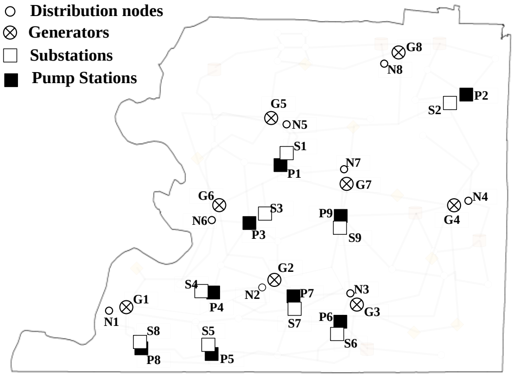

Figure 6. Dependent component pairs of the case systems.

4.2 CISs Model Development

The development of the model followed three steps, namely design of the simulation scenario, selection of the CIS domain models and simulation tools, and implementation of the interdependent CISs federation.

4.2.1 Design of the Simulation Scenario

A simulation scenario is designed that can showcase various system functionalities that are unique to each CIS domain, and hence reveal a variety of systemic heterogeneities among the simulated systems and how they affected system behavior.

Under the designed simulation scenario, the interdependent systems are simulated under normal operating conditions for 48 hours. The water flow and pressure requirements at each node during the simulation period are predefined based on a typical urban daily water consumption pattern, with the least demand between 12 am and 6 am, and peak demand around 8 am and 7 pm [15]. Water is pumped from water wells by the nine pump stations and delivered to the distribution nodes and elevated water tanks. If the actual water flow and pressure at the water distribution nodes is above the demand, the tanks will fill up, otherwise the tanks will empty out to increase the water flow and pressure at the distribution nodes. The operational state (open or closed) of each pump is controlled by the water level in tanks and the water pressure at the distribution nodes. Each pump has a performance curve which determines its power consumption during operation. This power is supplied by the power substation it depends on. To meet the power demand of the pump stations, the substations relay the power generated at the eight power generators of the power network.

4.2.2 Selection of CIS Domain Models and Simulation Tools

Highly specialized simulation tools were selected to accurately model the systems topology and functionalities, and to leverage the domain knowledge of each CIS. The water supply system was modeled using the EPANET v2.2 software, a widely used open-source software application for modeling and simulating water distribution systems that can execute a comprehensive set of hydraulic analyses. The electric power supply system was modeled using the OpenDSS v9.0 software, a comprehensive simulation tool for electric utility power distribution systems that has been used in support of various research and consulting projects requiring distribution system analysis. No additional system control and management simulators were required for this case study since EPANET and OpenDSS could model both the physical network and supervisory control system of the infrastructure systems. Communication between the federates was established using the CERTI v4.0 middleware, which is an open-source HLA RTI that supports HLA 1.3 specifications (C++ and Java), and partial IEEE 1516-v2000 and IEEE 1516-v2010 (C++) standards. In this case study, interactions between the federation and federation users were completed within the user interfaces of the federates selected above; thus, no additional tools belonging to the User module were required.

4.2.3 Implementation of the Interdependent CISs Federation

Based on the simulation scenario and datasets of the selected domain models, the publish-subscribe schemes of the federates were defined and illustrated in Figure 7. The publish-subscribe schemes and the dependency relationships between the system components were then used to develop the DPUs of each federate in MATLAB.

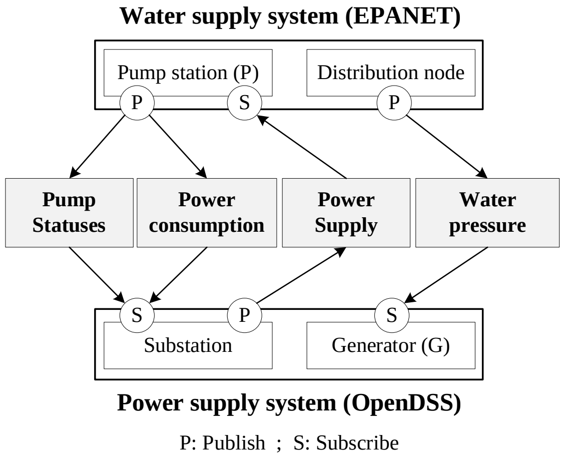

Figure 7. Dependent component pairs of the case systems.

The FOM was developed using an FOM editor tool developed by MAK Technologies and contained information about the data exchanged between the federates (also known as objects), and the event types that affected both systems (also known as interactions). Table 1 summarizes the main content of the FOM.

The federates were then connected to the RTI to create, test and debug the federation. To create the federation, the Master federate (in this case refers to the water system federate) loaded the FOM to the RTI and set a federation name. The federation was joined by both federates which then declared their publish-subscribe schemes. The Master federate initiated the LoadScenario interaction followed by the Start interaction, which triggered the simulators to load the simulation scenario data and simultaneously start executing the simulation scenario. The PauseResume interaction could be initiated by the Master federate at any time during the simulation to pause or resume the federation execution. The RTI managed the data exchange and time synchronization between the models and printed event logs that were used to debug the federation. The final simulation output of each federate was generated by its DPU as spreadsheets, enumerating all entity attributes of the federate at each simulation time step, for follow-up analysis. After the simulation was completed, the federates resigned from the federation execution and disconnected from the RTI. The federated interdependent CISs model was executed under the predefined simulation scenarios, and detailed results are reported in the following section.

Table 1. Main content of the FOM.

	Class	Attribute/Parameter
Interactions	LoadScenario	ScenarioName
		SimulationTime
	Start	
	PauseResume	
Objects	Pump	Status
		PowerConsumption
	DistributionNode	Demand
		Pressure
	Pipe	Flow
		Diameter
	Tank	WaterLevel
	SubstationLoad	PowerSupply
	Generators	Status
		PowerOutput
	Substation	Status
		Voltages
	TransmissionLine	Resistance

5 Simulation Results

The developed interdependent CISs model was simulated for 48 hours starting at midnight of day one. Figure 8 shows the statuses of the pump stations, Figure 9 shows the pressures at the distribution nodes over the simulation period, and Figure 10 shows the loads on substations supplying power to the pump stations. The initial status of all nine pump stations at timestamp 0:00 (midnight) was open. Then, water was pumped into the network to meet the water flow and pressure requirements at the distribution nodes. During the night period, the demand at distribution nodes was low, and thus the control system of the water network temporally closed pumps P2, P5, P6, P7 and P9 at timestamps 4:43, 3:35, 3:35, 2:59 and 2:59, respectively, as depicted in Figure 8.

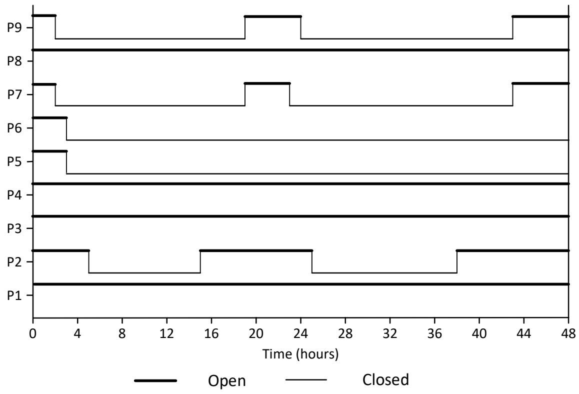

Figure 8. Pump statuses.

Around daybreak when the water demand at the distribution nodes began to significantly increase, a gradual drop in the water pressure throughout the network was observed, as depicted in Figure 9. This drop in the water pressure triggered the control system to reopen pumps P2, P7 and P9 at timestamps 14:02, 18:59 and 18:59, respectively. It can be observed that in the late evening and night, when the water demand was low, the pressure at distribution nodes increased rapidly, triggering the closure of pumps P2, P7 and P9 at timestamps 25:04, 23:22 and 24:36, respectively.

It can be observed from Figure 9 that distribution nodes N4 and N8 demonstrated a slightly smoother pressure pattern compared to the other nodes. This difference in the patterns was due to the positions of N4 and N8 within the networks. These two nodes were isolated from the action of the pump stations and were supplied directly by the tanks, resulting in a steadier water flow.

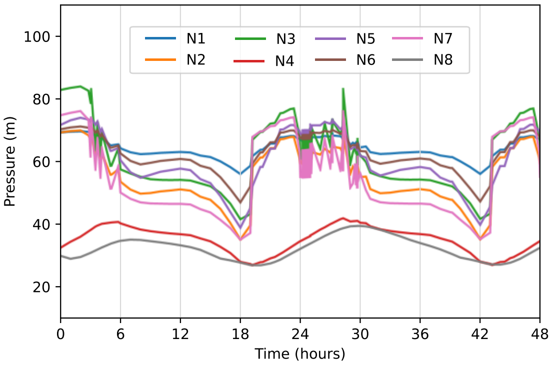

Figure 9. Water pressures at the distribution nodes.

From Figures 8 and 10 it can be observed that when the status of a pump station was closed, the load at the corresponding power substation was at minimal power value close to zero. On the other hand, when the status of a pump was open, the load on the corresponding substation would vary according to the power consumption of the pump. Changes in pump status would cause a sudden drop or rise of the power substations loads. In addition, it can be observed that during the night time when the pumps were less solicited, the loads reasonably dropped as it would be expected in reality.

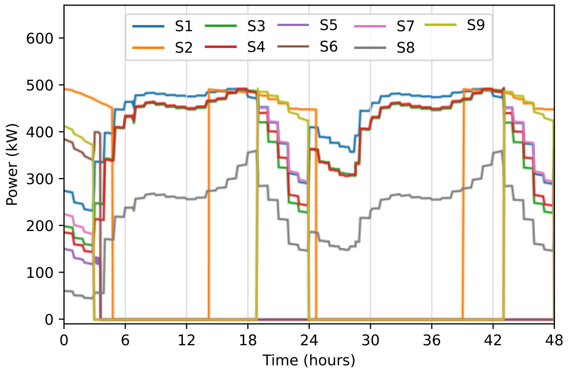

Figure 10. Loads on substations in scenario one.

6 Discussions

It can be inferred from the simulation results that by adopting domain specific models to simulate the CISs, the domain knowledge from each CIS was incorporated in the developed interdependent CISs model and significantly impacted the systems' behavior. The system components exhibited unique functionalities, interaction mechanisms and data types because different CIS components followed very distinct physical and/or logical laws specific to their domains. For example, it can be observed from Figure 10 that the power delivered by each power substation was continually changing, implying that the water system model was able to compute and provide specific values of pump power consumption at each time step based on the actual status of the water system. Also, the fact that N4 and N8 exhibited a completely different pressure pattern than other distribution nodes as depicted in Figure 9 shows that the water flow at different sections of the water network was calculated differently depending on the location of critical components such as pumps and tanks. These observations demonstrate a significant improvement in the level of details of the simulated systems behavior compared to existing interdependent CISs models in which only the operational states of system components or harmonized flow indices can be computed. It can therefore be inferred that incorporating a wide range of domain knowledge in the interdependent CISs models can help simulate more realistic and accurate system behaviors.

Previous studies have demonstrated that, by failing to adequately account for systemic heterogeneities when modeling interdependent CISs, the accuracy of the simulated systems behavior might be significantly affected [6]. To verify the efficacy of the proposed framework in capturing systemic heterogeneities among CISs, the simulation results should reveal a variety of systemic heterogeneities among the simulated systems and their impacts on the behavior of CISs. Among the systemic heterogeneities captured by the developed interdependent CISs model, the heterogeneity in material flow properties had the most significant impact on systems behavior. It can be observed from Figures 9 and 10 that changes in the water levels within the water network were relatively slow and gradual, while redistribution of flow within the power distribution system were abrupt. The heterogeneity in material flow properties can significantly affect the way and speed at which the systems respond to the events to which they may be subjected, such as component failures, system restoration sequences, and so on. By adopting homogeneous modeling frameworks and oversimplifying CIS models, the existing interdependent CISs modeling approaches fail to capture most of these critical systemic heterogeneities, resulting in their limited ability to accurately simulate system behavior, hence justifying the need for the proposed framework.

In summary, the developed model was able to leverage the domain knowledge of both CISs and capture various heterogeneity factors among the CISs, thus meeting the objectives of this study.

7 Conclusions

Critical infrastructure systems (CISs) interdependencies have a significant impact on CISs behavior under different operational conditions. As modern CISs are becoming increasingly complex, the modeling of their behavior requires models that can accurately represent the topological, functional, and operational characteristics of the systems. This study addresses the limitations of existing modeling approaches by proposing an HLA-based framework for modeling and simulating interdependent CISs that integrates the domain knowledge of CISs and accounts for systemic heterogeneities.

The case study results showed that by adopting CIS domain specific models, the developed interdependent CISs model was able to model the systems' topology and functions with more details, while revealing the impact of systemic heterogeneities on the interdependent systems' behavior. Therefore, models developed using the proposed framework can help unveil new knowledge on CISs interactions, responses, cascading failures, and so on, pushing the boundaries of research on interdependent CISs.

The proposed framework suffers two technical limitations. Firstly, when using off-the-shelf simulation tools to model and simulate the CISs, the amount of control the user has on the models strictly depends on the available simulator APIs. Secondly, when implementing CIS modules composed of multiple simulators with complex interactions between them, the overall updating rate of the module may be affected, resulting in longer processing time compared to other approaches. These limitations will be addressed in the authors' future works.

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